Recognition of hydrocarbon microseepage using microbial and adsorbed soil gas indicators in the petroliferous region of Krishna–Godavari Basin, India

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The present study aims at exploring the possible correlation between adsorbed light gaseous hydrocarbon distribution pattern and the hydrocarbon oxidizing microbes present in the sub-soil samples. To establish the role of the latter in identifying the upward migration of hydrocarbons, especially a known petroliferous Krishna–Godavari Basin has been investigated. Soil samples from oil and gas fields of Tatipaka and Pasarlapudi areas of the basin show the presence of bacterial population for methane (3.46×10^5 cfu/g), ethane (3.85×10^5 cfu/g) and propane (3.04×10^5 cfu/g) oxidizing bacteria in soil samples. Gas chromatographic analyses of adsorbed soil gases show the presence of C_1 to C_4 hydrocarbons. The concentration of adsorbed soil gases ranged for methane (C_1) = 1 to 115 ppb, ethane (C_2) = 1 to 99 ppb, propane (C_3) = 1 to 34 ppb, butane (nC_4) = 1 to 9 ppb and $\sum C_{2+}$ = 1 to 115 ppb. The scatter plots between C_1 and C_4 components depict a linear trend indicating that all gases are from the same source. The total organic carbon (TOC) content of the soil samples ranges from 0.18% to 1.34%. Pearson correlation analysis shows that the concentration of $\sum C_{2+}$ does not show any correlation ($r = 0.1$) with TOC, suggesting that the adsorbed gases are not derivatives of the organic carbon. Moreover, the values for methane $\delta^{13}C_1$ varied from –39.9‰ to –19.9‰ (V-PDP) Vienna PeeDee Belemnite indicate thermogenic origin. The integration of geomicrobial prospecting method together with adsorbed soil gas and carbon isotope studies shows a good correlation with the producing oil and gas fields of Krishna–Godavari Basin.

Keywords: Adsorbed soil gas, bacteria, hydrocarbon exploration, microseepage.

WITH the ever increasing demands for petroleum products and diminishing indigenous production, it has become necessary to look for probable potential zones with economic feasibility. Surface geochemical prospecting appears as one such technique that could be a vital component for any exploratory programme. The application is based on the evaluation of seepage of hydrocarbons from the subsurface reservoirs to the shallow surface environment. The study broadly comprises investigation of near surface soils/sediments for occurrence of hydrocarbons through various laboratory results. The basic assumption of all near surface geochemical prospecting techniques is that hydrocarbons migrate to the surface from the sub-surface petroleum accumulations through faults and fractures and leaving their signatures in the near-surface soils. The hydrocarbon migration mechanisms such as diffusion, effusion, advection with moving waters and permeation have been proposed and studied previously[1–5]. Microseeps can be recognized by the presence of anomalous concentrations of light hydrocarbons in the near surface soils/sediments[6]. Most studies on organic geochemical exploration concern the analysis of light gaseous hydrocarbons in recent sediments because these compounds migrate easier than the heavier, liquid hydrocarbons[7]. Hydrocarbons reaching the surface can be measured directly both in the sediments and in the overlying air or water[2,7–12]. The anomalous concentrations of hydrocarbon gases like methane, ethane and propane in surface soils serve as direct evidence for the presence of a petroleum system in and around the area[2,13]. The analytical system is based on acid extractable hydrocarbons adsorbed in soil particles, a method originally developed by Horvitz[14]. Adsorbed gases are loosely bound in the solid soil matrix or occluded in secondary minerals such as $CaCO_3$. The successful application of adsorbed soil gas surveys for hydrocarbon exploration in onland and offshore basins has been studied earlier[2,5,15–17]. Adsorbed soil–gas surveys are comparatively fast and cost-effective for initial evaluation of any basin for hydrocarbon exploration to draw future course of other investigations[18].

