Chapter 6: Discussion

To achieve the objective of the research work, the shales of Barren Measures of Raniganj Field were studied and described in the proceeding chapters. The Raniganj Field forms a part of Damodar Basin, represents an intracontinental extension tectonic basin formed during Permo Carboniferous time and extended up to Triassic. The basin has accumulated massive thickness of continental sediments deposited under fluvial, lacustrine environmental conditions, and in the initial period glacial and glacio marine deposits. During the evolution of the basin, syntectonic subsidence have induced number of faults and their movements created en-echelon faults, which developed asymmetric basin fills (Chakraborty *et al*, 2003; Dasgupta, 2005) tectonism and climate have controlled the configuration and evolution of the basin, which were reflected in the sedimentary characters and the lithological assemblages.

The basin had filled with glacial sediments followed by marginal marine deposits during Carboniferous- Early Permian time. This was followed by fluviatile sequence of sand, shale and coal. The humid climatic condition is represented by Barakar and Raniganj Formations. In between these two formations, there was a period of arid climatic condition which had enhanced Fe rich sediment deposition of fluvio- lacustrine and devoid of coal (Ghosh, 2002). This unit is referred as Barren Measures, which is mainly represented by various colour shades of silty shales and sand shale intercalations at the base; often exhibit gradational contact with the lower Barakar units. The vertical lithologs clearly suggest that the basal unit of sand shale intercalation represents the fluvial origin, while the dominant shale sequence reflects lacustrine deposits (Sengupta *et al,* 1979). The carbonaceous and siliceous shales are

pointing to the input of organic matters and terrigenous residue (quartz). The laminations within the litho units are indicating the change in the nature of sediment influx and also change in chemical conditions (Eh & pH) of the basin, along with different rate of sedimentation.

The bountiful records of higher plant remains within the shale units imply the sediments have derived from continents; their laminations demonstrate that the sedimentation must have taken place in quiet/ still aqueous conditions preferably in a lake. Occasional finning upward sequence is manifesting the fluvial environments. The colour of the shale is grey to black, on the other hand, the Fe rich reddish brown shale argue that both oxic and anoxic conditions were prevailed during the deposition of Barren Measures. Looking into the litho columns, the limited thickness (0.15m) of Fe rich shale units are restricted to oxic condition, whereas grey to black shales have more thickness connate longer duration of anoxic condition, which is also supported by presence of organic matter and the Fe rich sulphide and carbonates minerals (Demaison and Moore, 1980; Potter *et al*, 1980).

The Barren Measures shales comprise quartz, lithic grains, micas and Fe oxides (hematite), Fe carbonates (siderite), Fe sulphide (pyrites); having silt size grains along with argillaceous matrix. The quartz is the most dominant minerals (avg. 49.02%) and followed by clay minerals 20.69%. The sub-rounded to well-rounded quartz grains suggest that the sediments have been either transported from long distance or multi cyclic grains. Among the heavy minerals, the alumino silicates (andalusite, sillimanite) pinpoint metamorphic source while ilmenite and beryl manifestation mark the igneous source. This is also supported by the occurrence of fresh feldspar. The clay consists of illite, clinochlore ferron, chlorite, smectite, kaolinite reveal the phyllomorphic stage of diagenesis. The existence of kaolinite and smectite illustrate that low pH to high pH condition were prevailed during the deposition and/ or post depositional time. The most important minerals are pyrite, siderite, pyrrhotite

demonstrate that Eh (oxidation reduction potential) varied from positive to negative values. However, the quantity of Fe carbonate (siderite) and Fe sulphide (pyrite) point to more of reducing environment. The anoxic condition may be due to stagnant water in lakes (Schieber and Baird, 2001). Further, siliciclastic represented by silica and Fe carbonates indicate low pH to neutral to slightly alkali conditions.

To evaluate the hydrocarbon generation potential, type of organic matter, maturity, etc., of Barren Measures shale, the author has mainly relied on Rock Eval Pyrolysis and Leco EC-12 Carbon analyzers. The results of geochemical analysis were presented in chapter 4 under organic geochemistry. Here, the inferences from those results are brought out. Barren Measures shales are dominant of grey to black coloured indicates high content of organic matter, and the estimated TOC is 3.75 wt % to 20.9 wt %. Jarvie (1991) method was followed to calculate the original TOC from laboratory measured present day TOC. The calculated original TOC value ranges from 5.85 wt % to 32.65 wt %. Based on the parameters S1, S2, S3 and Tmax generated from Rock Eval pyrolysis, the author has calculated hydrogen index (HI), oxygen index (OI), production index (PI), genetic potential (GP) and maturity. The GP vs TOC and S2 vs TOC cross plots reflects good to excellent genetic potential of hydrocarbon. The values HI and OI of the shales find that the kerogen is type III, which is also supported by Van Krevelen diagram. Further, HI vs Tmax also points early to late matured stage of Barren Measures which are gas prone and capable to producing gas. This is also supported by the occurrence of continental higher plants remains in the shale units. The vitrinite reflectance value calculated individually backed the maturity range of 0.6% to 1.05% and also implies that the organic matters are derived from vascular plants, which can generate the gas. Tmax vs PI plot indicates the thermal maturity of organic matter. In addition, the analytical results of HI, OI and Tmax infer early to late maturity level of the shales. The source rock can generate gas; however the present temperature and depth level is not

necessarily an indicator of its maturity. Maximum burial and required temperature have been occurred in the geological past.

