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Rock Heterogeneity and Anisotropy in Permian Barren Measure Shale Formation, Damodar Basin, India

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Abstract

The Barren Measure Formation of Middle Permian age in Damodar Basin is a regionally extensive shale formation with an average thickness of nearly 500 -900m in different Lows. The Barren Measure Shale(BMS) are known to be deposited in the Fluvio-Lacustrine to shallow marine brackish water conditions with massive grey-dark grey to black carbonaceous shale containing abundant iron mineral (siderite in particular). The presence of high organic content (up to 14%) and considerable thermal maturity at shallow depths up to 1.1 VRo at <2000m, makes it interesting from shale gas point of view. The higher geothermal gradient in the basin is possibly attributed to igneous intrusions and maturity at shallow depth because of tectonic upliftment after burial. The syn-tectonic sedimentation favoured deposition of coarser clastic within BMS causing better inherited porosity and favouring the shale gas potential. Globally, majority shale gas producing formations belong to Paleozoic to Mesozoic age. The BMS represent very few examples of favourable shale formation in India falling in this window. The structural and lineament maps of the basin indicate that the basin is deformed by strike slip faults offsetting the formation boundaries. Influence of these faults on the thickness of the BMS depends on the pull-apart basin formation mechanism, during the sedimentation of the BMS (Dasgupta, 2005). The BMS have been probed in several wells drilled either for the CBM or Shale gas perspectives, besides the work based on the surface outcrops done by several Authors (Ghosh 2002, Chakrobarty et al 2003). The inherently heterogeneous properties & microfabrics in shales make necessary to critically characterize vertically and laterally to understand variability. The variability in terms of mineralogical composition, microfabrics, fracture geometry and orientation, rhythmic alternation of layers, organic richness, fissility, stress patterns cause significant heterogeneity and anisotropy. The petrological analysis of BMS have indicated significant amount of clay, present in laminate form which causes vertical shear slowness different from horizontal shear causing significant amount of TIV anisotropy (vertical axis of symmetry).The core and log data of the wells have been studied critically to identify the vertical variability in petrological characteristics and group them into coherent zones of sub-lithofacies. Thirteen such subfacies in the Raniganj wells and three sub facies in north Karanpura have been identified from well log correlations and corroborated by lithological associations. The rock heterogeneity and anisotropy has a crucial role in placing the well horizontals and frac designing. Maximizing fracture surface area in shales requires the existence of textural heterogeneity at reservoir scale and that needs to be adequately mapped. Therefore assessment of heterogeneity and anisotropy is of immense help in formulating the development plan.

Introduction:

Gondwana sedimentation(290-280Ma) in the Damodar Basin is contained within a series of grabens aligned in EW direction widely known for massive coal occurrences. The eastern most Raniganj sub-basin represents the largest among the series of coal bearing sub-basins. The Gondwana sediments of the Raniganj sub-basin are bounded to the north, south and west by Pre-Cambrian rocks whereas the eastern boundary is concealed beneath the alluvium beyond Andal High and extends in the Durgapur depression up to Domra-Panagarh area (Fig.1). Raniganj sub basin is found to be of prime exploration interest from shale gas point of view because of large thickness of the organic rich, thermally mature shales called Barren Measures Formation (BM)devoid of any coals. The Formation has been well probed both by surface studies and in subsurface encountered in several drilled wells. The BM shales have been further analyzed to characterize the internal variations in terms of depositional patterns, petrological descriptions, sub lithofacies identification for ascertaining the rock heterogeneity and anisotropy for better reservoir characterization and completion quality analyis.

Shale, with its inherent heterogeneity and anisotropy has always been problematic in many operations ranging from seismic exploration, well-log data interpretation, well drilling and wellbore stability issues, well stimulation to production. A rock may be heterogeneous in the five fundamental properties of its grains - composition, size, shape, orientation and packing. Anisotropy in sediments may develop during deposition or post-deposition. In clastic sediments, anisotropy can arise both during and after deposition. For anisotropy to develop during the deposition of clastics, there needs to be an ordering of sediments or uniformity from point to point followed by directional variability. Anisotropy at the bedding scale that arises during deposition may have two causes- one is a periodic layering, usually attributed to changes in sediment type, typically producing beds of varying material or grain size and the other results from the ordering of grains induced by the directionality of the transporting medium. Anisotropy is therefore governed not only by variation in the type of material but also by variation in its arrangement and grain size. The main cause of elastic anisotropy in shales appears to be layering of clay platelets on the micron (micrometer) scale and compaction enhances the effect.Thus both are inherently linked properties and gained significance recently, because of emergence of shale gas and its potential impact on recovery of gas from shales.