Microbial prospecting method for hydrocarbon exploration is based on the premise that light gaseous hydrocarbons migrate upward from subsurface accumulations through diffusion and effusion, and utilized by a variety of microorganisms present in the sub-soil ecosystem[19]. The methane, ethane and propane oxidizing bacteria

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exclusively use these gases as carbon source for their metabolic activities and growth[20] and are mostly found enriched in the shallow soils/sediments above hydrocarbon bearing structures and can differentiate between hydrocarbon prospective and non-prospective areas[2,5,21]. Application of hydrocarbon oxidizing bacteria in petroleum exploration has been considered as an effective tool[5,22,23] and as a reliable indicator of hydrocarbons present in the sub-surface[24]. The direct and positive relationships between microbial population and hydrocarbon concentration in the soil have been found effective in large number of oil and gas producing fields worldwide[2,24–26]. The microbial prospecting method can be effectively used to prioritize potential areas for drilling[24], wherein the success rate is reported to be around 90% (ref. 26). This assumption is based on the study conducted by Wagner *et al.*[25], wherein 17 oil and gas fields were identified using microbial prospecting for oil and gas (MPOG) method. This method can be further integrated with geological, geochemical, and geophysical data to critically evaluate hydrocarbon prospects and prioritize the drilling locations, thereby reducing exploration risks.

The present study focuses on geo-microbial signatures to investigate whether the geo-microbial anomalies correlate with adsorbed soil gas from Krishna–Godavari Basin to obtain evidence of seepage of hydrocarbons from subsurface reservoirs.

Geological setting

The Krishna–Godavari Basin emerged as a pericratonic rift margin system with archean basement on the east coast of Indian Peninsula (Figure 1)[27], covering an area of 28,000 sq. km onland and 24,000 sq. km offshore up to 200 m bathymetry[27]. The basin extends between 15°30′–17°N and 80°–82°30′E. The basin extends southeast into the deep water of the Bay of Bengal. A significant part of the onland basinal area is covered by recent alluvium. Archean crystalline basement and Upper Cretaceous sedimentary outcrops demarcate the basin margin. Out crops in the basin margin area includes Permean Chintalapudi sandstone, Cretaceous to Jurassic Gollapalli sandstone, Raghavapuram shale and Tirupati sandstone exposed around Dwaraka Tirumala area of West Godavari district[28]. The sandstones outcropped near Rajahmundry and Dowleswaram areas are red, felspathic, ferruginous and laterised of Miocene age, equivalent to the Ravva formation of offshore area. The basin is divided into Krishna, East and West Godavari depressions separated by basement highs at Bapatla and Tanuku horsts respectively[29]. The East Godavari sub-basin is further divided into Mandapeta graben, Narsapur–Razole high and Amalapuram high. The Matsyapuri–Palakollu and Mori faults are the two major NE–SW faults. The West Godavari sub-basin is further sub-divided into Gudivada–Bantumilli graben separated by Kaza–Kaikaluru horst[30]. The Tertiary sediments brought by Godavari delta system attained greater thickness south of the Matsyapuri–Palakollu fault as a result of continuous subsidence and growth[31]. Over the period, the depositional environment varies from continental to lagoonal, marine, littoral, infraneritic and deltaic conditions. Here, sediments yield rich faunal assemblages mostly with arenaceous foraminifera (*Ammobaculites* sp., *Ammodiscoides* sp., etc.), *Trigonia*, *Inoceramus*, *Lima*, *Pecten*, *Belemnites*, *Helicoceras*, *Cardita*, *Lamellibranchs* and *Gastropods*, etc.[31]. Table 1 describes the general stratigraphical succession of Krishna–Godavari Basin[32].

Materials and methods

Soil sampling

A total of 36 samples were collected from the top and from the depths varying from 2 to 4 m using hollow metal pipe by manual hammering to the drillable depth. Soil core samples (500 g) collected were wrapped in aluminum foil and sealed in poly-metal packs. For microbial analysis, about 100 g of soil samples were collected in pre-sterilized whirl-pack bags under aseptic conditions from a depth of about 1 m (ref. 26) and later stored at 2–4°C for laboratory analysis. All the samples were sealed in re-sealable plastic bags and marked with sample number with locations using the global positioning system (GPS). While collecting the samples, rocks, coarse materials, plant residues, and animal debris were screened out[19].