The evaluation of reservoir characteristics include petrophysical properties of rocks i.e. porosity, permeability, density, etc. it is vital to understand the porous media within shale rock to determine the gas storage capacity and gas flow within it. Pore shapes influence the behavior of porous media and flow of fluids. In the previous chapter, the author has described the reservoir parameters of Barren Measures shales which were derived from helium porosimetry, air permeability and advanced imaging techniques like micro computed tomography, scanning electron microscopy and transmission electron microscopy. The porosity of the shales varies from 0.02% to 1.3% and permeability ranged from 0 to 0.18 md. Further, the pores were classified based on SEM and TEM images as intergranular pores, intragranular pores, fracture or cracks and secondary pores developed due to dissolution activities. Most of the pores are meso pores and associated with organic matter and clay matrix. The microstructure, fabric, micro fractures and micro scale fabric anisotropy of the shale are resolved using micro computed tomography images which result 3 to 5% porosity of Barren Measures shales. The porosity results show that the shale is having poor to moderate reservoir quality. The shales are highly heterogeneous, moderate to well sorted and tight. The shale has complex pore structure and dimension, and predominantly nano pores. This has been reflected by TEM images.

In spite of low porosity and permeability, the Barren Measures shales have capacity to hold gas molecules in adsorb state. The quantity of gas adsorption is related to surface area and pore size distribution. The clays in the shales have enough surface area and they are also often negatively charged to attract and hold significant amounts of gas molecules (Kulia *et al*, 2012 & 2013). To understand the adsorb gas in Barren Measures, the BET analysis was carried out and discussed in the earlier chapter. The BET surface area ranges from 0.1201

to15.1135 m^2/g. DFT or t-plot is used for pore volume measurement which results a range of 0.02 to 21.0cc/g adsorbed gas volume of the shale. As per International Union of Pure and Applied Chemistry (IUPAC) classification, size of micropore is <2nm, mesopore 2 to 50 nm and macro pore >50 nm. The pore system of Barren Measures shale is comprised of mesopores with pore size between 20 to 50 nm and macropores with pore size up to 100 nm. The next step, the author has made an attempt to compare the results of Barren Measures shale with analogous gas producing shales of worldwide. To achieve the effective correlation the various parameters of the gas shales of different gas fields of the classical world examples are selected and given in table 6.1. In the proceeding paragraphs, the salient features are discussed. The author had limitation in collection of the boreholes samples, since drilling activities were going on through Barren Measures within Chalbalpur-Mahishmura area only. Though the southern part of Barren Measures is concealed below the Raniganj and occurring at deeper depth, the samples could not be collected. However, the author has extrapolated the subsurface Barren Measures shale lithounits into the southern margin; and visualized that the deeper and depocentres is identified based on the geological data. Further, it is on assumption that the data set have been extrapolated where ever necessary to understand the shales of Barren Measures and it is inferred that the excellent target zone is the deeper and thicker sequences of Barren Measures present at the depocentres of south and south eastern part of the field where maturity is greater than 1.1VRo% high and within gas window. Although the Barren Measures shale is tight and low permeability, modern technology may be utilized such as horizontal drilling and multi stage hydro fracturing to improve the permeability near the well bore. The high content of quartz (avg. 49.02%) and less clays content (20.69%) in the shale, make the shale behaves like more brittle in nature and this may help to stimulate more fractures during artificial hydro-fracturing. This view is supported from the classical example of gas producing Barnett shale which is producing gas from the litho units having 45% quartz

and 27% clay (Bowker, 2003). The similarity in the mineralogy is observed in other shales of New Albany, Marcellus, Woodford, Fayetteville, Antrim, etc.

The extensive studies of Jarvie and Lundell (1991), Jarvie *et al* (2001 & 2007) and Bowker (2003 & 2007) suggest that the US commercial gas shales have 1 to 25 wt % TOC and 0.7 to 3.8% VRo maturity. The Barnett shale is having 3 to 12% TOC and 1.2 to 2% VRo. The Barnett shale is mainly kerogen type II and producing gas from both oil and gas window from 1828 to 2743m depth. The shale is capable to generate 30% gas in oil window (Jarvie *et al,* 2007). The other gas producing shales such as Woodford, Marcellus, Fayetteville, Haynesville, Antrim, etc have TOC content 3 to 14%, 3 to 10%, 4 to 10%, 0.5 to 8% and 1 to 25% respectively. This implies that the geochemical properties of Barren Measures shales resemblance with commercial gas shales of the above. Considering the depth factor, the Antrim shale (Michigan Basin) and New Albany shale (Southern Indiana and Northern Kentucky) are producing gas from shallow depth. The Antrim shale is of both thermogenic and biogenic origin with 0.4 to 0.6% VRo and producing from the depth of 350 to 790m. The New Albany shale is having 0.4 to 0.6% VRo and producing from 160 to 600m depth. Although the Barren Measures shale is at shallow depth in the study area, the depth increases towards south, even the shale is sandwiched between Barakar below and Raniganj at top where the Raniganj Formation is acting like a cap for Barren Measures shales to restrict the free gas escape.