The paper brings out the studies on heterogeneity and anisotropy of BM shales and its implications on completion analysis.

Barren Measure Shale: Characteristics

The Barren Measure formation consists of a dark grey shale/clay, siltstone and some sandstone. Maximum thickness of this shale sequence is found to be about 300 to 900 m. During the Barren Measure deposition period, a northerly tilt of the basin floor is well documented. During the lower BM deposition, probably a high energy fluvial regime predominated in all parts of the basin except the northern margin where a thick pile of dark shale was deposited in a lake setting under reducing oxic conditions (Ghosh,1975). Towards the end of BM sedimentation the stream velocity had weakened and the area was overwhelmed by an influx of finer detritus.The BM Formation represents quiet water sedimentation of a near-continuous nature, anaerobic or dys-aerobic bottom conditions; associated terrigenous materials indicate a partial volcanic source with other contributions derived from a granitic/ metamorphic basement complex. Proximal to a fluvio-deltaic (and / or backshore) system is associated with coal deposition. The environment of deposition is mostly basinal marine although any direct fossil evidence has been obscured by siderite diagenesis. The presence of radiolarians or calci-spheres based on numerous siderite spherical (replacement) patterns is expected.In the Barren Measures shales, the organic carbon of sediments is more than 2.0%. Quantity of soluble as well as insoluble organic matter indicates the presence of very good potential source rocks in Damodar graben. VR values of OM indicate that BM shales are have attained thermal maturity and fall within the zone of hydrocarbon generation at shallow depths (Ro ranges upto 1.1% at just 2000m depth). Some samples analysed from BM shales show good remaining hydrocarbon generation potential (Kayal et.al. 1982).

In Durgapur depression two R&D exploratory wells viz. Y and Z(Fig.3)for conventional oil & gas have been drilled, while in the adjacent Ranigang area three exploratory wells for CBM exploration and two dedicated shale gas wells have been drilled.Well Y has been drilled down to 1833 m and terminated in BM Formation whereas well Z has been drilled down to 1658.8 m penetrating nearly 46 m in to the Archaean basement. The shale gas wells in Ranigang area were terminated in the BM Formation at 2000 (well-X) and 2200m (well-A) depths.

Mineralogical, Textural and Micro-fabric Characterization:

Barren Measure shales in cores of Raniganj well appear dark gray to black, faintly planar and/or wavy laminated, non-calcareous mudstone; well-indurated but possessing many induced fractures in a multitude of orientations. Generally it is remarkably monotonous but contains detrital silt(and some increased amount of light grey sand-sized) grains, more abundant carbonaceous material (plants), peloids, muscovite and biotite, pyrite, with small amounts of dolomite/ankerite, and major quantities of diagenetic siderite. The siderite imparts a high grain density to the rock and does occur in abundance in occasional instances creating very hard “bones” or nodules within the dominant mudstone sequence. Microscopically, siderite replaces many elements within the textural framework, including clay matrix, terrigenous clastics (volcanic rock fragments and feldspar),and probable microfauna. While pyrite is found in many textural locations, the occurrence in the centre of these circular bodies may represent the replacement of organic material or the infilling of originally open intra-organic void space. Other than these conclusions, other clearly-recognizable biotics are confined to organic spores. The terrigenous silt/sand is mainly quartz and feldspar, but the quartz in particular appear partially derived from a volcanic source, possessing both shard-like shapes (needles) and deeply embayed features, petrographically referred to as embayed quartz. Many biotites are euhedral or hexagonal and such textural evidence also likely indicates a partial volcanic origin to some of the clastic material. While filled or partially filled natural fractures are fairly isolated here, many bedding plane and decidedly oblique shears are common with associated slickensides and common high-lustre polish or patina. The mineralized fractures are mostly evident in the densely sideritic bones, interbeds, and/or nodules, and the fracture in fill can be a combination of iron-rich calcite, dolomite/ankerite, siderite, and silica. In thin section, many of these fractures or veins are clearly reopened, thus indicating preferential zones of weakness that are likely to reopen during hydraulic fracture stimulation (KDMIPE unpub report, 2012).The XRD analysis indicates around 50-65% of clay with illite/smectite as dominant clay and significant presence of kaolinite. Quartz percentage ranges 7-33% with 1-5% of feldspar. The siderite percentage vary from 5-15 % and as high as 72 % has been reported at depth 1737.08m. The significant higher percentages of kaolinite coupled with high iron rich components(Siderite) is typically not found in other global commercial shale gas plays.

