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Geo-microbiological studies in conjunction with different geo-scientific studies for the evaluation of hydrocarbon prospects in Proterozoic Vindhyan Basin, India

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ABSTRACT

The Proterozoic Vindhyan Basin is considered to be prospective for hydrocarbons and is grouped under category III sedimentary basins of India. The major part of the study area is covered by the Deccan Traps, hindering the exploration of Mesozoic hydrocarbon targets, surface geochemical prospecting based on microseepage of hydrocarbons from subsurface accumulations, which could be advantageous in such areas. Geo-microbiological study was carried out in conjunction with different geo-scientific studies to characterize the seeping natural gases and to evaluate the hydrocarbon prospects of the study area. Total 70 soil samples were collected in reconnaissance pattern, and the study revealed the presence of high bacterial counts for methane (3.7×10^5 cfu/g), ethane (3.2×10^5 cfu/g), propane (3.0×10^5 cfu/g) and butane oxidizing bacteria (2.3×10^5 cfu/g), which signify the seepage of hydrocarbons from the subsurface. The compositional characteristics of the hydrocarbon gases desorbed from soil samples of study area indicate the presence of light gaseous hydrocarbons methane through butane, thus suggesting that hydrocarbon generation has taken place in the basin probably of thermogenic origin. The trend followed by the hydrocarbons $C_1>C_2>C_3>iC_4>nC_4$ further confirms the petroliferous nature of the gases. The stable carbon isotope values of light hydrocarbons desorbed form the soil samples indicate a clear signature of thermogenic gas. The concentrations of TOC and TIC in the soil samples of Sagar vary from 0.09% to 0.93% and 0.003% to 0.82% respectively. The TOC and TIC correlates poorly with the adsorbed soil gases ($r=0.3$, $r=0.2$), representing a lack of association of adsorbed soil gases with the surfacial organic matter thus indicate seepage related surface anomalies. The study revealed the presence of high concentrations of hydrocarbon oxidizing bacteria and adsorbed soil gases near Sagar area of Vindhyan Basin. The integrated geo-scientific studies showed excellent correlation and suggests that the Sagar area is considered to be potential for hydrocarbon generation and entrapment.

1. Introduction

The growing concern for the depletion of fossil fuels throughout the globe has led to the implementation of different geochemical methods that can give principal evidence on the occurrence of hydrocarbon anomalies in large areas for finding the undiscovered oil and gas accumulations. Surface geochemical prospecting is one such unconventional technique that has emerged as one of the vital components of any exploratory program. It is based on the seepage of light gaseous hydrocarbons from the subsurface reservoirs to the shallow surface environment and results in surface hydrocarbon anomalies (Devleena et al., 2011b). These anomalies arise from the fact that no oil or gas reservoir cap rock is completely impermeable, and so hydrocarbons and other compounds such as nitrogen and carbon dioxide which occur in minor quantities escape from the reservoirs and the more volatile components migrate to the surface where they may be trapped in soils or subsequently diffuse into the atmosphere or oceans (Schumacher and Abrams, 1996). Through the use of surface indicators like hydrocarbon oxidizing bacteria and other hydrocarbon induced alterations of soils and sediments, the seepage prone zones can be differentiated from the barren ones. The surface microbiological and geochemical anomalies can be reliably correlated with the subsurface accumulations. Thus, these

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methods are helpful in the quick evaluation of hydrocarbon prospects, generation of exploratory leads, and reduction of exploratory risk (Rasheed et al., 2008).

Microbial prospecting method for hydrocarbon research and exploration is based on the premise that light gaseous hydrocarbons migrate upward from the subsurface petroleum accumulations and are utilized by hydrocarbon oxidizing bacteria present in the sub-soil ecosystem and results in microbial anomaly at the surface soils (Horvitz, 1939; Tedesco, 1995). The methane, ethane, propane and butane-oxidizing bacteria exclusively use these gases as carbon source for their metabolic activity and growth. They are mostly found in the shallow soil/sediments above hydrocarbon bearing structures and can differentiate between hydrocarbon prospective and non-prospective areas (Tucker and Hitzman, 1994). Although bacterial activity is most pronounced in surface soils, it can occur at all depths above a leaking hydrocarbon accumulation. The most obvious result of hydrocarbon oxidation is a decrease in the concentration of free soil gas hydrocarbons (interstitial), hydrocarbons dissolved in pore fluids, occluded hydrocarbons, and adsorbed hydrocarbons (Schumacher and Abrams, 1996). The isolation and enumeration of specific C_{2+} alkane oxidizing bacteria are used as indirect petroleum prospecting method. A positive relationship between the microbial population and hydrocarbon concentration in the soil has been observed in various producing reservoirs worldwide (Sealy, 1974; Miller, 1976; Pareja, 1994; Wagner et al., 2002). The methane-oxidizing bacteria are usually predominant over gas fields as the gas reservoirs are commonly dominated by methane (Jones et al., 2000). Ethane, propane and butane are assumed to be originated from the migration of thermogenically produced petroleum and are usually not associated with generation in shallow soils (Tedesco, 1995). The microbial prospecting method has proved to be a useful and successful tool in petroleum exploration. Since the drilling operations are costly, it is essential to use appropriate and efficient exploratory methods, either alone or in integration, in order to cut down the drilling cost of dry holes, on proper integration with geological and geophysical studies. Based on a study conducted by Wagner et al. (1998), oil and gas fields were identified using Microbial Prospecting for Oil and Gas (MPOG) method and the success rate has been reported to be 90% (Wagner et al., 2002). This method can be integrated with geological, geochemical, geophysical methods to evaluate the hydrocarbon prospect of an area and to prioritize the drilling locations thereby reducing drilling risks and achieving higher success in petroleum exploration (Pareja, 1994; Tucker and Hitzman, 1994; Wagner et al., 2002).