 Considering the mineralogy, TOC, maturity, and thickness of the Barren Measures shale, the shale can be characterized as good to excellent prospect for shale gas play. Moreover, assessing the important factors of reservoir characterization such as porosity, permeability, micro fractures, adsorb gas content, pore throat network, pore size distribution, etc, the shale can be also considered as moderate to good reservoir.

Table 6.1: Correlation of Barren Measures shale properties with analogous gas shales (compiled after Frantz, 2005; Jarvie *et al*, 2007; Bowker, 2007; Wang & Carr, 2012; Slatt and Rodriguez, 2012; Liu *et al*, 2013)

Shale	Basin	Depth (m)	Thickness (m)	TOC wt%	Maturity Vro%	Quartz %	Clay %	Porosity %	Age
Barnett	Forth Worth	1828-2743	60-155	3.0-8.0	1.2-2.0	40-60	33	4.0-6.0	Upper Mississipian
Woodford	Andarko	1828-4227	20-100	3.0-10.0	1.1-3.0	60-80	20-45	3.0-9.0	Devonian
Marcellus	Appalachian	465-790	20-100	2.0-10.0	0.6-3.0	40-60	33	5.5-7.5	Lower Devonian
Fayetteville	Appalachian	457-1981	20-110	4.0-10.0	1.2-4	40-60	20-60	1.6-7.0	Upper Mississipian
Haynesville	Arkansas	3048-4267	50-110	0.5-8.0	1.5	<40	20-60	6.0-12.0	Jurassic
Antrim	Michigan	350-1000	100-305	1.0-25.0	.78-1.2	<40	<40	1.0-6.0	Late Devonian
New Albany	Illionis	160-600	100-300	0.5-8.0	0.4-0.6	<40	20-50	--	Devonian & Mississippian
Barren Measures	Raniganj	70-1200	80-800	3.75-20.9	0.6-1.1+	49.02	20.69	0.13-5	Late Permian

The commercial gas producing shales have 1 to 14% porosity. Barnett shales have average 6% microporosity where most of the pores are less than 10nm. The typical porosity value is 5 to 8% at 3800psi (Slatt and O'Brien, 2011). In the present study, 3 to 5% porosity was recorded for Barren Measures shale in m CT study while helium porosity was measures as 0.1 to 1.3% at 400psi. The conventional laboratory set up is not capable to measure brittle shales at higher pressure condition. However, micro CT, SEM, TEM give qualitative analyses of micro to nano pore systems of Barren Measures shales which are analogous to US commercial gas shales.

In the nutshell, the Barren Measures contain favorable mineralogy, geochemistry and reservoir characters for characterizing it as a target shale gas play. The shale properties are identical to US commercial gas shales. Moreover, the micro scale fabric anisotropy of the shale can help in development of variable fracture networks which can boost the artificial hydro fracturing. The Barren Measures may have excellent prospects for shale gas exploration if the exploration strategies are focused considering the depth factor. In general, it

may be concluded that the deepest and thickest shale sections of the Raniganj Field, will have the most favorable conditions for hydrocarbon generation prospectivity.

Way forward

The author could not collect the geophysical data, since petrophysical well logs and seismic sections were not recorded in those wells. It is therefore before entering into the final conclusion; several geophysical well logs can be used to delineate organic rich shale facies, its porosity, permeability, bulk density etc. In future, well logs along with seismic profiles can be studied. Other than conventional well log techniques, Gamma Ray-Deep Resistivity Overlay, Neutron-Density separation, SP and CMR logs etc. can be adopted to evaluate the shales. The resource estimation may be taken up to understand the quantitative outputs of the gas volume of the reservoirs.

In the present study, permeability of the shales were measured using Ultra-perm-400 by measuring the steady state flow rate through the sample under a given pressure gradient depending on available laboratory conditions. For these types of tight shales, the pressure pulse techniques can be used in future. Moreover, Shale Matrix Parameter can be used for determining matrix permeability on gas shale samples.

Previous studies has shown that TOC can be estimated rapidly using Near Infrared Spectroscopy. Future studies should consider the feasibility of combining Mid-infrared (for minerals) and Near Infrared (TOC) techniques for estimating the major minerals and TOC content of shales. FTIR spectroscopy may be plan to do in future, to build a Mineralogy Log which can be calibrated against major downhole wireline log data to investigate field characteristics.

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