Lithofacies, Rock Heterogeneity & Anisotropy Assessment in the BM Shale

Extensive coring was carried out in the well-X and A. The cores at surface revealed considerable lateral and vertical variations within BM Formation in Raniganj sub basin(Fig.2)**.**The sandstone-shale alternations of the Barren Measures succession can be correlated with the tectonic cyclothems developed on the hanging wall dip-slope and adjoining trough in a continental half-graben setting. Episodic rejuvenation of the basin margin faults thus caused development of tectonic cyclothem on the hangingwall block. (P.Dasgupta, 2005). The BM cores were subjected to identifying and classifying the individual rock classes based on textural and compositional attributes including their geologic context using well logs and core analysis, for defining the vertical and lateral heterogeneity. This served as the building block for erecting the continuous profile of the heterogeneous BM shales. Thirteen electrofacies could be identified in well-X and correlated across with wells # Y & Z indicating vertical variability (Fig.3). However with lithotype/petrologic classifications based on the abundance of particular detrital grains, the composition of the microcrystalline matrix, diagenetic minerals and organic richness as observed in rock in thin section and confirmed by XRD and SEM analyses, the same has beenbroadlygrouped in eight sub litho-facies.

1. Argillaceous mudstone; 2.Sideritic-argil mudstone; 3.Organic argil mudstone; 4.Sideritic argil claystone; 5 Sideritic sandstone; 6.Muddy sandstone; 7.Argillaceous claystone; 8.Fine sandstone

These sub types have been further regrouped in four major ***petrologic categories*** based on ***coherence in properties*** vertically in the B M Shales in the Raniganj wells cored samples.

