J. Ind. Geophys. Union (July 2006)
Vol.10, No.3, pp.241-254

Electro lithofacies analysis for depositional history and stratigraphy of Manuguru Coalfield using geophysical well logs

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ABSTRACT
The present study is perhaps the first attempt of applying geophysical log method in stratigraphic correlation of Permian Gondwana sequences of India. The concepts of electrofacies analysis and sedimentary environments from the conventional geophysical well logs of partially cored wells formed the basic data to build up the Permian stratigraphic framework and depositional history of Manuguru Coalfield of Pranhita-Godavari Valley, Andhra Pradesh, India. The regionally extensive coal seams located at different stratigraphic levels and easily identified by their finger prints/signatures on the geophysical logs are chosen as the genetic sequential stratigraphic boundaries to map the facies distribution of the enclosing strata and view the basin at different stages of development. The correlated strata are also analysed using standard facies maps and suitably interpreted for geometry and depositional architecture. This type of approach that integrated the geophysical and geological information provides an excellent methodology to unravel the stratigraphic complexities of the valley, and a predictive framework to coal and coal-bed methane exploration programmes.

INTRODUCTION

The Pranhita-Godavari Valley located in the southeastern quadrant of Indian peninsula (Fig.1) lacks a reliable stratigraphic succession because of scanty field exposures, gradational contacts of formations. It is therefore opined that the resolution of Permian sequences is possible from borehole data (Dutta 1996; Lakshminarayana 1996; Ramana Murty & Madhusudan Rao 1996). Rao et al. (1996) and Uday Bhaskar, Srinivasa Rao & Shanmukha Rao (2002) established that the geophysical logs are also an important means to analyse the Permian sequences and convincingly proved that the divergent views on the Permian stratigraphy of the valley are because of improper correlation of coals and assigning different age periods of Early Permian Barakar and Late Permian Raniganj/Kamthi to the one and the same coal seam in southern (Kothagudem and Chintalapudi) and northern (Godavari) sub-basins of the valley respectively by the earlier workers. It is therefore suggested considering these regionally extensive coals, easily recognised on the geophysical logs, as the conformable genetic sequential boundaries to map the coeval sedimentary facies of enclosing strata and provide a new understanding of the valley.

The present study, possibly taken up for the first time in India has considered the geophysical logs of 150 wells to build up the depositional history of the Permian sequences of Barakar, Barren Measure and Raniganj formations of Manuguru Coalfield of Godavari Valley (figs 1 and 2 a). In this area, the wells drilled by Singareni Collieries Company Limited are usually cored in the coal bearing Barakar. The overlying formations are mostly non-cored whose analyses are therefore now based on the log data. Also, the present study is a distinct departure from the earlier sub-surface studies that were limited to the Barakar Formation (Vijayam & Sarma 1971; Ramana Murty 1982; Muralidharan 1985; Deshpande & Vijayam, 1989; Rama Rao 1993).

GEOLOGICAL SETTING

The Pranhita-Godavari Valley is a major NNW-SSE trending belt on the Precambrian platform extending over 470 km in strike length from Eluru on the east coast of Andhra Pradesh in the SE to Boregaon of Maharashtra in the NW (Fig.1). It is a 'Crevice' type of platform rift zone containing 4,000 m to 5,000 m fluviatile sediments of Early Permian to Early Cretaceous and considered as the largest single

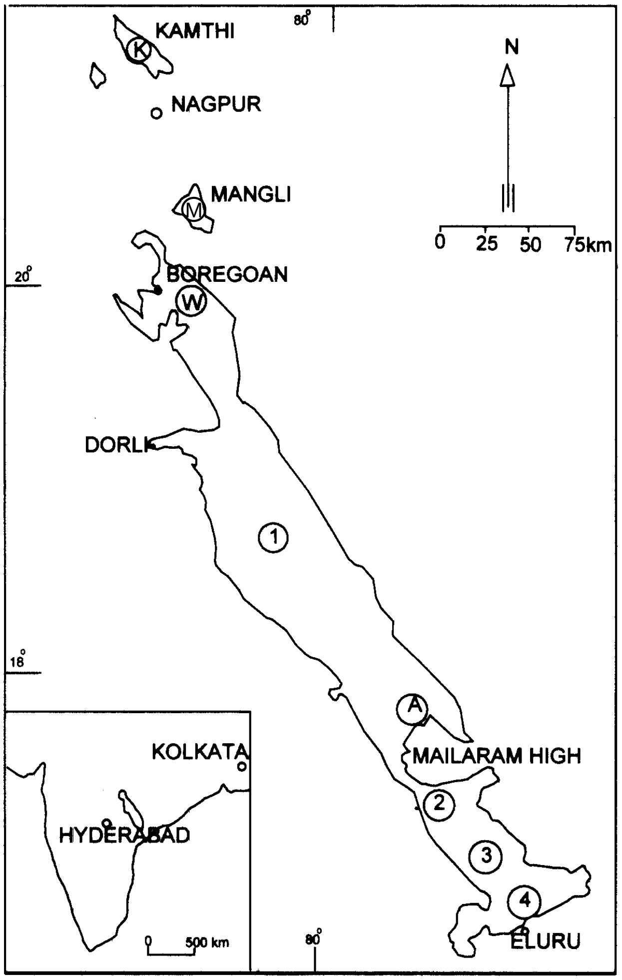

Figure 1. Inset shows the location of Pranhita-Godavari Valley. Simplified geological out line of Pranhita-Godavari Valley. K- Kamthi Coalfield, M-Mangli Coalfield, W-Wardha Valley, 1)- Godavari sub-basin, 2) Kothagudem sub-basin, 3) Chintalapudi sub-basin. 4) Krishna-Godavari sub-basin (After Ramana Murty &. Parthasarathy 1988). A) Study Area.

Gondwana basin belt. Based on the geological and geophysical data the valley is divided into four sub-basins from north to south as Godavari, Kothagudem, Chintalapudi and Krishna-Godavari (Ramana Murty & Parthasarathy 1988) (Fig.1). The potential coal deposits occur essentially in the Early Permian Barakar Formation and partly in the Lower Kamthi/Raniganj of Late Permian period. The Manuguru coalfield located on the southeastern part of the Godavari sub-basin forms the area of study, which is in the Manuguru Mandal of Khammam district of Andhra Pradesh. It falls partly in the Survey of India Topographic Sheet No. 65 C/9 and 65 C/13, being bound by latitude 17° 54' 50" N to 17° 59' 50" N and the longitude 80° 43' 03" E to 80° 50' 47" E (Fig. 2a).

