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Organic geochemistry of the Vindhyan sediments: Implications for hydrocarbons

A.M. Dayal [a,*], Devleena Mani [a], T. Madhavi [a], S. Kavitha [a], M.S. Kalpana [a], D.J. Patil [a], Mukund Sharma [b]

[a] CSIR – National Geophysical Research Institute, Uppal Road, Hyderabad 500007, India
[b] Birbal Sahni Institute of Palaeobotany, 53, University Road, Lucknow 226007, India

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ABSTRACT

The organic geochemical methods of hydrocarbon prospecting involve the characterization of sedimentary organic matter in terms of its abundance, source and thermal maturity, which are essential prerequisites for a hydrocarbon source rock. In the present study, evaluation of organic matter in the outcrop shale samples from the Semri and Kaimur Groups of Vindhyan basin was carried out using Rock Eval pyrolysis. Also, the adsorbed low molecular weight hydrocarbons, methane, ethane, propane and butane, were investigated in the near surface soils to infer the generation of hydrocarbons in the Vindhyan basin. The Total Organic Carbon (TOC) content in shales ranges between 0.04% and 1.43%. The S_1 (thermally liberated free hydrocarbons) values range between 0.01–0.09 mgHC/gRock (milligram hydrocarbon per gram of rock sample), whereas the S_2 (hydrocarbons from cracking of kerogen) show the values between 0.01 and 0.14 mgHC/gRock. Based on the T_{max} (temperature at highest yield of S_2) and the hydrogen index (HI) correlations, the organic matter is characterized by Type III kerogen. The adsorbed soil gas, CH_4 (C_1), C_2H_6 (C_2), C_3H_8 (C_3) and nC_4H_{10}, (nC4), concentrations measured in the soil samples from the eastern part of Vindhyan basin (Son Valley) vary from 0 to 186 ppb, 0 to 4 ppb, 0 to 5 ppb, and 0 to 1 ppb, respectively. The stable carbon isotope values for the desorbed methane ($\delta^{13}C_1$) and ethane ($\delta^{13}C_2$) range between −45.7‰ to −25.2‰ and −35.3‰ to −20.19‰ (VPDB), respectively suggesting a thermogenic source for these hydrocarbons. High concentrations of thermogenic hydrocarbons are characteristic of areas around Sagar, Narsinghpur, Katni and Satna in the Son Valley. The light hydrocarbon concentrations (C_1–C_4) in near surface soils of the western Vindhyan basin around Chambal Valley have been reported to vary between 1–2547 ppb, 1–558 ppb, 1–181 ppb, 1–37 ppb and 1–32 ppb, respectively with high concentrations around Baran-Jhalawar-Bhanpur-Garot regions (Kumar et al., 2006). The light gaseous hydrocarbon anomalies are coincident with the wrench faults (Kota – Dholpur, Ratlam – Shivpuri, Kannod – Damoh, Son Banspur – Rewa wrench) in the Vindhyan basin, which may provide conducive pathways for the migration of the hydrocarbons towards the near surface soils.

1. Introduction

The Proterozoic Vindhyan basin consists of more than 5000 m thick sedimentary sequence of sandstones, shales and limestones, which are characterized by the presence of rich fossil assemblage (Banerjee and JeevanKumar, 2005; Kumar, 1995, 2001; Sharma, 2006; Sharma et al., 2009; Sharma and Sergeev, 2004; Sharma and Shukla, 2009; Srivastava and Bali, 2006; Saha and Mazumder, 2012; Srivastava, 2012 and others). Organic rich black shales containing microbial mats (Banerjee et al., 2006; Dutta et al., 2006; Sharma, 2006) and stromatolitic limestones (Banerjee et al., 2007; Kumar, 2012; Sharma, 1996) have been reported from the sedimentary formations of the basin. Such Proterozoic rocks with rich organic matter have sourced commercial hydrocarbons in other basins of world like China, Russia, Oman and Australia (Craig et al., 2012; Hunt, 1996; Tissot and Welte, 1978). The favorable tectonics indicating discrete episode of subsidence necessary for accumulation of organic rich sediments and entrapment conditions with numerous step faults corroborate further to the hydrocarbon potential of Vindhyan basin, making it a geologically prospective Category III sedimentary basin of India (DGH, 2012). The Vindhyans are considered analogous in terms of their petroleum geology with the other Proterozoic sedimentary basins of the world which have shown commercial discovery of hydrocarbons (Jokhan Ram et al., 1996; Jokhan Ram, 2012; Vardhan et al., 2007; Cozzi et al., 2012).