1. **Muddy Sandstone and fine grainedSideritic Sandstone**: The rocks exhibit ripple cross-stratification on centimeter scale, with cross-beds alternately composed of angular quartz sand and thin (less than 1 mm) siderite pellet-rich and organic-rich laminae. Framework mineralogy is primarily quartz, with little or no feldspar. Siderite pellets and particles in muddy laminae contain relict grain textures, suggesting replacement of original feldspars and rock fragments. Accessories include abundant biotite and potassium mica and a lesser amount of chlorite as flakes. Organic matter occurs as woody fragments and lenses, primarily in siderite-rich and argillaceous laminae, most commonly, chert and kaolinite, with minor ferroan dolomite.(Fig1a)
2. **Sideritic, Argillaceous Mudstone &Claystone**:Rocks containing siderite in amounts of 10% or more are designated sideritic argillaceous mudstones and claystones. The siderite in these rocks is present mainly as particles and pellets. Clay minerals constitute the predominant matrix components, although siderite crystals are abundant in some samples. The mixtures of clay species which make up the matrices are mixed layer illite-smectite (I/S), illite and kaolinite in similar quantities, along with subsidiary chlorite. Organic matter in sideritic lithotypes tends to display amorphous, to webby and particulate morphologies. Siderite is pervasive, and forms elongate, coalesced masses resembling pellets in a few cases.Silt and sand are present in reduced quantities compared with argillaceous lithotypes, typically 5-20%. Silt consists most commonly of angular to subrounded quartz and feldspar grains. A larger class of detrital grains is observed in quantities between 1% and 10%, consisting of volcanic quartz, feldspar, biotite and rock fragments. Rocks with silt and sand of less than 10% (visual estimate) have been termed as claystones.(Fig1b)
3. **Argillaceous Mudstone and Claystone**: Argillaceous mudstones and claystone are the most common lithotype in the cored interval. Siderite particles and spheres are present in almost all the argillaceous samples, but in lesser quantities than in sideritic types. Argillaceous mudstones are characterized by matrices composed mainly of clay minerals, generally mixtures of I/S, illite and kaolinite, with subsidiary chlorite. The ratio of clay species is similar to that found in sideritic litho-types except that kaolinite is less abundant in argillaceous rocks. Clay morphologies tend to be crenulated to clumpy for I/S, and platy for illite and micas. Kaolinite commonly filled in voids in organic particles, or vermicular clusters in the matrix. Organic matter occurs most often as mixtures of disseminated amorphous material and webby and particulate forms.Silt and sand make up 10-25% of argillaceous litho-types by visual estimate in thin section. Silt grains are angular to sub rounded quartz and feldspar. Larger sand makes up a few percent of most samples, and grains include volcanic quartz, feldspar, biotite and rock fragments.Smaller amounts of quartz, kaolinite, and pyrite are common in most samples. (Fig1c)
4. **Organic Argillaceous Mudstone**; A subset of argillaceous mudstones which exhibit high TOC values (greater than 10% by weight) are identified as organic argillaceous mudstones. In matrix composition, detrital components, and clays compositions are similar to argillaceous lithotypes, except that the textures and lamination are influenced by the high concentrations of organic matter. Clay mineral species represent mixed layer illite-smectite (I/S), illite and kaolinite in subequal amounts; chlorite is present in small quantities (1-5%). Organic matter occurs as mixtures of disseminated amorphous material and webby and particulate forms. The organic-rich lithotype is similar in other respects to argillaceous mudstones, including texture, diagenetic features, and lack of fossil grains. Siderite, kaolinite, quartz and pyrite are the most common secondary minerals.(Fig1d)

The anisotropy in shales are of two types, compositional and structural and may be caused through many sources (Koesoemadinata et al, 2004), like aligned crystals, direct stress-induced, lithologic alignment, aligned fractures, cracks and pores, and the nature of their infilling material (e.g.clays,hydrocarbons,water,etc.),or because of fine layering/laminations.The intrinsic anisotropy in shales is normally in the form of transverse isotropy which is because of composition & micro-fabrics i.e. result of preferential orientation of the sediment grains and pores that can be created by sediment composition, grain size and shape, and deposition and compaction. While the induced anisotropy (structural) is caused by the strain associated with applied stress, fractures and mainly diagenesis. The two types of anisotropy resulting due the styles of alignment in constituent materials include: horizontal alignment with vertical axis of symmetry-*vertically transverse isotropy (VTI*) and vertical alignment with horizontal axis of symmetry - *Horizontally transverse isotropy (HTI*).

The rock heterogeneity analysis in the Raniganj well-X, revealed fine alternating layering pattern of conductive (more clay) and resistive layers within Barren Measure Shales(Fig.4) besides the large scale variabilityin composition& micro-fabrics. The layering patterns, their intensity, inclination, the fracture density and patterns were clearly mapped by the FMI logs also (Fig.5). Dominantly fractures are southerly dipping but having few northerly dipping sets as well. The evident break out direction observed is N-S oriented. Induced fractures are roughly E-W oriented and same is the direction of tensile fractures indicating direction of maximum horizontal stress. Advanced sonic logging measurement is a powerful method for elastic stiffness characterization, and anisotropy type analysis (Ostadhassan, et al 2012). The traditional sonic electrolog tool was constrained to identify anisotropy with horizontal axis (HTI) of symmetry only, which is generally caused by stresses, fractures etc, but with advent of new generation logging tools the VTI anisotropy (Transverse anisotropy) can also be measured precisely primarily caused due to alternating laminations. With the advent of new 3D acoustic measurement has made it possible to measure C66 (Walsh et al, 2006). In case of shale, due to presence of profuse laminations it is observed that C66>>C44, which means shear in the horizontal direction is distinctly much higher than in the vertical direction(Sarkar,2013) (Fig.6).