Isolation of hydrocarbon oxidizing bacteria

Isolation and enumeration of propane oxidizing bacteria were carried out using enrichment culture technique. One gram of soil sample was suspended in 9 ml of pre-sterilized water to prepare decimal dilutions (10^{-1} to 10^{-5}). Aliquot 0.1 ml of each dilution was placed on to mineral salts medium (MSM)[33]. These plates were later placed in glass desiccator, filled with propane with 99.99% purity and zero air-purified atmospheric gas devoid of hydrocarbons with 1 : 1 ratio. Similarly, to isolate methane oxidizing bacteria, the desiccator was filled with methane gas and zero air. To isolate ethane and propane oxidizing bacteria, the desiccator was filled with hydrocarbon gas and zero air respectively. These desiccators were further kept in bacteriological incubators at 35 ± 2°C for 10 days. Following incubation, the developed bacterial colonies of methane, ethane and propane oxidizing bacteria[2,4,26] were counted using colony counter and reported in colony forming units (cfu g^{-1} of soil sample)[19].

Total organic carbon analysis

Soil sample (1.5 g of 63 μm) was treated with 3 to 4 drops of HCl to remove inorganic carbon and kept

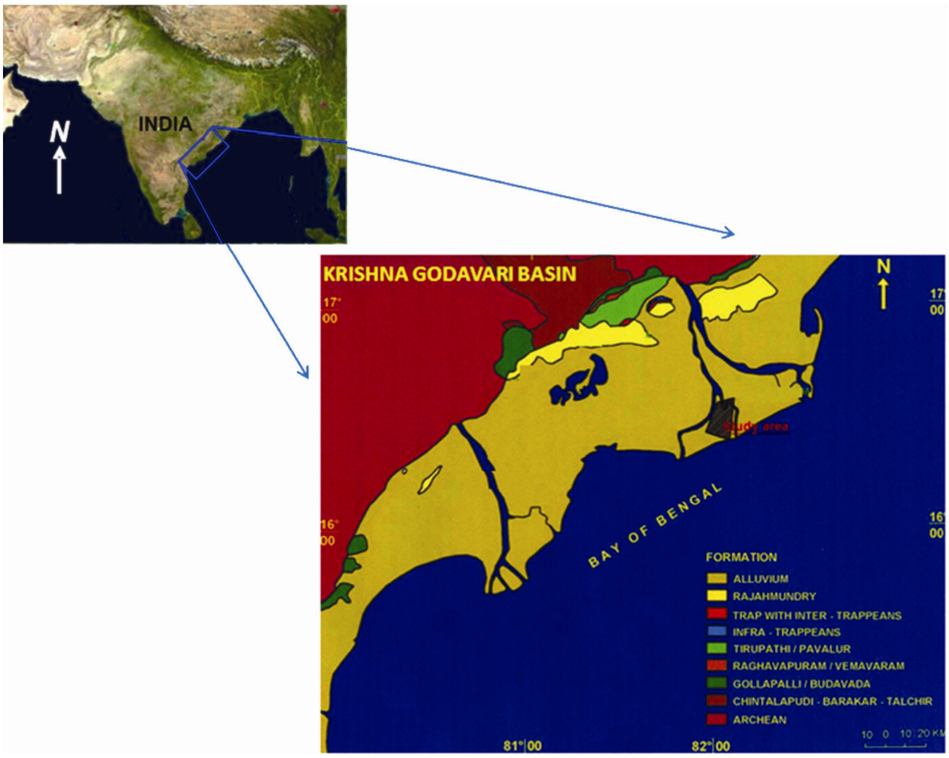

Figure 1. Geological location map of the study area of Krishna–Godavari Basin.

Table 1. Stratigraphic sequence of Krishna–Godavari Basin, Andhra Pradesh, India[32]