* Corresponding author. Tel.: +91 04023434608; fax: +91 04023434651.
E-mail address: dayalisotope@rediffmail.com (A.M. Dayal).

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The Vindhyan strata have been studied extensively for biostratigraphy (McMenamin, 1983; Sharma, 2006, Sharma and Shukla, 2012; Venkatchala et al., 1996), geochronology (Bengston et al., 2009; Gopalan et al., 2013; Rasmussen et al., 2002; Ray et al., 2003; Sarangi et al., 2004; Sarkar et al., 2005, 2006) and sedimentary depositional environment (Bose et al., 2001, 2008, 2012; Chakraborti, 1990; Chakraborty, 2004; Singh, 1980 and others). Although, few studies on the bulk and molecular organic matter have been reported (Banerjee et al., 1992, 2006; Dutta et al., 2006; Krishnamurthy et al., 1987), the organic geochemistry of Vindhyans needs considerable significant discussion for assessment of the hydrocarbon generation potential of the basin. In the present communication, the hydrocarbon prospects of Vindhyan basin is described in light of organic geochemical parameters studied in the outcrops samples and near-surface soils of the basin. The quantity, quality and type of organic matter provide insights onto the geological processes under which the carbonaceous sediments got deposited and were well preserved in the source rocks, leading to generation of hydrocarbons.

Rock Eval (RE) pyrolysis is one of the most basic organic geochemical methods for characterization of the sedimentary organic matter. The pyrolysis technique is based on the steady heating of rock samples so that the evolved hydrocarbons can be monitored as a function of temperature (Behar et al., 2001; Espitalié et al., 1987; Lafargue et al., 1998). During pyrolysis, experimental temperatures are set somewhere between 300 °C and 650 °C, which is much higher than those found naturally in the subsurface (60–220 °C), so that appreciable reaction for the generation of hydrocarbons can occur in a reasonably short time (~1 h) compared to the geological ages of oil and gas formation. Thus, the amount of generated hydrocarbons relative to the total potential of the source rock is determined (Nuñez-Betelu and Baceta, 1994; Tissot and Welte, 1978).

Thermally generated low molecular weight alkane gases (methane through butane), which reside in near-surface soils after migration from the subsurface reservoirs, are another widely used geochemical indicator to study the hydrocarbon prospects in a frontier and/or producing sedimentary basin (Abrams, 1996a,b; Brown, 2000; Klusman, 1993; Mani et al., 2012; Schumacher, 1996, 2003). The quality and quantity of the light hydrocarbon gases (C_I–C_4) are determined using a gas chromatograph coupled to a flame ionization detector (FID), and the source of these gases is studied using the stable carbon isotopic ratios measured on a gas chromatograph–combustion–isotope ratio mass spectrometer (GC–C–IRMS). The relationships amongst the alkane gases and that between their isotopes suggest the type of hydrocarbons i.e. oil, gas, condensate and their thermal maturity (Bernard et al., 1976; Mani et al., 2011a; Schoell, 1983). The magnitudes of the hydrocarbon gases observed in the near surface soils are controlled by regional geology, tectonic activity and fault/lineament pattern (Duranti and Mazzini, 2005; Mani et al., 2011b; Rollet et al., 2006).