The Sonic Scanner log,(by an advance sonic tool) which was recorded in the Ranigang-X well was interpreted and its results analysis revealed a lower horizontal anisotropy and high vertical anisotropy. This finding played an important role in stress computation while identifying the zones of interest and completion quality analysis. Some of the sections appearing apparently uniform and massive, when computed though full waveform sonic data, indicated marked variability in the stress profile of Barren Measure, and with noticeable contrasts because of VTI (transverse) anisotropy caused by fine laminations.Without considering the VTI effect in shales,there may be major implications in computing the Youngs Modulus and Poisson’s ratio which are essential geomechanical properties in fracture designing. In well-X,in-situ stress testing (MDT) was used to calibrate the stress profile generated from the Sonic Scanner log and zones having lower stress were selected for proposed completion zones associated with adequate stress barriers. Similarly advanced sonic log data acquired in two producing wells in the Bakken Formation, were analysed. It has been found that the Upper and Lower Bakken are highly TIV because of the alignment of platy clay particles, while the middle member is isotropic or slightly anisotropic (Ostadhassan M. 2012) which compares well with the analysis and results in Raniganj-X well.

In the Fig.7 the left curve in this track is the stress profile generated when ignoring the VTI anisotropy. As previously discussed, this anisotropy actually increases with the stress profile. This anisotropic stress profile is shown as the right curve on this track. The three measured in-situ stresses closely match those predicted by the anisotropic model thus validating it. There is little stress contrast through the BM shale. This is not unexpected given the high and relatively consistent clay mineralogy throughout the interval. The laminations pervasive in such shales can frequently hinder height growth as fractures can slip on bedding planes with different mechanical properties/tensile strength.

Conclusions

Barren Measure shale formation was studied by engaging electrologs, and cores. Different analyses were made by sedimentological, petrologic, petrographic and basin depositional history to work out the vertical variability in mineralogy, texture and micro-fabrics of the rock. The vertical shale column was divided into coherent sub lithofacies within Barren Measure shales. The micrio-fractures, their orientation, cracks, and laminations were also studied involving the suitable electrolog suites like FMI, Sonic Scanners to assess the causes of intrinsic anisotropy and its impact on completion objectives.

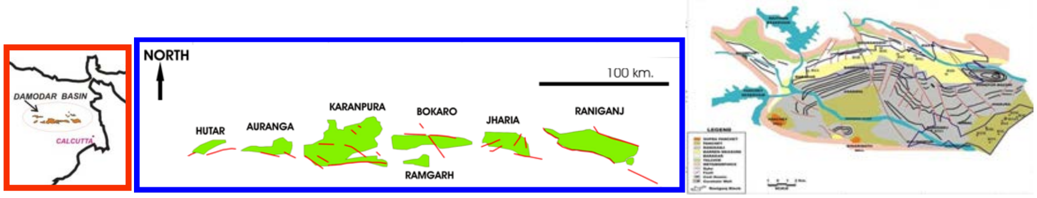
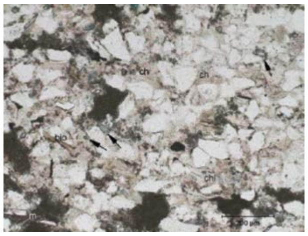
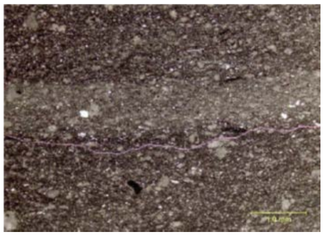


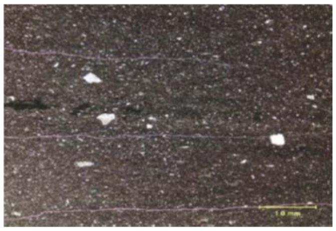
Fig.1: Index map, Damodar Basin with Structural map of Raniganj Sub Basin



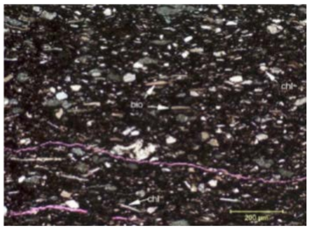
(Fig.1a)



(Fig1b)



(Fig1c)



(Fig1d)

