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Full Length Article

Porosity controls and fractal disposition of organic-rich Permian shales using low-pressure adsorption techniques

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ABSTRACT

The pore structure characteristics of the Lower and Upper Permian shales belonging to the Barren Measures and Raniganj Formations, respectively, were investigated using the low-pressure N_2 adsorption-desorption experiments. It was found that the kaolinite content of the Barren Measures shales strongly influenced the Brunauer-Emmett-Teller specific surface area (BET SSA). However, it was the Rock-Eval temperature maxima (T_{max}) for the Raniganj Formation shales that influenced the BET SSA values. These shales are dominantly mesoporous and display a negative correlation between BET SSA and average pore radius. Nitrogen adsorption-desorption isotherms are of type IIB and type IV, displaying H2, H3, and hybrid H3-H4 hysteresis patterns. A strong positive correlation exists between average pore radius and the difference in volumes of gas adsorbed at the last-two-highest relative pressures measured. Samples with steeper isotherm slopes at the higher relative pressure range were those with the highest average pore radii. Porosity fractal dimension, D2 displayed a positive correlation with BET SSA and T_{max}, and a negative correlation with average pore radius. It is thus concluded that shales with the lowest average pore sizes and highest thermal maturities are marked by larger SSA and more complex pore structures. One of the tested samples (CG 1019) with the highest D2 value is associated with the lowest D1 fractal dimension value. That counter intuitive relationship may reflect analytical constraints of the nitrogen adsorption method at lower relative pressures.

1. Introduction

The significant increase in research on shale-petroleum systems, is a consequence of the unconventional petroleum-reservoirs contributing substantial oil and gas resources to global supply [15,54,42,32,43]. Shales are characterized by complex and wide pore-size distributions [43,55,12,58]. A wide range of pore sizes is displayed by shales, which following the classification provided International Union of Pure and Applied Chemistry (IUPAC) on pore-sizes [23], covers the three main subdivisions of nanoporosity, incorporating: micropores (< 2 nm), mesopores (2–50 nm) and macropores (> 50 nm). Proper understanding of the complex pore structure, pore size distribution, and sorption dynamics, of organic-rich shales is critical, in assessing the flow and petroleum-recovery potential from petroleum-bearing shales [54,57,64,65]). Gas in shale-reservoirs exists primarily as free gas within the larger pores and fractures, and as adsorbed gas within the larger pores, and small amount of dissolved gas [15,91]. Consequently, to estimate and predict the gas storage capacity and gas deliverability at reservoir conditions, detailed understanding of the pore-structural framework within shales is required.

A range of techniques is applied for characterizing pore-systems within shales. These include: high-resolution electron microbeam imaging or scanning electron microscopy (SEM) techniques on Ar-ion milled rock surfaces [16,9,43,52,53,7,41] and mercury intrusion [12,87]. Low-pressure gas adsorption-desorption techniques using nitrogen and carbon dioxide has been successfully applied to provide an understanding of the pore size distribution (PSD), specific surface area (SSA), microporosity, pore-structure framework of gas-shale systems [66,10,11,36,88,38,29]. Moreover, gas adsorption data has also revealed that activate carbons, coals, and shales have porosity networks

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that display fractal dimensions [44,89,88,83,38].

India possesses several significant and potentially exploitable petroleum-bearing shale reservoirs, and the technically recoverable gas-shale resources are estimated to be approximately 63 TCF [17]. Oil and Natural Gas Corporation Limited (*ONGC*) reported encouraging results from their first shale-gas test well drilled by Schlumberger in eastern part of Raniganj basin [40], analysis pertaining to organic richness, hydrocarbon generation potential, biomarkers, methane sorption capacity, mineralogy, matrix influence on Rock-Eval parameters of several of India's Permian shales basins has been presented [74–78,46,26–28,1,2,73,50]. However, only a few in-depth studies pertaining to characterization of the pore-framework within these shales have been reported. The main objective of the present work is to analyze the pore-framework using low-pressure nitrogen gas adsorption-desorption technique, within the Barren Measures Formation (Lower Permian) and Raniganj Formation (Upper Permian) shales, from the Raniganj basin in India. The findings on inter-relations between the specific surface area, pore size distributions, and fractal dimensions of the Raniganj basin shales provides new insight to their petroleum-exploitation potential.

2. Geological setting

The Raniganj basin is the easternmost preserved Gondwana sedimentary accumulation of the Damodar Valley basin, India, covering an area of approximately 1900 km^2. It is bounded by latitudes 23°22′N and 23°52′N, and longitudes 86°36′E and 87°30′E and represents one of the few coal basins of peninsular India where both the Lower Gondwana (Permian) and Upper Gondwana (Upper Permian – Triassic – Lower Cretaceous) formations are present [20]. Details about the structure of the basin, the depositional-model framework, tectonics can be found in Fox [19], Gee [20], and Ghosh [21].

The Raniganj basin is contained within the Precambrian crystalline basement. The geographic locations (Fig. 1) and stratigraphic position (Table 1) of the shale samples studied here are restricted to the Upper Permian Raniganj Formation and the underlying Lower Permian Barren Measures Formation within that basin.