In the present work, we studied the distribution, source and maturity of organic matter preserved in the outcrops, and also the adsorbed light alkane gases (methane through butane) in near surface soils of the Vindhyan basin for the evaluation of its hydrocarbon prospects. The outcrops and near surface soil samples were collected from the study area following the standard established protocols (Schumacher, 2003) and ensuring negligible surficial contaminations. The organic rich shales describe the characteristics of the potential source rocks that may source the hydrocarbons at depth in the basin, whereas the adsorbed light gaseous hydrocarbons in the near surface soils provide information on the microseepage of hydrocarbons from the subsurface source rocks/reservoirs. The results obtained are interpreted in the light of sedimentary history and regional geology of the basin to provide insights into the quantity and quality of organic matter and its implication on the hydrocarbon generation, preservation and near surface manifestations in the Vindhyan basin.

2. Geological setting and lithostratigraphy

The Vindhyan basin is the largest Proterozoic basin that developed in the central part of the Indian shield. It covers an area of 1,62,000 km^2 over the states of Rajasthan, Madhya Pradesh, Uttar Pradesh and Bihar. It began as an intracratonic rift basin during Palaeoproterozoic times in extensional settings and subsequently converted to a passive margin set-up during the post-Neoproterozoic Era (Auden, 1933; Santosh, 2012). The Vindhyan sequence overlies a range of Precambrian basement rocks that form the basin floor. It is bounded by the Narmada-Son lineament towards south and extends northwards under the Indo-Gangetic plains (Chakraborti, 2006; Jokhan Ram et al., 1996). The Bundelkhand Granitic Complex lies in the center. The western part of Vindhyan basin is mostly covered by the Deccan Traps (Fig. 1; after DGH, 2012). It consists of unmetamorphosed, tectonically less disturbed and well preserved Palaeo-Neoproterozoic sedimentary sequence in India (Auden, 1933; Srivastava et al., 1983). The Vindhyan succession is divided into the Lower Vindhyan (Semri Group) which is overlain unconformably by the Upper Vindhyan (Kaimur, Rewa, and Bhander Groups) (Kumar and Sharma, 2012; Prasad et al., 2005; Sastri and Moitra, 1984). The principal rock types include the quartzite, sandstone, shale and limestone. Radiometric dates bracket the age of the Vindhyan Supergoup between 1700 and 900 Ma (Bengston et al., 2009; Gopalan et al., 2013; Rasmussen et al., 2002; Ray et al., 2003).

The basin is divided in two sub-basins, the Son Valley in the east and the Chambal Valley in the west. The entire basinal sequence belongs to two distinct depositional cycles. The first is dominantly calcareous and argillaceous and is characteristically developed in the lower part (Lower Vindhyan). The second is arenaceous and argillaceous, and is developed in the upper part (Upper Vindhyan). These two depositional successions are separated by a well-marked erosional unconformity (Jokhan Ram, 2012). Generalized litho-stratigraphy of the basin is given in Table 1 (after, DGH, 2012). The Son Valley of the Vindhyan Basin includes the Palaeo-Mesoproterozoic sequences referable to the Semri Group. Exposures of the Semri Group occur in three areas: (i) as a linear belt along the Son River (Eastern Vindhyans), (ii) north of Panna, fringing the Bundelkhand Massif in the central part, and (iii) in the Chittorgarh–Nimach–Brijiraj Nagar areas towards the west (Chambal Valley). In the southern part of the Son Valley and the Chittorgarh–Nimach–Brijraj Nagar area of the Chambal Valley, the group is dominantly calcareous and consists of limestone, shale, sandstone and porcellanite beds (Ojha, 2012). In the northern part of the Son Valley, it comprises sandstone, shale, conglomerate and minor limestone (Fig. 2).

Thick Neoproterozoic sediments corresponding to Kaimur, Rewa and Bhander Groups are present in the Chambal Valley. The exposures consist of mainly calcareous and argillaceous facies in the northern part with rich algal mats (stromatolites) in Lakheri and Chambal limestone. The southern part of Chambal Valley is covered by the Deccan Traps (Jokhan Ram, 2012).

2.1. Petroleum geology

The Vindhyan basin largely consists of unmetamorphosed sediments with well preserved organic matter that could develop as a source rock for the generation of hydrocarbons in the subsurface. The occurrence of stromatolitic limestones in the basin suggests abundant organic activity during the deposition of the Vindhyan sediments. The existence of Infra-Cambrian reservoir sequences, source–seal relationships and the widespread presence