Geologically, the coalfield is located on the northeastern margin of Godavari Valley in its southeastern part and extends over a strike length of 14 km from the right bank of River Godavari in the NE to the village Bugga in the SW. It preserves 900-1000 m of fresh water sediments of the successively deposited Talchir, Barakar, Barren Measure and Raniganj Formations of Permian period (Lower Gondwana) resting unconformably on the phyllite/ quartzite basement rocks of Precambrian Pakhal Formation. The Triassic sequences (Upper Gondwana) of Kamthi, Maleri and Kota are exposed in the dip side of the coalfield. The strike of the formations varies from NE-SW in the eastern and northeastern parts to E-W in the western parts with corresponding northwesterly and northerly dips of 10° to 20°. The Barakar is the principal coal-bearing unit and the overlying Raniganj Formation contains sub-economic carbonaceous horizons. Based on the sub-surface data, the stratigraphy of the coalfield is revised from time to time (Fig.3). The stratigraphic succession proposed by Bose & Chakravarty (1979) and Rao & Bose (1979) was revised by Muralidharan (1984), who considered the Seam-I to be the Barakar, where as the palynological studies found the Seam-I to be equivalent to the Raniganj Formation and that of the underlying strata to the Barren Measure Formation of Damodar Valley (Srivastava & Jha 1992). Accordingly, Ramana Murty & Madhusudan Rao (1996) revised the stratigraphic succession into Talchir, Barakar, Barren Measure and Raniganj formations. Based on the distinct changes in lithology, the Raniganj is now resolved into the Lower and Upper members.

Basement complex and its control on Gondwana Sediments

The analyses of borehole data indicate the presence of topographic highs on the basinal floor in the southcentral and northwestern parts (Fig. 2). The basement highs maintained their identity during the deposition of Talchir and sank below the depositional level by the middle stages of Barakar. Accordingly, the thickness of the Barakar varies from 60 m on the basement highs to 200 m on the depressions. The near absence of Talchir in the west (10-20 m) and its presence in the east (100-150 m) indicates that the western part was a major palaeo high at the onset of Gondwana sedimentation.

METHOD OF STUDY

The spatio-temporal variations of depositional environment produce latero-vertical variations in the

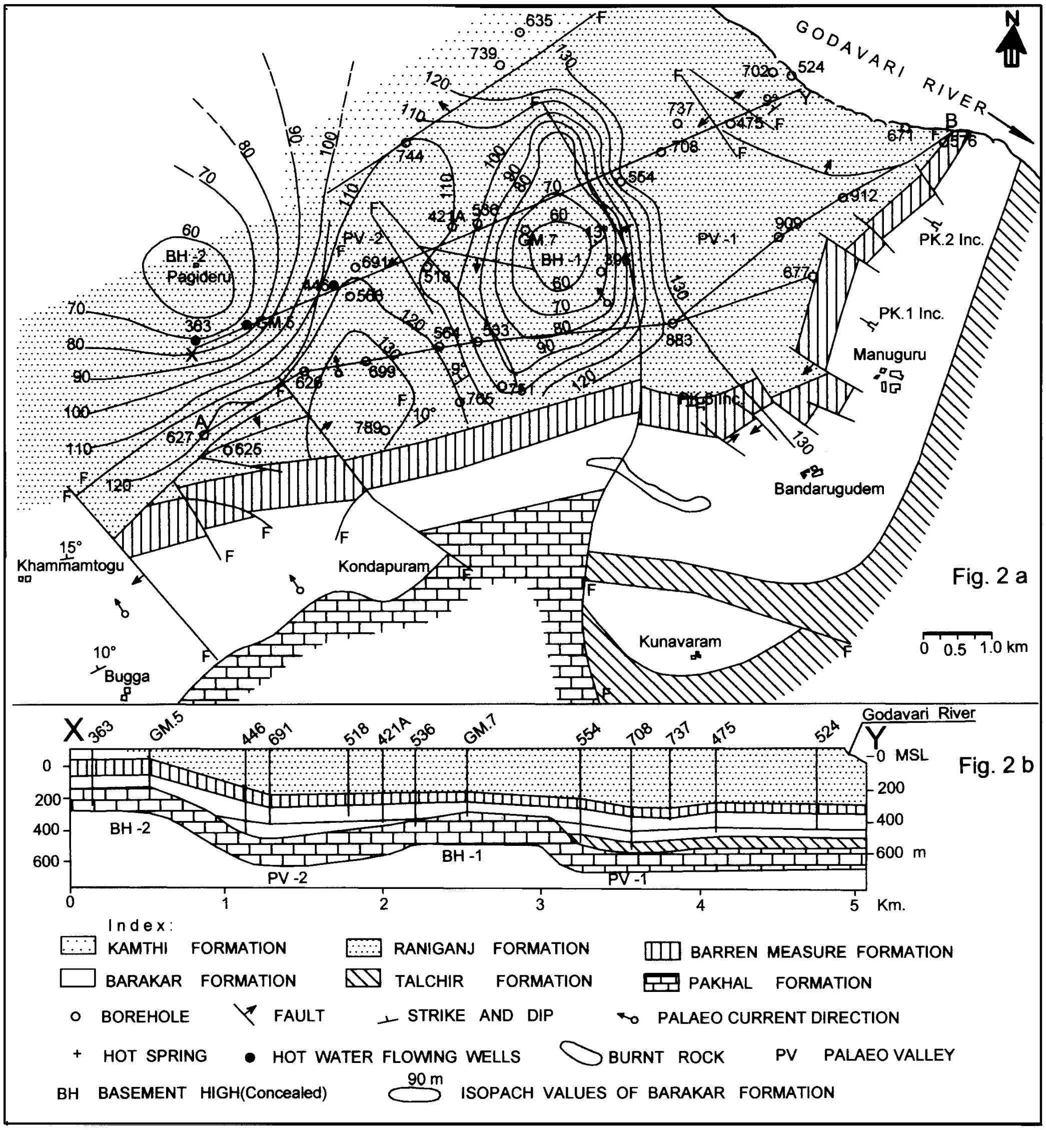

Figure 2a. Geological Map of Manuguru Coalfield and Isopach Map of Barakar Formation and **2b.** Geological Cross-Section Along X-Y (Location in Fig. 2 a)

lithofacies whose analyses enable to reconstruct the depositional history of a sedimentary basin. Serra & Abbot (1980) extended the concepts of lithofacies to geophysical logs and defined electrofacies as a set of log responses that characterise the sediment and differentiate it from the other sediments. The lithofacies thus interpreted from electrofacies is called electro-lithofacies and now considered to reconstruct the depositional history of the Manuguru Coalfield.

The electro-lithofacies of sand-shale-coal sequences dominating the Permian sequences are interpreted from a combination of single point resistance (SPR), short normal resistivity (SNR), natural gamma ray intensity (NG), self potential (SP), gamma-gamma density (G-G), and neutron-neutron (N-N) logs of 150 wells. The grey to greyish white sandstones classified as calcareous subarkose, calcareous arkosic wackes and arkosic wackes have a resistivity of 100-200 Ohm.m (SNR logs), moderate values on SPR curves and negative anomalies (sand line) on SP logs respectively. The wide variations in the NG logs from 40-200 cps are attributed to the variations in the concentration levels of radioactive grains like potassium feldspars, micas, and thorium and heavy minerals in the sand bodies (Rao 1993; Rider 1996) (Fig. 3). The sandstones having a dry density of 2.05 to 2.25 gm/cc, a porosity of 15-25 percent display minimum (50-100 cps) and moderate values (600-1000 cps) on G-G logs and N-