Age	Formation		Lithology
Holocene			Alluvial sands, clays and kankar, earthy grits, marls and sandstone
	-----Unconformity-----		
Post-Pliocene			Calcareous, gypseous and pyritiferous clays, gravelly sands, silts and poorly stored sand
Miocene–Pliocene	Rajahmundry		Coarse-grained, friable, ferruginous sandstones, grits, conglomerates and kaolinitic claystone
	-----Unconformity-----		
Pre-Miocene			
	-----Unconformity-----		
Palaeocene–Eocene	Infratrappean, Deccan trap volcanics and intertrappean beds		Coarse grits, calcareous sandstone, gritty limestone, basalts and local differentiates, limestone with claystone and marlstone
	-----Unconformity-----	UPPER GONDWANA	
Cretaceous	Tirupati Sandstone Raghavapuram Shale and Vemavaram Shale		Medium-coarse grained clayey and lateritized sandstones Variegated brittle shales and soft clays with thin lenses of sandstone
	-----Unconformity-----		
Middle Jurassic	Golapalli Sandstone and Budaveda Sandstone		Micaceous grits, ferruginous sandstone with claystone and limestone
	-----Unconformity-----		
Late Permian	Chintalapudi Sandstone (Lower Gondwana)		Conglomerates, ferruginous sandstones and siliceous shales
	-----Nonconformity-----		
Archean	Gneiss		Khondalites, schists, charnockites and pegmatites

overnight at 50°C in oven and 50 mg of this dried sample was loaded onto the quartz boat and transferred to the furnace of the solid module at 1000°C – a modification of the liquid total organic carbon analyzer basic unit for total organic carbon measurement. Similar procedure was adopted for the samples, blank, and the soil standard (Boden soil standard, 4.1% TOC). The CO_2 released due to chemical oxidation of the organic carbon was measured by infrared (IR) detector and expressed in wt%. The % RSD of the procedure is ≤1%.

Analysis of light gaseous hydrocarbons

Light gaseous hydrocarbons were extracted from soil samples using a gas extraction system[34]. One gram of 63 μm wet sieved soil sample was used to extract light gaseous hydrocarbons after acid treatment in specifically designed glass degasification apparatus and the subsequent analyses were carried out using Varian CP 3380 gas chromatograph fitted with Porapak Q column, equipped with flame ionization detector. The gas chromatograph was calibrated using external standards with known concentrations of methane, ethane and propane and the results are expressed in parts per billion (ppb)[16].

Analysis for carbon isotopes of light hydrocarbons

Carbon isotopic composition of light hydrocarbons ($\delta^{13}C_1$) in soil samples was determined using GC–C–IRMS[19], which comprises Agilent 6890 GC coupled to a Finnigan–Delta Plus^{XP} isotope ratio mass spectrometer via a GC combustion III interface. The carbon isotopic composition is reported in per mil (‰) relative to the PeeDee Belemnite (PDB). The precision of the isotopic analysis was ± 0.5‰. The $\delta^{13}C$ was calculated using the equation

$$\delta^{13}C = \{(^{13}C/^{12}C)_{sample}/(^{13}C/^{12}C)_{PDB}) - 1\} \times 100.$$

Results and discussion

Microbiological studies

Soil samples collected from Krishna–Godavari Basin, (Andhra Pradesh) were analysed for the presence of methane, ethane, and propane oxidizing bacteria using enrichment culture technique. The bacteria, which can utilize methane/ethane/propane gas as a sole carbon source, developed into bacterial colonies on the MSM plates[35]. As the medium does not contain any carbon source, the hydrocarbon gases were supplied externally for the growth of bacteria[36,37]. During the experiment, the positive controls of known hydrocarbon oxidizing bacterial strains namely, *Rhodococcus rhodochrous* MTCC 291, *Mycobacterium* sp. MTCC 19, *Pseudomonas* sp. MTCC 129 were inoculated onto MSM plates and incubated along with test soil samples (these bacterial strains were brought from Microbial Type Culture Collection Centre and Gene Bank (MTCC), Institute of Microbial Technology, Chandigarh). Usually, CO_2 is released as a byproduct and in order to avoid CO_2 fixing bacteria, KOH pellets in a petri dish was placed at the bottom of the desiccator so as to indicate that methane/ethane/propane oxidizing bacterial colonies developed by utilizing the given hydrocarbon gases act as a sole carbon source. The results of hydrocarbon oxidizing bacterial population are given in Table 2. The study area shows that the hydrocarbon oxidizing bacterial counts for methane oxidizing bacteria (MOB), ethane oxidizing bacteria (EOB) and propane oxidizing bacteria (POB) ranged from 2.35×10^5 to 3.64×10^5 cfu/g, 1.08×10^5 to 3.85×10^5 cfu/g and 1.0×10^2 to 3.04×10^5 cfu/g of soil samples