Amongst the geochemical methods, detecting the presence of high concentrations of adsorbed light gaseous hydrocarbons in the subsurface soils and sediments is frequently employed. Adsorbed light hydrocarbon gases which are bound on soil surfaces can be released by acid treatment (Horvitz, 1939, 1979; Kalpana et al., 2010b). Gas chromatographic techniques are used in the analysis of adsorbed hydrocarbon gases (Philp and Crisp, 1982). By using composition and ratios of the light hydrocarbons such as methane, ethane, propane and butane, it is possible to predict whether oil or gas is more likely to be discovered in the prospect area (Jones and Drozd, 1983). The carbon isotope ratios are the characteristic of the genetic origin of the gas even if the gas has migrated over a long distance (Abrams, 1996a, 1996b; Bernard et al., 1976; Stahl, 1979; Schoell, 1983a, 1983b; Clayton et al., 1990; Whiticar, 1999). Recent works have shown the influence of mixing and migration on the natural gases. But, in general, the thermogenic near-surface hydrocarbon gases hold importance as they provide a direct indication for the possibility of hydrocarbons at depth and their δ13C signatures can be used to imply reliably the source and maturity (Cai et al., 2005; Cai et al., 2007; Devleena et al., 2011a).

Microbial prospecting has advantage over adsorbed soil gas method. There is a possibility that chemically detectable petroleum gases will be deficient where high soil microbial activity exists. The consumption of vertical migrating light hydrocarbons by bacteria results in varying degree of depletion of the hydrocarbons in the free soil gas and in hydrocarbons adsorbed soil gases (Klusman, 1993). The light hydrocarbons microseepage is preferentially consumed over the area of highest seepage, resulting in a high rate of bacterial activity. The bacteria present over the petroleum accumulation would consume petroleum gases, and the edges will show high concentration of gases as not being utilized by bacteria where the microbial activity is very low. Thus geochemical technique of quantitative and qualitative determination of adsorbed soil gas analysis may have limitations in place where high soil microbial activity exists resulting in partial or complete utilization of soil gases by microbes. The distribution of light hydrocarbons will show halo anomaly. The ratio of bacterial activity to hydrocarbon concentrations then exhibits an apical anomaly. The microbial indicators are therefore target specific, associated directly over the oil pool microbes and flourish utilizing upcoming hydrocarbon gases. The halo anomaly is reconciled on the basis of microbiology, and has significant importance in hydrocarbon exploration (Rasheed et al., 2008).

The Proterozoic basins of the world have proven source of oil and gas reserves (Kalpana et al., 2010a). In India Proterozoic basins (also called as Purana Basins) are poorly explored for hydrocarbon prospects. India has six Proterozoic basins viz. Vindhyan, Cuddapah, Chattisgarh, Bastar, Bhima and Kaladgi which are grouped under categories III and IV (prospective and potentially prospective) basins by Directorate General of Hydrocarbons (DGH), Noida. The Vindhyan Basin is grouped under category III potentially prospective basins. Tectonically, Vindhyan Basin is comparable to Proterozoic basins of the Siberia (Lena-Tunguska basin in Ural) and Amadeus Basin of Australia which are commercially hydrocarbon producing (Srivastava et al., 1983).

The seepage of hydrocarbons was reported in some areas of Sagar, Vindhyan Basin. The present study was carried out to investigate whether the seepage is associated with the occurrence of subsurface petroleum deposits, and a detailed study was conducted in the basin comprising of microbiological, adsorbed soil gas, carbon isotopes, total organic carbon (TOC) and total inorganic carbon (TIC) studies to characterize the seeping natural gases and to evaluate the hydrocarbon prospects of Vindhyan Basin.

2. Geological settings

The Vindhyan Basin of central India is situated just north of SONATA (Sone–Narmada–Tapti) rift zone, and forms one of the major geotectonic segment of the Indian subcontinent which is associated with complex thermo-tectonic history. The geology and tectonics of Vindhyan Basin are given in Fig. 1a and b respectively. The Vindhyan Supergroup is one of the largest and thickest sedimentary successions of the world, deposited in an intra-cratonic basin, composed of shallow marine deposits (Ray, 2006). Southern part of this basin is known to contain favorable conditions for hydrocarbon entrapment (Srivastava et al., 2009). The Vindhyan sediments have appreciable thickness comprising sandstone–shale–limestone sequence, with suitable structures, good reservoir rocks and caprocks for the entrapment of hydrocarbon. Major part of the basin consists of unmetamorphosed sediments, providing suitable environments for the generation and entrapment of hydrocarbons. Almost all the limestone units in the Vindhyan are stromatolitic (Prasad and Verma, 1991) which indicates the existence of algal life in the Vindhyan times. Stromatolitic algae and bacteria are potential sources capable of generating petroleum and consequently stromatolitic bearing Precambrian/Proterozoic carbonate rocks are