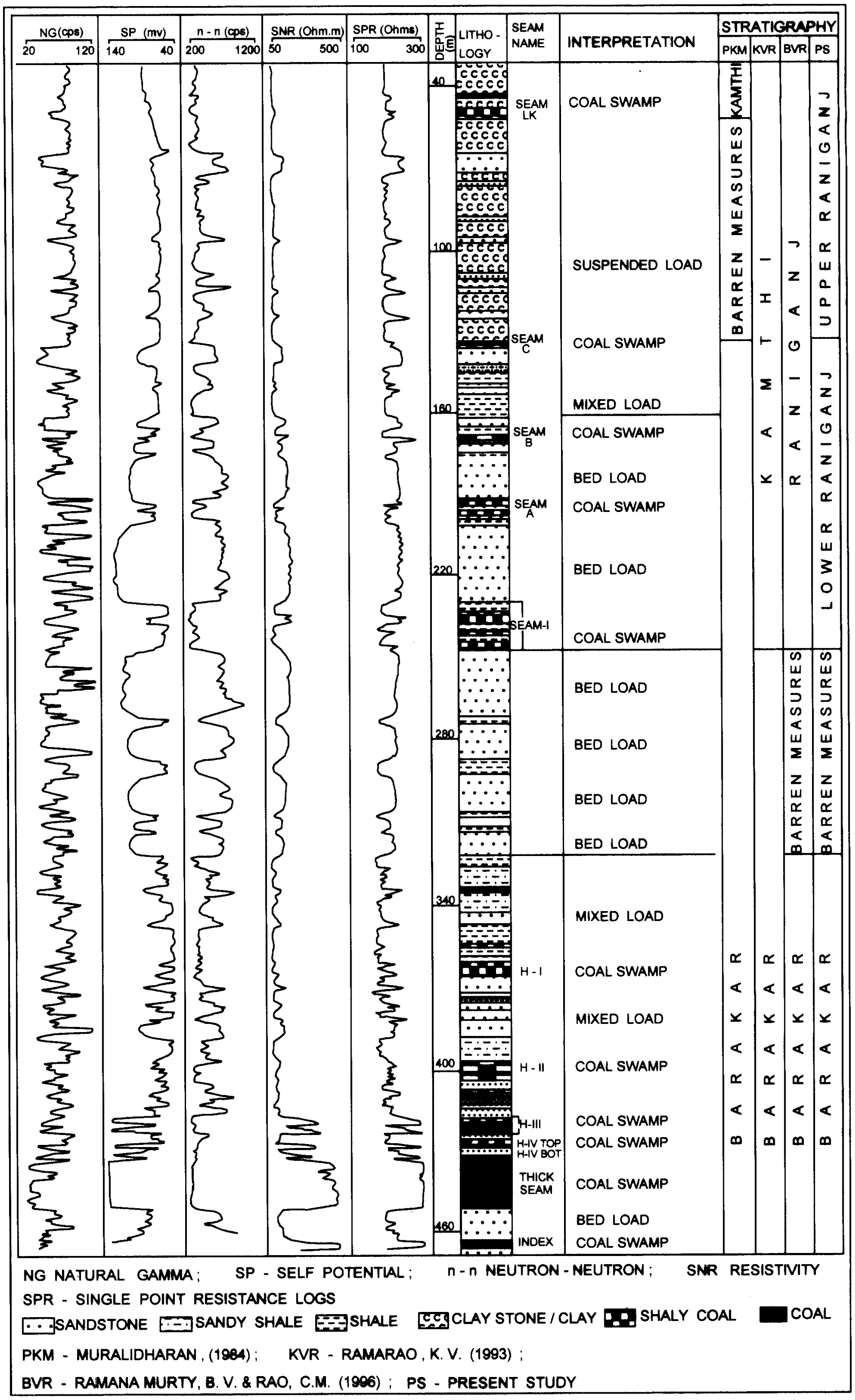

Figure 3. Stratigraphic and Depositional Details Using Geophysical Logs, BH 563, Manuguru Coalfield (Borehole Location in Fig. 2 a).

N logs respectively. The tensile and compressive strengths vary from 10 to 30 and 100 to 200 kg/ cm^2 respectively and the Youngs modulus 0.3 to 0.5. The compact and impermeable hard siliceous sand beds of 2.50-3.00 gm/cc density (10-50 cps, G-G), 3-10 percent porosity (2000-3000 cps, N-N) and a resistivity of 300-600 (SNR) appear as resistive and negative peaks on SNR on SP curves respectively and display low values of 20-40 cps on NG curves. The argillaceous sequences comprising sandy shale, shale and clays display 10 to 50 Ohm.m on SNR and low values on SPR/, N-N (200-500 cps) and high NG counts of 100-200 cps. The SP curves show positive anomalies and form the shale line. The variations in the electrical and N-N log curves within the sand-sandy shale-shale/clay sequences indicate the variations in the grain size and shale content. The densities of the argillaceous sequences being similar to the sandstones display low values of 50-100 cps on G-G logs. The intercalated shales with sands and sandy shales have densities greater than 2.40 gm/cc, higher values of tensile (35 kg/cm^2) and compressive strengths (400 kg/cm^2). The indurated clays and claystones have high densities of 2.65-3.25 gm/cc. The coal seams with ash and moisture contents of 8 to 30 and 3-8 percent respectively and a specific gravity of 1.40 to 1.55 show high resistivity of 500-600 Ohm.m, low values of 20 to 50 cps on NG logs. The G-G and N-N logs record maximum and minimum values respectively. The SP logs show both positive and negative values across the coals. An increase in the ash and moisture contents (30-50) increases and lowers the specific gravity and resistivity to 1.55-2.00 and 500-50 Ohm.m respectively and increases the gamma counts to 50-150 cps. Accordingly the carbonaceous horizons are classified into carbonaceous shale (55%>ash+moisture<75%), shaly coal (40>ash+moisture<55%) and coal (ash+moisture<40%). The various coal seams show characteristic responses called 'finger prints/signatures' on the log curves indicating the unique depositional conditions and facilitate easy identification and correlation from one well to another

The sedimentary environments were interpreted by comparing the shapes of electrical and N-N log curves with the depositional patterns of Allen (1975), Galloway & Hobday (1983) and Serra (1989) (Fig.3). The massive sand bodies having sharp contacts with the underlying and overlying shale beds exhibiting cylindrical shapes on electrical and N-N logs are interpreted as the sediments of braided (bed-load) channels. The inter-bedding of sand, silt and shale of varying thickness indicate a series of changing conditions of environment existing in a shifting river channel or flood plain and are considered the mixed-load deposits. The argillaceous sequences of shale, clay and claystone are interpreted as the flood basin (suspended-load) deposits. The electro-lithofacies sections/maps were constructed to interpret the spatio-temporal variations in depositional environments prevailed during a stratigraphic unit. The stratigraphic maps (isopach and net sand percent maps) bringing out the three dimensional geometry of the depositional system were constructed and interpreted by following the principles of Krumbein & Sloss (1963). The data of Talchir being scanty and limited to few boreholes did not give scope for detailed studies.