Table 2. Results of hydrocarbon oxidizing bacteria in soils of Krishna–Godavari Basin

Sample no.	MOB (cfu/g)	EOB (cfu/g)	POB (cfu/g)
KGW/01	305,000	141,100	111,700
KGW/02	325,000	156,000	120,500
KGW/03	310,000	193,700	62,800
KGW/04	280,400	159,800	0
KGW/05	271,600	134,000	500
KGW/06	298,000	156,700	0
KGW/07	261,500	183,100	400
KGW/08	276,500	151,200	26,100
KGW/09	250,000	160,000	287,300
KGW/10	295,600	210,300	69,500
KGW/11	251,200	235,800	169,500
KGW/12	274,100	180,500	700
KGW/13	303,700	202,300	304,300
KGW/14	346,300	191,800	400
KGW/15	277,400	223,800	500
KGW/16	293,900	108,700	11,000
KGW/17	272,600	146,800	2,100
KGW/18	262,600	161,700	0
KGW/19	291,800	138,100	188,200
KGW/20	305,600	139,900	0
KGW/21	308,100	164,100	43,000
KGW/22	270,000	209,000	21,700
KGW/23	294,700	196,600	145,600
KGW/24	277,900	201,300	500
KGW/25	295,600	133,800	15,400
KGW/26	263,200	148,700	9,800
KGW/27	261,000	193,400	43,700
KGW/28	284,400	269,800	183,100
KGW/29	270,400	385,100	236,800
KGW/30	313,300	320,000	217,500
KGW/31	267,000	256,500	252,500
KGW/32	241,400	184,000	42,200
KGW/33	276,000	185,000	130,500
KGW/34	235,500	113,300	247,000
KGW/35	266,600	238,100	249,700
KGW/36	307,800	226,100	85,900

cfu/gm, Colony forming units per gram; MOB, Methane oxidizing bacteria; EOB, Ethane oxidizing bacteria; POB, Propane oxidizing bacteria.

(Table 3). The results of hydrocarbon oxidizing bacterial population and adsorbed soil gas concentrations are plotted and the anomalous zones for methane, ethane and propane oxidizing bacteria have been worked out (Figures 2–4). The patterns of reduced microbial counts adjacent to production wells and further reduced counts to older producing fields and low in well-drained gas reservoirs indicate that seepage is directly proportional to the confining pressure in reservoirs. When a well is brought into production, the drive mechanism changes from vertical buoyancy driven force to horizontal gas streaming to the pressure sinks created around producing wells. The change in drive mechanism and microbial population densities can be used to define reservoir drainage direction, radius, and heterogeneities all around the existing wells in developing fields[21]. The possibility of discovering oil or gas reservoirs using microbiological method is emphasized by the fact that the hydrocarbon-oxidizing bacteria range between 10^3 and 10^6 cfu/g in soil/sediment receiving hydrocarbon micro-seepages depending on ecological conditions[19,20]. In the study area, the concentration of hydrocarbon oxidizing bacteria ranges between 10^4 and 10^5 cfu/g of soil sample, and substantiates the seepage of lighter hydrocarbon accumulations from oil and gas reservoirs[19,26,35].

Table 3. Statistical evaluation of hydrocarbon oxidizing bacteria in of Krishna–Godavari Basin

Parameters	MOB (cfu/g)	EOB (cfu/g)	POB (cfu/g)
Minimum	2.35×10^5	1.08×10^5	0
Maximum	3.46×10^5	3.85×10^5	3.04×10^5
Arithmetic mean	2.82×10^5	1.91×10^5	9.43×10^4
Standard deviation	2.83×10^4	5.62×10^4	1.0×10^4
Positive samples (%)	100	100	86.12
Nil samples (%)	0	0	13.88