The basement surrounding the Raniganj basin is generally coarse and porphyritic, containing quartz, microcline, orthoclase, oligoclase, and biotite, with minor components of apatite and green hornblende [34]. The basal sedimentary unit in the basin is the Talchir Formation, which marks the initiation of the Gondwana Supergroup with the deposition of glacio-lacustrine and fluvio-glacial sediments. These were deposited in erosional depressions within the Precambrian basement that constitute the Raniganj basin. The Barakar Formation (Lower Permian), Barren Measures Formation (Lower Permian), and the Raniganj Formation (Upper Permian) overlie the Talchir Formation, and these three formations together constitute the Damuda Group [21].

The Barakar Formation (name derived from the Barakar river) is characterized by white to fawn colored arkosic sandstones, carbonaceous shale, fireclay and coal seams, designating a braided to fluvio-lacustrine alluvial deposit [22]. This is the main exploited coal-bearing formation of the Lower Gondwana sediments in India. Coal seams are interbedded with sandstones and mudstones and tend to be thicker in the lower and middle members [22]. The Barakar Formation is best developed in the western and northern parts of the basin, gradually thinning towards the east and south [22]. Recent exploration and studies have led to enhanced understanding of this formation due to coalbed methane extraction and possible CO_2 storage potential [79,80,81,82].

The Barren Measures Formation is separated from the Barakar Formation by an unconformity and is characterized by a sequence of thick, dark-grey, and black shales with bands and lenses of fine-grained, hard, cryptocrystalline clay ironstone [19,22]. This formation was recognized by Williams [86] and was termed as the Kulti shales by Fox et al. [18]. The Barren Measures Formation achieves a maximum thickness of 600 m in the Chanch-Begunia-Kulti areas in the western part of the basin [22]. The Barren Measures Formation shale samples studied are from a borehole (borehole 1) in the Kulti area of the basin (Fig. 1). The black shales belonging to the Barren Measures Formation

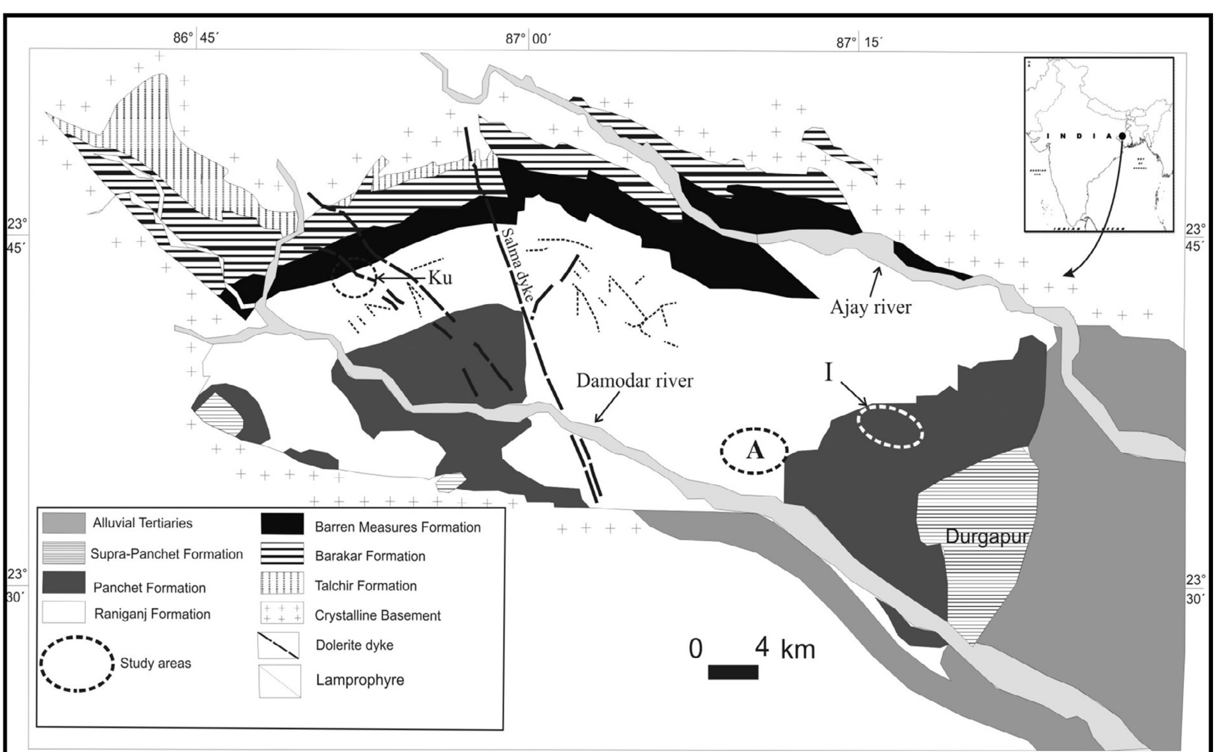

Fig. 1. Geological map of the Raniganj basin, India (after [20,22]. The study areas are identified as: Ku is the Kulti area; A is the Andal area; and, I is the Icchapur area.