DISCUSSION

Electro-Lithofacies Analysis of Barakar Formation

The Barakar has a maximum thickness of 200 m and contains sandstone, clay, shale, siltstone, carbonaceous shale and seven persistent coal seams locally known as Index Seam, Bottom and Top sections of Thick seam, H-IV (Bottom and Top), H-III, H-II and H-I in ascending order (figs 3, 4 & 5). The Index Seam of 2 m thickness lies about 20 m to 30 m above the boundary of the Talchir and Barakar formations (BH-699, 627, Fig. 4). The Talchir being made up of fine grained sandstone and shale appears as a conductive feature (25-50 Ohm.m) facilitating its easy resolution from the overlying Barakar made up of medium to coarse grained grey sandstone having higher resistivity of 100-150 Ohm.m. The sandstone extending from the base of Barakar to the floor of Index Seam is now considered the Basal Barakar or Lower Member and the overlying strata extending up to the base of Barren Measure is the coal bearing Upper Member. The sandstone beds displaying cylindrical shapes on the log curves and the argillaceous sediments dominate the enclosing strata of the Index to H-III and H-III to the Barren Measure respectively. Accordingly, the Upper Barakar is now further resolved into the underlying Lower Sequence of bed-load deposits and the Upper Sequence of mixed-load to suspended-load deposits.

The central part of the electro-lithofacies section depicts the development of composite Thick Seam of 24 m thickness, due to the coalescence of Index Seam, Bottom and Top Section of Thick Seam, H-IV (Bottom & Top), H-III and rests directly over the basement high-I. The composite seam splits and diverges into various independent coals due to the development of thick sand beds whose thickness increases towards the palaeovalleys in the east and west. Accordingly, the Lower Sequence of Upper Barakar, which is about 26 m thick and almost made

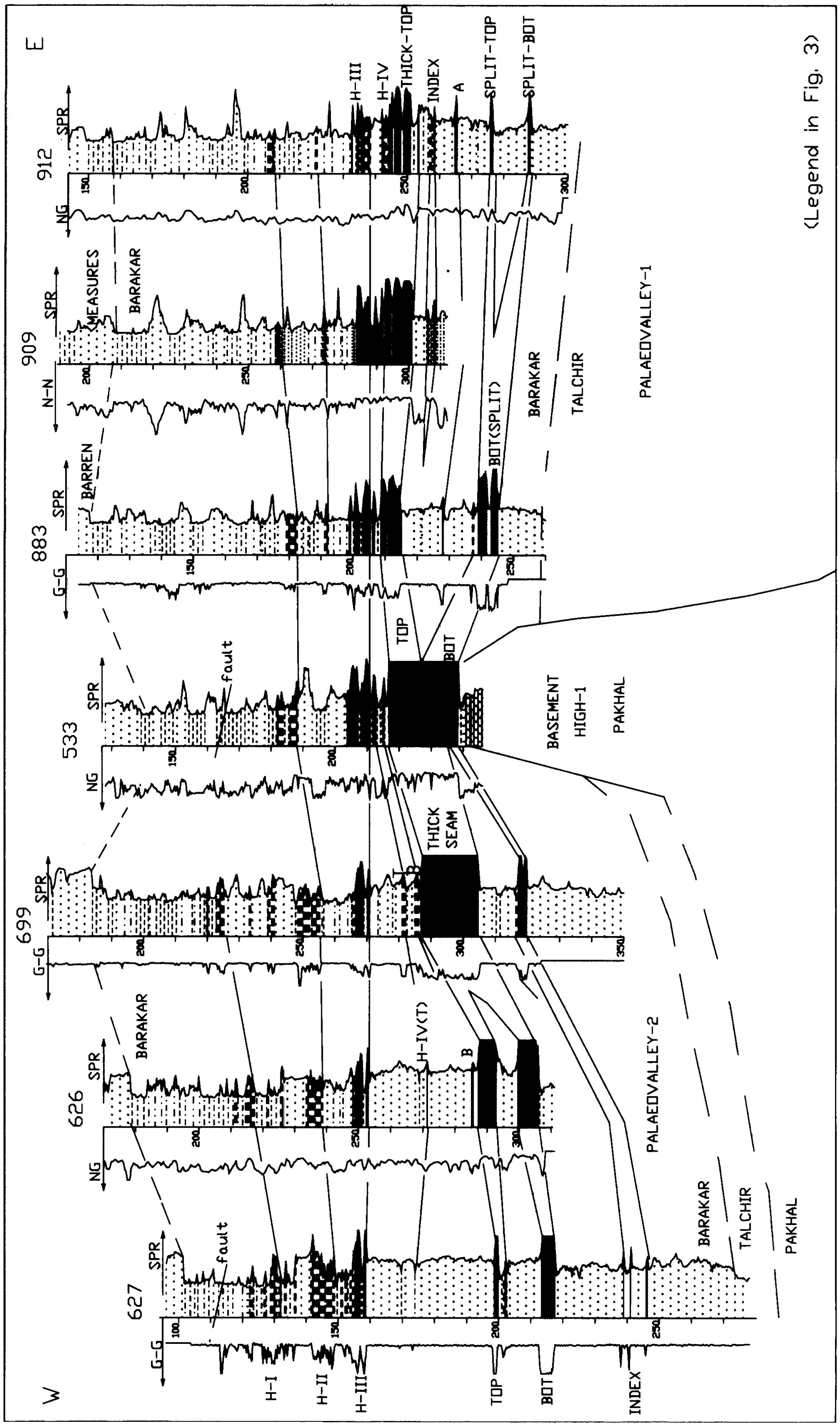

Figure 4. Geophysical Log Responses of Barakar Formation (Borehole Locations in Fig. 2 a)