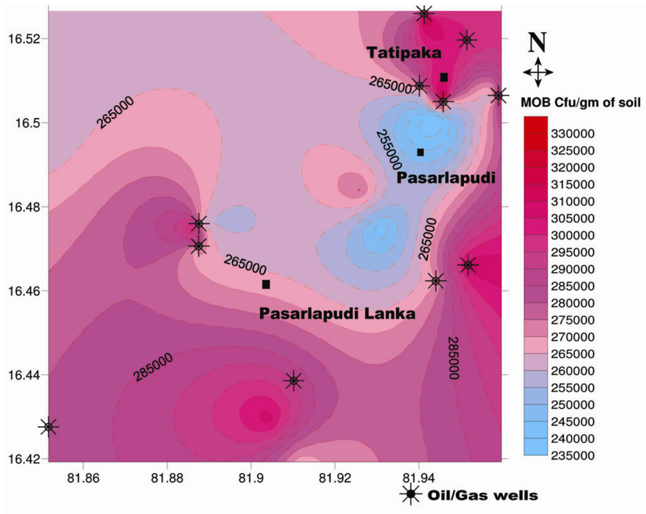

Figure 2. Concentration distribution of methane oxidizing bacteria in the Krishna–Godavari Basin.

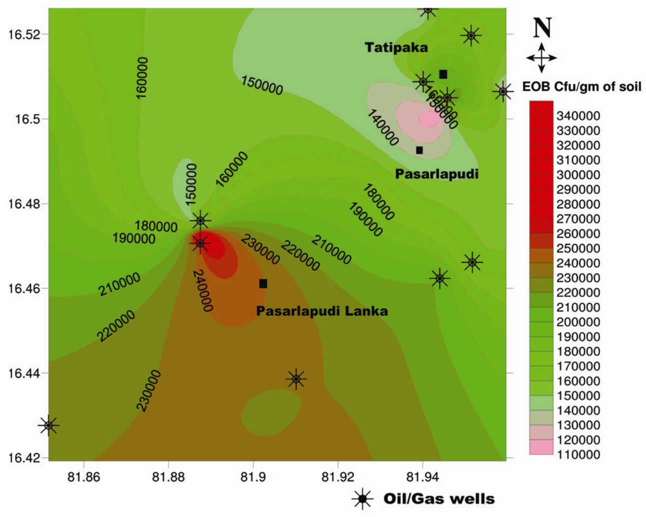

Figure 3. Concentration distribution of ethane oxidizing bacteria in the Krishna–Godavari Basin.

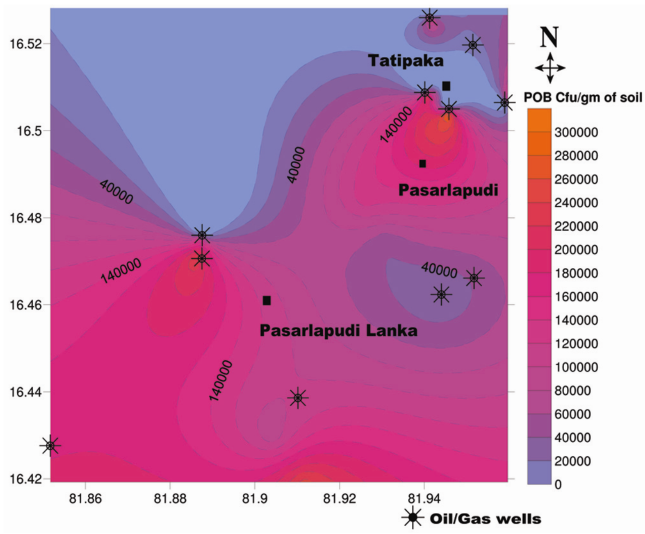

Figure 4. Concentration distribution of propane oxidizing bacteria in the Krishna–Godavari Basin.

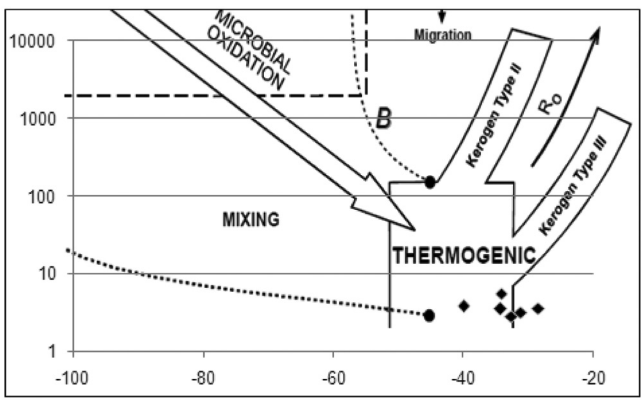

Figure 5. Bernard's plot showing the thermogenic source of the desorbed soil gases from the study area.