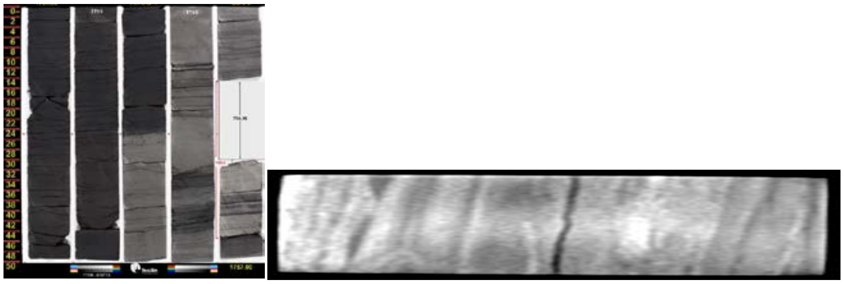


Fig.2 Core photo indicating the gross variability, laminations in appearance and apparent heterogeneity (1754.50 - 1757.00 m)

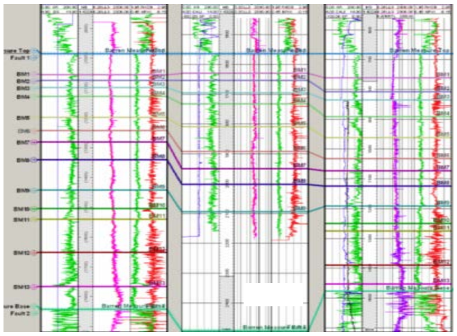


Fig. 3 Thirteen Intra Barren Measure lithofacies identified in well #X and correlated with wells #Y and #Z.

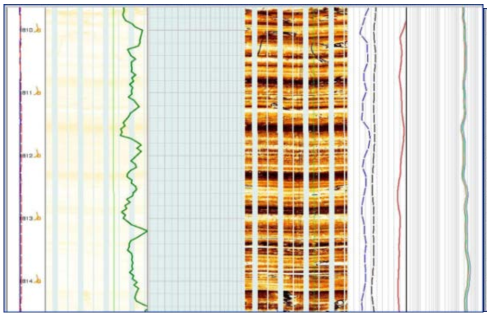


Fig. 4 Fine layering pattern of conductive (more clay) and resistive layers within Barren Measure Shales in Raniganjwell#X.

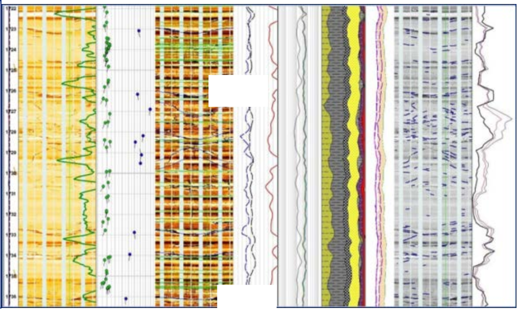


Fig. 5 The fractures mapped through FMI in Raniganjwell#X

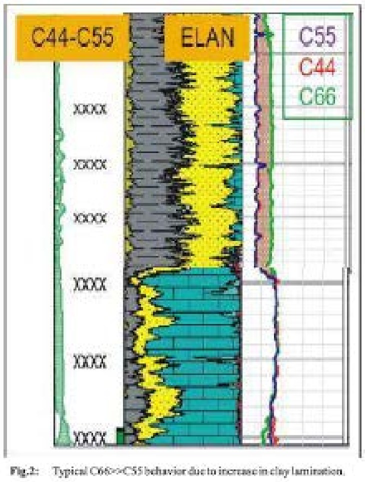


Fig.6Typical C66>>C55 behaviour in shales with laminations(Sarkar,2013)

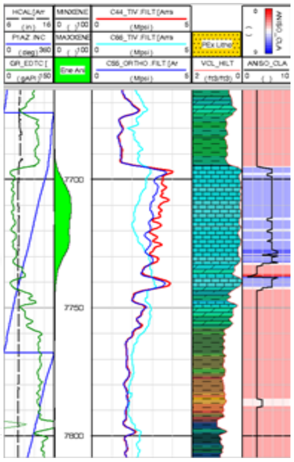


Fig. 7 Stress profile integrating Sonic Scanner 3D anisotropy in the Barren Measure Shale in RaniganjWell#X.

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