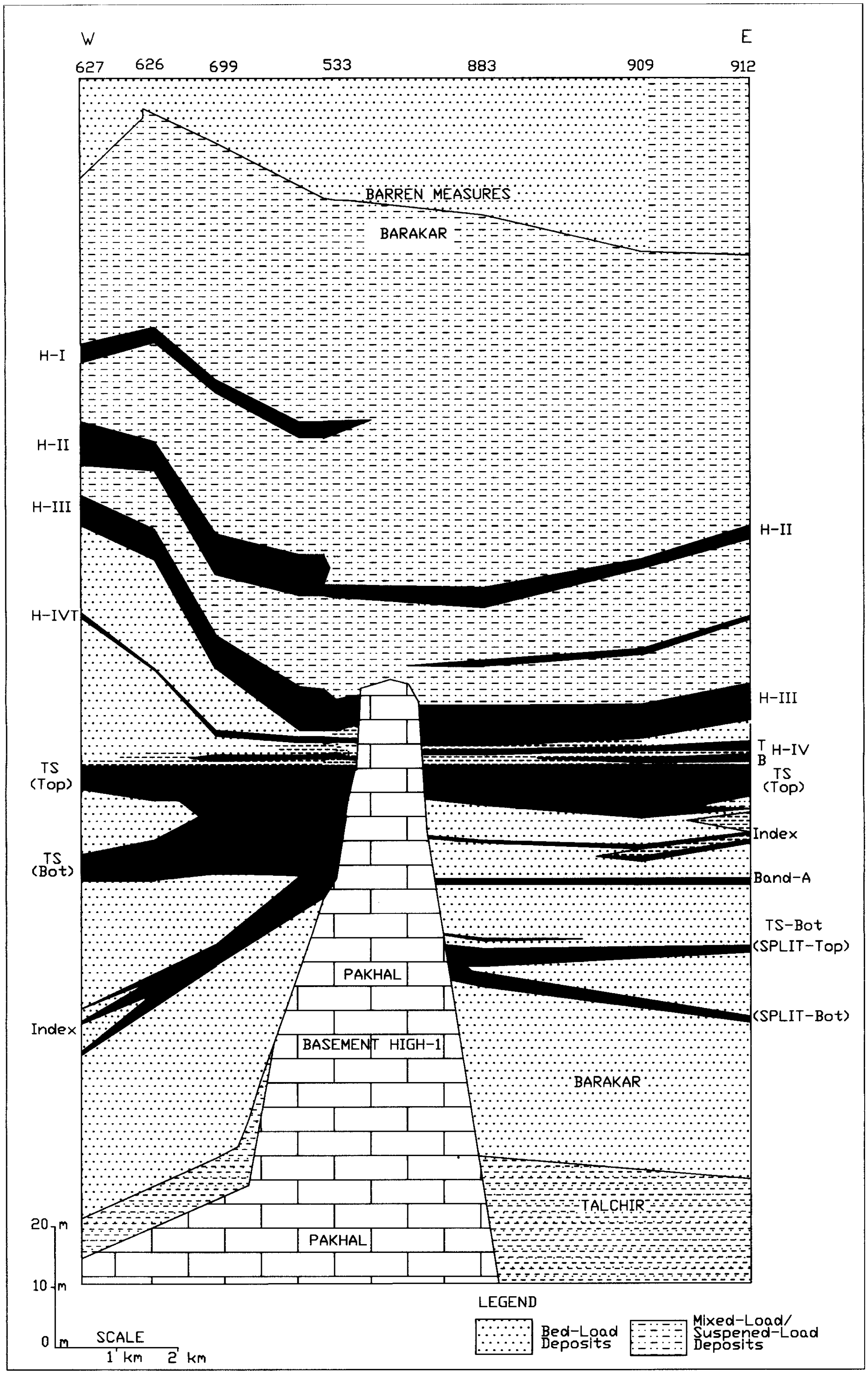

Figure 5. Electro-Lithofacies of Barakar Formation Along Section A-B (Location in Fig. 2 a).

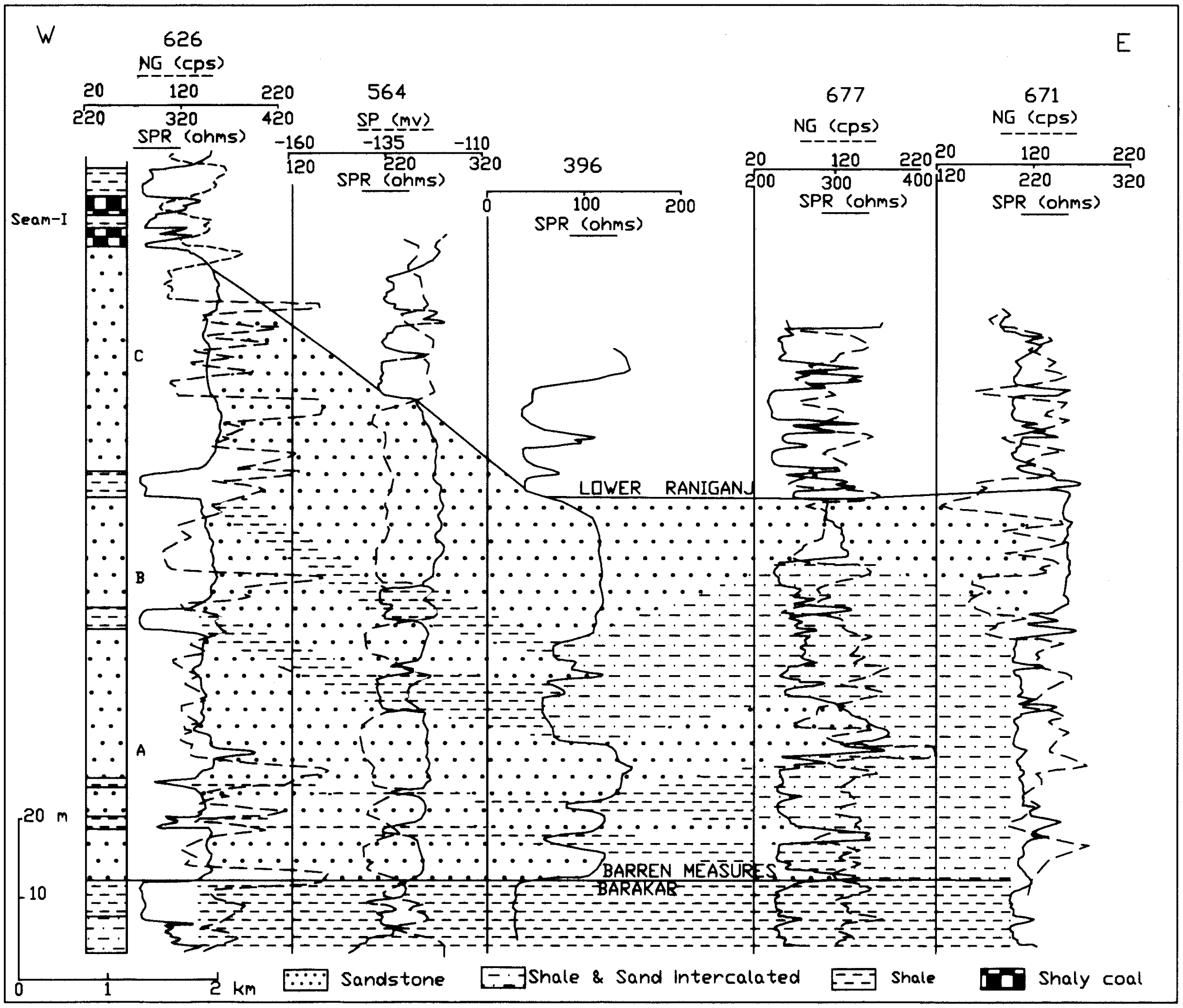

Figure 6. Electro-Lithofacies of Barren Measure Formation (Borehole Locations in Fig. 2 a).

up of coals in the central part, attains a maximum thickness of 90 m and 50 m in the west and east respectively. The sand bodies between the coal seams are interpreted as the stacked fluvial bed-load deposits and the argillaceous sequences in the central and eastern parts are the products of flood basin deposits. The stacking of sand bodies and their separation by the coal seams suggests multiple episodes of abandonment and re-establishment of the fluvial system. The western flanks of the basement high-I favoured the extensive development of Thick Seam and its coalescence with the overlying coals. The bed-load channels that contemporaneously occupied the low land areas of the palaeovalleys produced multiple splits and partial washout of the Thick Seam, indicating the prevalence of turbulent conditions. The splitting which is gentler in the west is more abrupt and geometric in the eastern parts of the basin.