Table 4. Results of adsorbed soil gas data of Krishna–Godavari Basin

Sample no.	Longitude	Latitude	C_1 (ppb)	C_2 (ppb)	C_3 (ppb)	C_{2+} (ppb)
KGW/01	81.9414	16.5258	59*	6	0	6
KGW/02	81.9414	16.5253	51	4	0	4
KGW/03	81.941	16.5266	10	0	0	0
KGW/04	81.942	16.5265	30	3	0	3
KGW/05	81.9402	16.526	45	3	0	3
KGW/06	81.9401	16.5088	7	0	0	0
KGW/07	81.9403	16.5093	8	0	0	0
KGW/08	81.9394	16.5087	8	0	0	0
KGW/09	81.9403	16.5085	24	2	0	2
KGW/10	81.9411	16.5091	14	2	0	2
KGW/11	81.9458	16.505	52	4	0	4
KGW/12	81.9448	16.5051	9	0	0	0
KGW/13	81.9453	16.5042	4	0	0	0
KGW/14	81.9458	16.5055	34	3	0	3
KGW/15	81.9466	16.5055	28	3	2	5
KGW/16	81.9586	16.507	95	69	34	103
KGW/17	81.9581	16.508	74	55	28	83
KGW/18	81.9581	16.5061	23	0	0	0
KGW/19	81.9597	16.5072	107	51	3	54
KGW/20	81.9595	16.5058	48	32	11	43
KGW/21	81.9518	16.4661	15	0	0	0
KGW/22	81.9441	16.4624	12	0	0	0
KGW/23	81.8873	16.4755	113	99	10	109
KGW/24	81.8873	16.4764	31	17	7	24
KGW/25	81.8864	16.476	10	0	0	0
KGW/26	81.8884	16.4756	9	0	0	0
KGW/27	81.8517	16.4943	37	0	0	0
KGW/28	81.8878	16.4705	17	0	0	0
KGW/29	81.8878	16.471	16	0	0	0
KGW/30	81.8873	16.471	12	0	0	0
KGW/31	81.8868	16.4705	26	2	0	2
KGW/32	81.9307	16.4746	18	0	0	0
KGW/33	81.9258	16.4839	18	0	0	0
KGW/34	81.944	16.5018	18	0	0	0
KGW/35	81.9116	16.4192	23	0	0	0
KGW/36	81.9042	16.4295	19	0	0	0

ppb, parts per billion.

Table 5. Statistical evaluation of adsorbed light gaseous hydrocarbons in soils of Krishna–Godavari Basin

Parameter	C_1 (ppb)	C_2 (ppb)	C_3 (ppb)	$\sum C_{2+}$ (ppb)
Minimum	4	0	0	0
Maximum	113	99	34	109
Arithmetic mean	32.65	11.94	3.39	14.71
Standard deviation	27.96	22.75	7.50	28.89

Adsorbed soil gas and carbon isotope studies

The gas chromatographic analysis of 135 soil samples and the magnitude of each of the organic constituents CH_4, C_2H_6, C_3H_8 and n-C_4H_{10} were measured and expressed in ppb of the soil gas mixture (Table 4). The concentrations of adsorbed soil gases varied for methane (C_1) from 1 to 115 ppb, for ethane (C_2) from 1 to 99 ppb, for propane (C_3) from 1 to 34 ppb, for butane (nC_4) from 1 to 9 ppb and for $\sum C_{2+}$ from 1 to 115 ppb (Table 5). The cross-plots between C_1, C_2, C_3 and $\sum C_{2+}$ show good correlation (r = >0.9) and the data gathered (Table 6) indicates that (i) the hydrocarbons are genetically related; (ii) hydrocarbons are not affected by secondary alteration during their migration from subsurface to subsequent adsorption on to the surface soil and (iii) hydrocarbons might have been generated from a thermogenic source. The interpretation followed the standard genetic diagram for correlating gas wetness, i.e. $C_1/(C_2 + C_3)$ ratios with the $\delta^{13}C$ of methane to classify natural gas types as biogenic or thermogenic[38]. Molecular ratios of $C_1/(C_2 + C_3)$ less than −50‰ are typical for thermogenic hydrocarbon gases with $\delta^{13}C_1$ values between –25‰ and −50‰ (VPDB; Vienna PeeDee Belemnite) whereas the ratios of $C_1/(C_2+C_3)$ above 1000 with $\delta^{13}C_1$ values between −60‰ and −85‰ (VPDB) are indicative of biogenic origin of hydrocarbon gases. Methane usually has a quite isotopically depleted ^{13}C ratio of less than −60‰. The carbon isotopic composition of $\delta^{13}C_1$ in soil samples ranged between –36.6‰ and −22.7‰ versus VPDB. The isotopic values of the samples are characteristic of thermogenic range (Figure 5).

