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Geochemical and petrophysical characteristics of Permian shale gas reservoirs of Raniganj Basin, West Bengal, India

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ABSTRACT

Thick shale horizons of Permian age emerged as the potential source of gas through primary investigation, and resulted into the first Indian pilot-scale gas recovery demonstration project in the Raniganj basin. However, the relation of geochemical properties with shale pore matrix, porosity and permeability mechanism are yet to be evaluated for better dealing the phenomena of diffusion, transport and gas recovery. In this study, the analyses like proximate, Rock-Eval, TOC, VR_o, low pressure N_2 sorption, porosity, permeability, SEM-EDX and image processing have been carried out. The values of S1, S2, TOC and T_{max} indicated fair to excellent source rock potential of the shales having type III/IV kerogens prone to thermal gas genesis. The low pressure N_2 desorption curve of Raniganj Formation shales shows the Type H3 hysteresis comprising slit-shaped pores. The Barren Measures shales have Type H2 and H3 hysteresis patterns specifying to ink bottle-shaped pores and slit-shaped pores. Whereas, the oldest Barakar Formation shales are having ink bottle-shaped pores caused due to blocking effect. The slit-shaped pores favour the pore network and characteristically excellent for the flow of gas. The results of SEM-EDX are indicating alteration stability in the order of $O < C < Si < Al < Fe < K < Na < Ca$ following the trend of least to strong weathering (Barakar < Barren Measures < Raniganj). The siliciclastic facies (Al-Si-Fe) signifying massive and laminated shale beds deposited under fluvio-lacustrine palaeoenvironment favouring alteration and accumulation of K-feldspar and aluminous minerals to clay.

The increasing T_{max} values with a centric decrease in porosity and permeability, specifying the role of devolatilization, disintegration and blocking of pore spaces/openings is a function of the thermal gradient. The linear evolution of multipoint BET surface area with increasing porosity suggests that the porosity values from 2.0 to 6.5% mainly corresponds to pore size of 3.0–11.0 nm. Similarly, the inverse relationship between average pore size and porosity attributed to a greater contribution of smaller pores in total porosity. The pore network model derived through the SEM image processing has shown two types of connectivity - i) various pore sizes of diverse pore throats with dual opening directions, and ii) interlinked large and small pores obeying similar normal distributions. The Barren Measures shales have shown higher pore connectivity than the Raniganj and Barakar Formation shales.

1. Introduction

Shale gas is an emerging unconventional energy resource in India. Laterally varying thick shale beds of the Tertiary and Gondwana ages occurs in 26 sedimentary basins (Mendhe et al., 2015, 2017a; Mani et al., 2014). Very limited information is available on shale composition (organic, clay, mineral contents), maturity, gas content, storage and flow mechanism in these shale beds. Shale is very fine clastic sedimentary rock mostly contains clay/muds and was considered as impervious cap rock seal for the conventional gas reservoirs. The technological break-through in horizontal drilling and hydraulic fracturing made the impervious shale become a potential source of gas (Horsfield and Schulz, 2012; Montgomery et al., 2005; Curtis, 2002; Jarvie, 1991). As a result, there is a boost in the evaluation of shale gas reservoir

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characteristics and potentiality of Indian sedimentary basins (Mishra et al., 2016; Mendhe et al., 2015). Oil and Natural Gas Corporation Ltd (ONGC) has drilled Asia's first shale gas wells RNSG-1 and 2 at Icchapur in the Raniganj basin (LNG report, 2011). It was demonstrated that the Permian (Lower Gondwana) shales of the basin housed in Raniganj, Barren Measures and Barakar Formations have potentially viable shale gas resources (Varma et al., 2014; ONGC, 2010). Moreover, the Barren Measures Formation has a relatively thick sequence of shale beds ($>$ 600 m) containing high organic matter (3 to 20 wt.%) of type III/IV kerogen with excellent gas generation potential (Boruah and Ganapathi, 2015; Varma et al., 2014, 2015; ONGC, 2010). Similarly, the coal bearing Raniganj and Barakar Formations positioned on top and bottom, respectively of the Barren Measures equally having potential shale gas reservoir properties.

The surface area, pore distribution and associated pore structures are important parameters governing the gas storage in shale matrix (Mendhe et al., 2015; Wu et al., 2012; Ambrose et al., 2010). These parameters are strongly related to the organic and inorganic contents of shales. Because, kerogen and clays/minerals formed surfaces of pores retain sorbed gas (Ross and Bustin, 2007). The pore size distribution and pore structure differ remarkably; however, micropores dominate in the gas shale systems as compared to conventional reservoir rocks (Tan et al., 2014; Loucks et al., 2009, Loucks and Ruppel, 2007: Jarvie et al., 2007). Different researchers have suggested the various models and empirical equations considering the surface area, pore size and pore volume relating to the porosity and permeability (Mastalerz et al., 2013; Tian et al., 2013; Groen et al., 2003; Sing et al., 1985). Therefore, the accurate measurement of porosity and permeability is very important to plan and model the gas recovery process of the shale reservoir. The meso- and micropores ($<$ 10 nm) occur in blocks of clay like kaolinite, illite and smectite formed by a stacking of elementary unit cells called tachoids (Ross and Bustin, 2008). These tachoids are bundled together to form macroscopic clay platelets or 'aggregates' ($-$ 1 μm) in the shales (Kuila and Prasad, 2013; Cases et al., 1992; Aylmore and Quirk, 1971). These clay aggregates form a locally aligned matrix with varying orientations depending upon the silt content, depositional conditions and stress history (Sayers, 2005; Johansen et al., 2004; Hornby et al., 1994).