The Upper Sequence of the Upper Barakar dominated by mixed-load to suspended-load deposits is 70-80 m and contains shaly coals H-III, H-II and H-I characterising the decline in coal content. A near parallelism in the various beds and the coals with clastic incursions indicate the prevalence of stable conditions during their deposition with the basin registering slower rates of subsidence. The absence and/or thinning of coal seams in the east indicate the far off regions from the source material. The Seam H-I marking the limit of the coal forming conditions is developed mostly in western parts and is replaced by shale in the east. The mixed-load to suspended-load deposits make up the upper portion of the Upper Sequence and terminate against the sandstone of

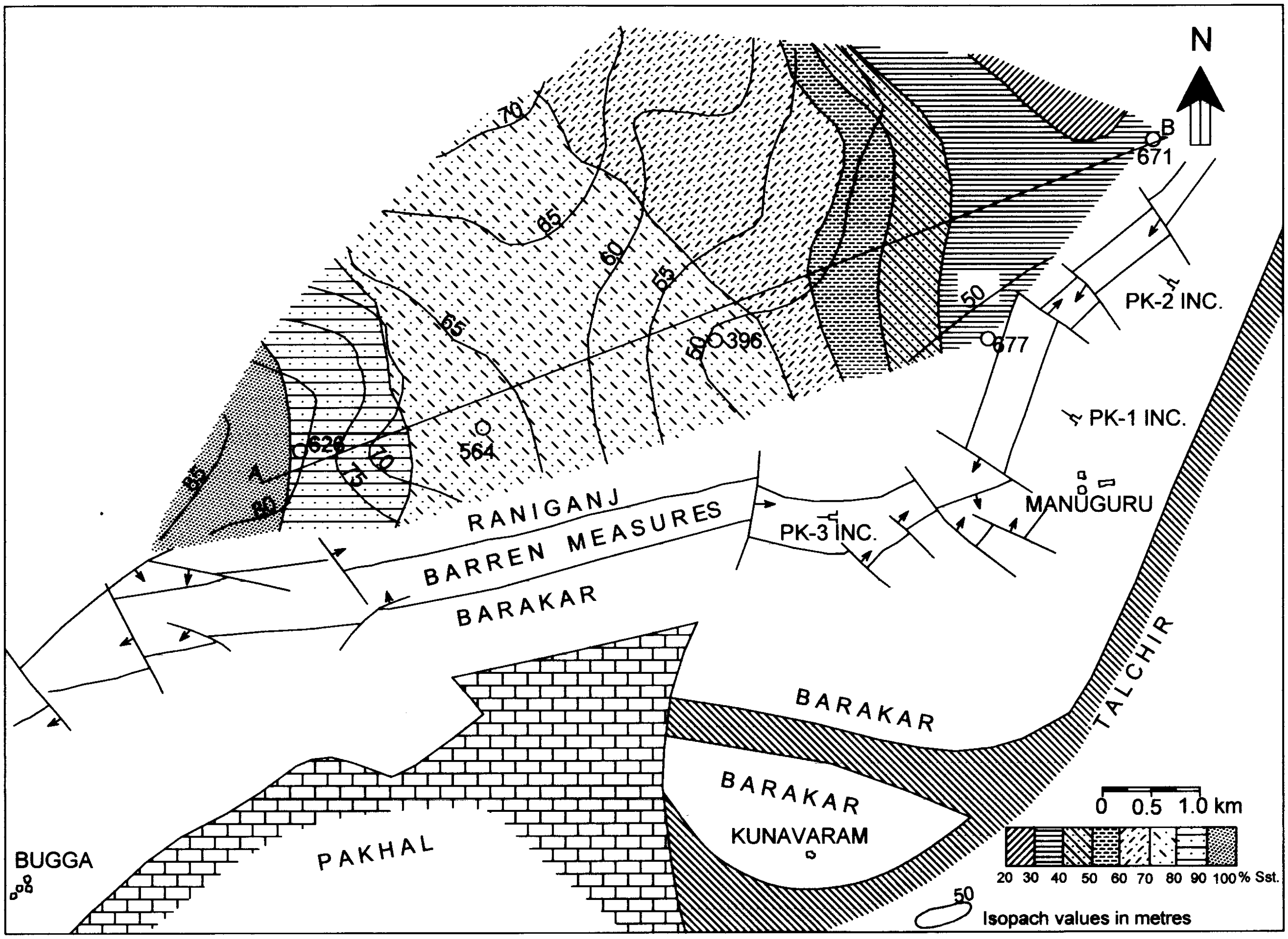

Figure 7. Isopach and Sandstone Percentage Maps of Barren Measure Formation.

Middle Permian Barren Measure Formation.

Thus, the present study brought out the limited development of Lower Barakar and that the variations in the thickness of Upper Member (170 m to 100 m) are due to the presence of topographic highs on basinal floor and extensive coalescence-splitting of coals in Manuguru. On the other, the extensive development of Lower and Upper Barakar of 120 m and 220 m thickness respectively in the north Godavari sub-basin suggest the prevalence of higher rates of syn-sedimentary tectonics towards the north and irregular subsidence and sedimentation in the south (Uday Bhaskar. Srinivasa Rao & Shanmukha Rao, 2002).

Electro-Lithofacies Analysis of Barren Measure Formation

The Middle Permian Barren Measures devoid of coal forming conditions gradationally succeeds the Barakar and marks the return of the braided channels to their earlier courses due to changes in basin tectonics and climatic conditions. The formation of 50-90 m thickness contains a succession of medium to coarse-grained to pebbly massive grey to greyish-white sandstone beds A, B and C of 10-30 m thickness and is punctuated by relatively thin beds of shale and clay (figs 3 & 6). The cylindrical shape of logs indicates them as the bed-load deposits and the overlying shale beds as the inactive channel sequences. The electro-lithofacies section indicates the attenuation and lateral gradation of Sandstone-A and B to argillaceous sequences along the east and the persistence of Sandstone-C over the entire basin with a variable geometry. The lateral gradation of Sandstone–A and B indicates that the bed-load channel was initially limited to the western and central parts and the eastern parts constituted the overbank/flood plain. Later on the bed-load channel covered the entire coalfield and deposited Sandstone-C.

The isopach map of Barren Measures characterises

NE-SW trends in the east to a near N-S in the central parts and tend to close down in the west (Fig.7). The closures of minimum and maximum thickness of 50 m and 85 m in the east and west respectively reflect a westward increase in the subsidence. The western parts constituted the axial parts of the braided channel and accumulated a maximum of 95 percent of sand. The eastern parts being the over bank/flood plain portions of the fluvial system received a minimum of 35 percent of sand and higher amounts of shale (65 percent). The trends of the sand percent and isopach contours reveal the northward flowing channel was straight to slightly sinuous bed-load channel with a high width to depth ratio and is comparable to the theoretical models of Galloway & Hobday (1983, page 71). The discordance in the strike of the isopach and sand percent contours reflects that the composition and thickness of accumulating sediment differed in their response to the contemporaneous subsidence. Also, the gross reduction in the thickness of the formation from 500 m in the northern parts of Godavari sub-basin to 50 m in the south Godavari, Kothagudem and Chintalpudi sub-basins indicates that the southern and southeastern parts of the valley experienced gradual upliftment during the Middle Permian period (Uday Bhaskar, Srinivasa Rao & Shanmukha Rao 2002).

Electro-Lithofacies Analysis of Raniganj Formation

The Late Permian Raniganj Formation having the Seam-I as its base succeeds the Barren Measures along a gradational contact and marks the return of coal forming conditions reflecting changes in basin tectonics and climatic conditions (figs 3 & 8). The coal seams and braided channel deposits and argillaceous sediments dominate the lower and upper parts of the formation respectively indicating distinct changes in syn-sedimentary tectonics with in the Late Permian period. Accordingly, the Raniganj of 600 m thickness is now divided into Lower and Upper Members of 90 m to 120 m and 500 m thickness respectively with the Seam-C as the interface. Similar observations are also made in the north Godavari sub-basin (Ramana Murty & Madhusudan Rao 1996). The Lower Member is now further resolved into Lower and Upper Sequences with the Seam-A as the interface, which marks a change to the mixed-load deposits from the underlying bed-load and coal deposits. The Seam-I of 18 m thickness covers the entire coalfield whose alternating bands of shale and coal reflect the transformation of the depositional sites into a flood basin, within which the coal swamps were developed. The prevalence of tranquil and stable tectonic conditions enabled the Seam-I to accumulate in the entire basin. This was followed by the migration of bed-load channels to their earlier courses and deposited the Sandstone-D of 24 m to 44 m thickness. The limited persistence of Sandstone-E and F of 22 m and 8 m thickness respectively indicates that the bed-load channels were restricted to the west and the eastern parts constituted the mixed-load to suspended-load channels during the period of Upper Sequence. The Seam-A, B and C which are hardly of 1 m thickness indicate periodic transformation of basin into coal swamps with a sharp decline in coal content. The isopach contours of Lower Raniganj having trends similar to the structural strike trend in a near NE-SW direction and swerve to a near E-W in the central regions. A gradual increase in the thickness from 92 m in the SE to 120 m in the NW reflects northwesterly increase in the subsidence (Fig. 9). The localised closure corresponding to a maximum thickness of 120 m observed in the southwestern parts was the main depocentre during the Barakar (200 m) and Barren Measures (85 m). The elongation of the sand percent contours along the NW-SE and net maximum percent in the west reflects that the fluvial system was flowing towards the north with axial parts located in the west, and the eastern parts constituted the over bank/flood plain of the fluvial system. The discordance in the strike of net sand percent and structural and isopach contours indicates that the thickness of the accumulating sediment differed in response to the contemporaneous subsidence.

The Upper Member of Raniganj characterises distinct changes in basin tectonics due to which the depositional sites were transformed into flood basin and accumulated 500 m thick suspended-load deposits comprising light green sandy clay, claystone, and sandy shale, variegated and indurated clays and is devoid of arenaceous sediments. The formation contains 3 m thick shaly coal bed locally known as the Seam-LK, which is located about 80-90 m from the base of the Upper Member (Fig. 3). The argillaceous sequences of Upper Raniganj therefore characterises a decline in the basin's relief, uniform subsidence and a stable environment with an uninterrupted fluvial supply which prevailed up to the Kamthi Formation of Triassic period marking the return of bed-load fluvial system due to changes in basin tectonics.

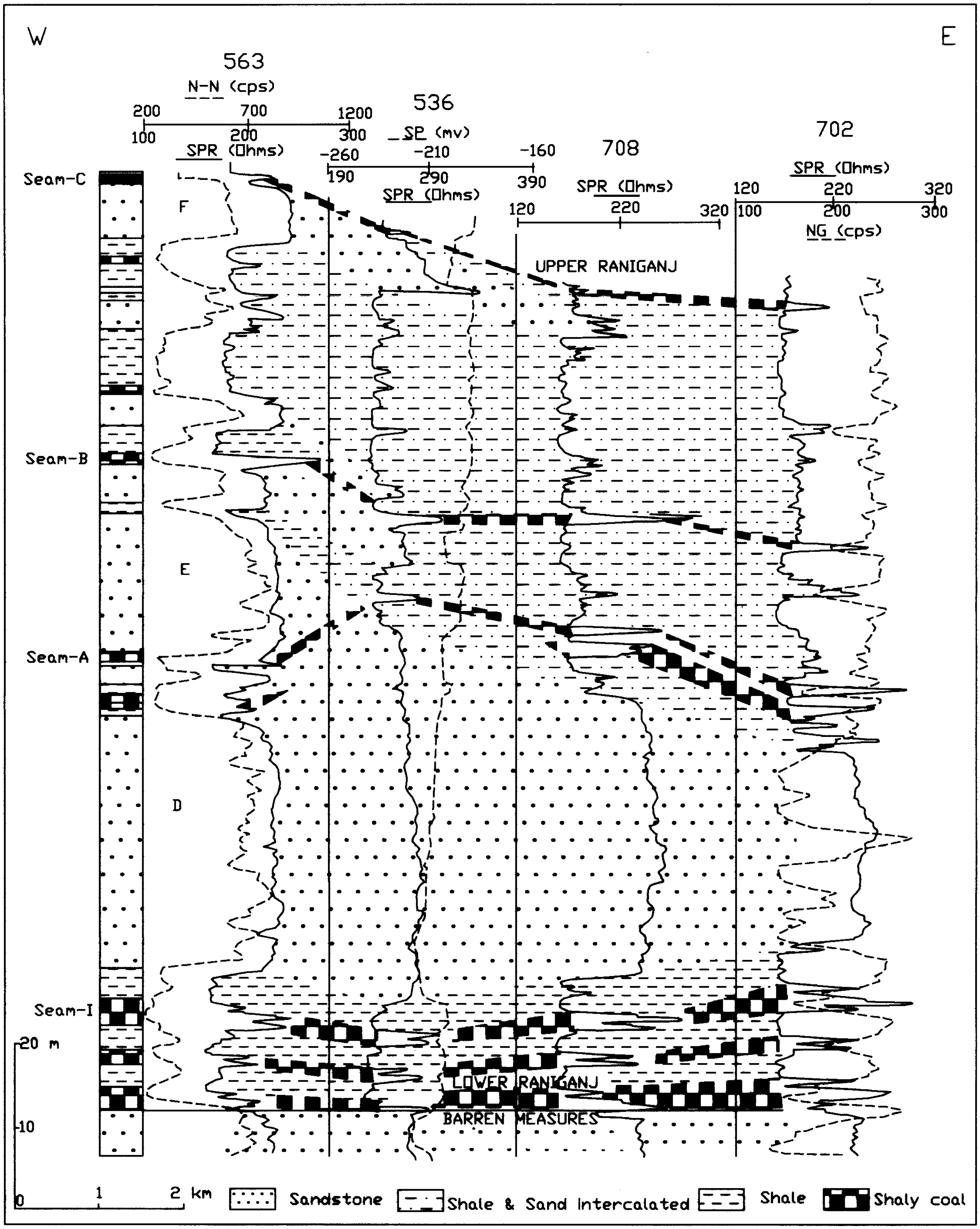

Figure 8. Electro-Lithofacies of Lower Raniganj Formation (Borehole Locations in Fig. 2 a).