The knowledge of pore distribution helps to estimate the storage and transport properties of shale beds. According to IUPAC, pores are classified based on their diameters such as micropore $<$ 2 nm, mesopores 2–50 nm and macropores $>$ 50 nm (Rouquerol et al., 1994, 1999; Sing et al., 1985). The BET theory describes the adsorption isotherms, and correlated with an adsorption theory provides data on the total specific surface area of a porous matrix (Gregg and Sing, 1982). In the present work, the shale core samples from the Raniganj basin have been analysed for geochemical constituents like Rock-Eval, total organic carbon (TOC), low pressure N_2 sorption, scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX) parameters. The porosity and permeability of shale core samples are measured under reservoir simulated confining pressure. The major focus of the study includes geochemical and geological influences on the surface area, pore size distribution, pore volumes, the dynamics of pore structures, throats and orientations.

2. Geological setting and shale core sampling

2.1. Geological setting - Raniganj basin

The Raniganj basin is the intra-cratonic rift basin of the Damodar Valley, covers an area of 1900 km^2 between the Damodar and Ajay rivers and is marked by a semi-elliptical, elongated shape (Dutt, 2003; Gee, 1932; Fig. 1). The Gondwana Super-group is laterally varying and attain a maximum thickness of $>$ 3000 m in the southern and north-eastern parts of the basin. The basin has igneous intrusives of dolerite or basalt and lamprophyres of Jurassic to Cretaceous period accountable for the upsurge of thermal gradient (Ghosh, 2002). The Precambrian basement separated the eastern and western sub-basins of the Raniganj basin during the deposition of the Damuda Group containing Barakar, Barren Measures and Raniganj Formations of Permian (Lower Gondwana) age. The lower Gondwana is known for commercial coal deposits in both the Barakar and Raniganj Formations. The non-coal bearing Barren Measures Formation is the chief target for shale gas exploration in the basin, which has organic rich shale beds with a cumulative average thickness of about 400 m (Mendhe et al., 2017a,c; Mishra et al., 2016; Hazra et al., 2015). These shale deposits are the result of suspension settlements of fines in deeper water below the reach of the storm or fair weather waves to subaerial fluvial flow including a variety of oscillatory and combined flow processes (Dutt, 2003).

2.2. Shale core sampling

The shale core samples of size 48 mm (NQ) were collected from the exploration wells in northern part of Raniganj basin, mainly targeting Raniganj (sample nos. SC-1R – SC-11R), Barren Measures (nos. SC-12BM – SC-20BM) and Barakar (sample nos. SC-21B – SC-33B) shales of Permian age, in airtight canisters immediately after reaching the core to the surface. The locations of sampling boreholes are shown in Fig. 1. The generalised stratigraphic succession, representative borehole section, and targeted shale core sampling Formations of the Raniganj basin are presented in Fig. 2.

3. Experiment and methods

3.1. Geochemical analyses

The proximate properties of shale cores were determined following the Bureau of Indian Standards (BIS (Bureau of Indian Standard), 2003). The core samples were fragmented, mixed and quarter-coned. The portion of a sample was manually crushed/powdered and screened through 72 mesh size (212 μ) sieve. Out of four (IM, Ash, VM and FC), the first three constituents are determined experimentally in the laboratory for each samples, while the fixed carbon content is estimated by subtracting the sum of the total of percentage moisture content, ash yields, and volatile matter yields from 100 [i.e. Fixed carbon = 100 − (Moisture % + Ash % + VM %)].

The Vinci Technologies Rock-Eval 6 Plus TOC module system is used to analyse the shale samples following the methods suggested by various authors (Ogala, 2011; Jarvie et al., 2001, 2005; Lafargue et al., 1998). Analyses were performed on about 1 to 2 g of shale sample of size $<$ 150 mesh (106 μm) prepared with the help of agate mortar. The prepared individual sample was placed in an automatic mounting stage and carried out pyrolysis in different phases. The amount of free hydrocarbon (mg HC/g rock) liberated at 300 °C is denoted as S1. The volume of hydrocarbons released from cracking of kerogen (mg HC/g rock) during temperature programmed pyrolysis (300–600 °C) is represented by S2. Whereas, the amount of CO_2 evolved from breaking of carboxyl groups and other oxygen-containing compounds during pyrolysis recorded at a reduced temperature range of 300–390 °C represents the S3 peak. The TOC is determined by oxidising the pyrolysis residue in a second oven at 600 °C in air (Jarvie et al., 2001, 2005; Peters and Cassa, 1994; Ekweozor and Gormly, 1983).

The shale samples were crushed and passed through the ± 18 mesh sieve (between ± 1.0 and 2.0 mm). The samples were embedded in a homogenous mixture of epoxy resin and hardener and subsequently, polished using alumina grade I, II and III as per the specifications of International Committee for Coal and Organic Petrology (ICCP, 2001, 1993, 1971). The reflectance were measured on vitrinite maceral in monochromatic light (wavelength: 546 nm) on Leica DM 4500P microscope, using immersion oil (refractive index: 1.518), 50 × objective lens along with a pair of l0 × oculars and Saphire (0.594) along with Yttrium-Aluminum-Garnet (0.904) and Gadolinium-Gallium-Garnet