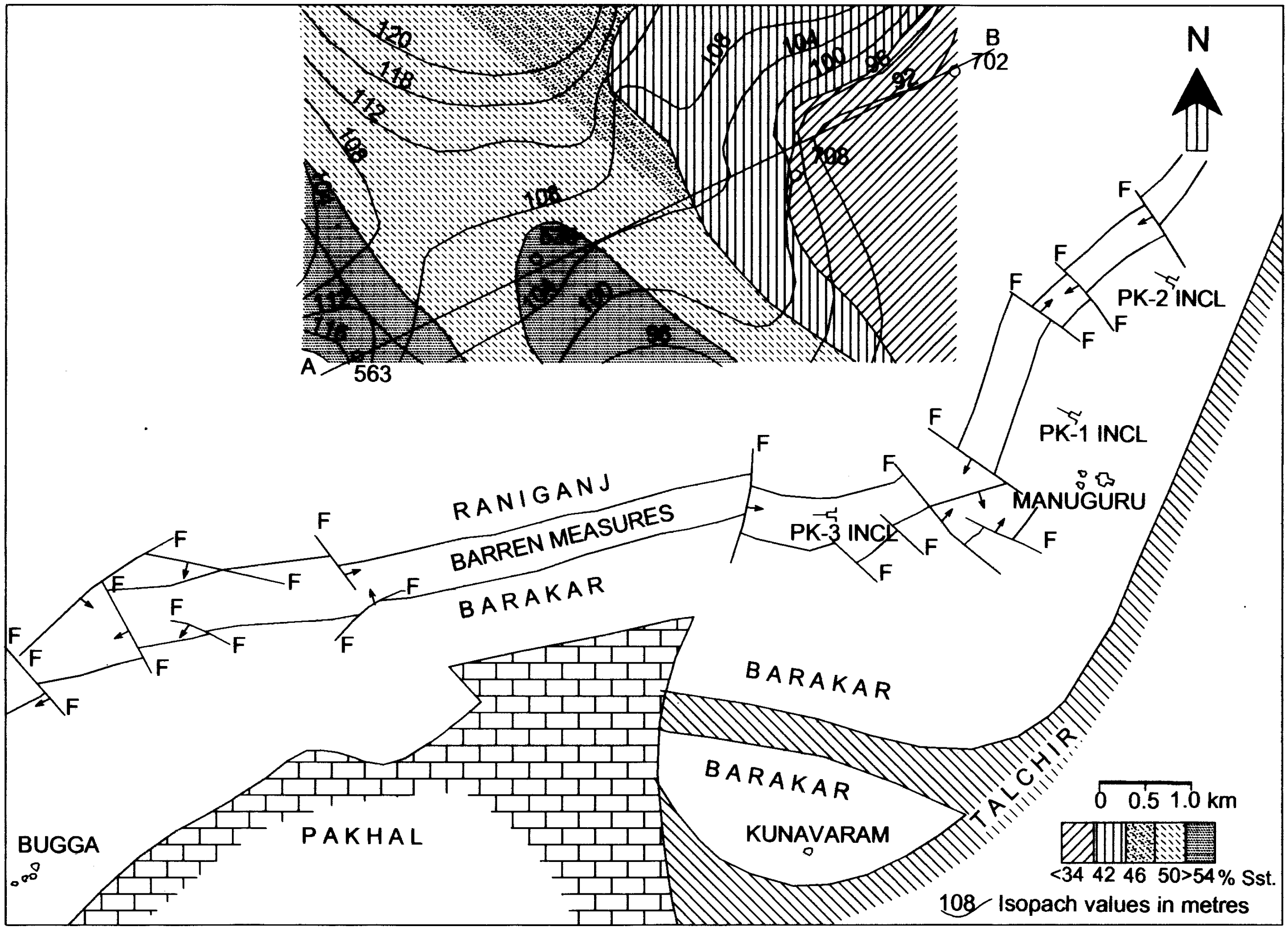

Figure 9. Isopach and Sandstone Percentage Maps of Lower Raniganj Formation.

CONCLUSIONS

The present study has shown that the regionally persisting coal seams characterised by unique signatures/finger prints on the log curves are the appropriate genetic sequential boundaries to resolve the Permian stratigraphic units made up of similar depositional episodes. The characteristic seam signatures can as well form a basis to determine the age periods of the coals by palynological methods. The logs avoid undue dependence on subsurface core samples in providing information of variations in the sub-environments of the fluvial system leading to spatial and temporal variations of lithofacies of the Permian sediments.

The floor of the Manuguru Coalfield was highly undulatory and exercised direct control on the deposition of Early Permian lithounits. At the onset of Gondwana sedimentation, the western parts of the coalfield formed a major topographic high and the deposition of Talchir was restricted to the depression in the east. A limited development of Lower Barakar also indicates a non-deposition/erosional feature. The subsidence-deposition was revived during the Lower Sequence of Upper Barakar and the topographic highs sank below the depositional sites by the period of Upper Sequence. The Upper Barakar depicts multiple episodes of channel abandonment favouring coal forming conditions and development of seven regionally persistent coal seams. The coalescence-splitting and pinching-wash out of lower set of coals and the topographic highs resulted in wide variations in the facies and thickness of Barakar. The Barren Measure devoid of coal forming conditions reflects the rejuvenation/ migration of bed-load channel to its earlier courses in the west and later on extended up to the east. The Raniganj is characterised by transformation of depositional sites into a big coal swamp. The tranquillity in basin's tectonics and change in climatic conditions favoured the basin-wide development of Seam-I and Seam-LK during the Lower and Upper Raniganj respectively. The bed-load channel persisted through the Lower Sequence of Lower Raniganj and was replaced by mixed-load to suspended-load systems during the Upper Sequence and Upper Raniganj respectively.

The calcareous subarkose-arkosic wackes and arkosic wackes reflect a high relief in the adjoining landmass, nearer source of weathered metamorphic or igneous rocks, short transportation, rapid deposition and quick burial with less reworking of sediments. The deposition of the sediments took place on a plain drained by near parallel to low sinuosity braided rivers having their origin in SSW side of the valley and flowed unidirectional towards north. The channels having a high width to depth ratio of 83 changed their sinuosity and position from 1.06 and SSW respectively in the Barakar period to 1.19 and SW to SSE respectively by the period of Raniganj Formation (Hanmanth Reddy & Prasad 1988). The discordance in the trends of stratigraphic maps indicates that the composition and the thickness of the accumulating sediment differed in response to the contemporaneous subsidence and produced variations in the thickness and facies of stratigraphic units even on a local scale. Also, the varied tectono-geomorphic conditions on a regional scale produced significant variations in thickness of Barakar and Barren Measure from 300-350 m to 200 and 500 m to 50 m respectively from the north Godavari to southern sub-basins of the valley. The Raniganj of 600-700 m thickness indicates a near uniform subsidence-sedimentation with varying depositional/sedimentary environments in the basin. The present approach that integrated the geophysical and geological information has provided a new understanding of Manuguru coalfield and can be easily continued to other areas to generate a much-needed unique and comprehensive Permian lithostratigraphy of Pranhita-Godavari Valley.

ACKNOWLEDGEMENTS

The author sincerely thanks the reviewers for their comments and suggestions to improve the quality of the paper. He is grateful to the management of the Singareni Collieries Company Ltd, for permitting to publish this paper presented at the XVIII convention of Indian Association of Sedimentologists, Aligarh Muslim University, Aligarh, held in the year 2001. He specially thanks Sri M. Basava Chary, General Manager (Exploration) for his encouragement. Part of the material is derived from the author's Ph. D Thesis submitted to the Indian School of Mines, Dhanbad under the guidance of Prof. B. N. P. Agrawal, Department of Applied Geophysics, I. S. M., and Sri. K.V. Rao, Dy. General Manager (Geophysics). The views are those of the author but not of the organisation to which he belongs.

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(Accepted 2006 April 18. Received 2006 March 20; in original form 2005 October 24)

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