Relationship between $\sum C_{2+}$, total organic carbon and total inorganic carbon

Surface geochemical data sets require authentication to verify whether there are physical or chemical attributes influencing the hydrocarbon yields not related to hydrocarbon seepage. Total organic carbon (TOC) and total inorganic carbon (TIC) are two important controlling factors for sorption of hydrocarbons in soils[39] and the concentration for 20 selected samples respectively, varies from 0.18% to 1.34%, 0% to 0.38%. The Pearson correlation analysis shows that concentration of $\sum C_{2+}$ in soils does not show any correlation ($r^2 = 0.065$) (Figure 6) with soil TOC indicating that the adsorbed gases are not derived from organic carbon present in the soil or relict gas. The relationship between $\sum C_{2+}$ and soil TIC indicates that there appears no significant correlation with the surficial organic matter and the possibility of interaction between the seeping hydrocarbons.

Table 6. Pearson correlation coefficient for adsorbed soil gas

	C_1	C_2	C_3	$\sum C_{2+}$
C_1	1.00			
C_2	0.40	1.00		
C_3	0.27	0.97	1.00	
$\sum C_{2+}$	0.26	0.95	0.99	1.00

Table 7. Results of TC, TOC and TIC concentration of soil samples of KG Basin

Sample ID	TC (%)	TOC (%)	TIC (%)
KGW/01	0.954	0.5963	0.3577
KGW/02	0.6525	0.5941	0.0584
KGW/03	0.8862	0.5698	0.3164
KGW/04	0.747	0.5789	0.1681
KGW/05	0.7589	0.7083	0.0506
KGW/06	0.6517	0.5573	0.0944
KGW/07	0.5946	0.5775	0.0171
KGW/08	0.5997	0.5921	0.0076
KGW/09	0.8444	0.4874	0.357
KGW/10	0.62	0.358	0.262
KGW/11	0.7141	0.4417	0.2724
KGW/12	0.6333	0.6016	0.0317
KGW/13	0.4419	0.4078	0.3737
KGW/14	0.6146	0.2895	0.3251
KGW/15	0.7001	0.5996	0.1005
KGW/16	0.4907	0.1823	0.3084
KGW/17	0.4082	0.1839	0.2243
KGW/18	1.122	0.7408	0.3812
KGW/19	0.576	0.4589	0.1171
KGW/20	1.469	1.341	0.128
KGW/21	0.5948	0.5248	0.07
KGW/22	0.6911	0.6493	0.0418
KGW/23	0.7601	0.72	0.0401
KGW/24	0.6541	0.6386	0.0155
KGW/25	1.058	0.9753	0.0827
KGW/26	0.4948	0.4887	0.0061
KGW/27	0.4082	0.1839	0.2243
KGW/28	0.6482	0.6372	0.011
KGW/29	0.6146	0.2895	0.3251
KGW/30	0.6023	0.6001	0.0022
KGW/31	0.6819	0.679	0.0029
KGW/32	0.6519	0.5475	0.1044
KGW/33	0.6333	0.6016	0.0317
KGW/34	0.5946	0.5775	0.0171
KGW/35	0.6911	0.6493	0.0418
KGW/36	0.747	0.5789	0.1681

TIC, Total inorganic carbon; TOC: Total organic carbon; TC, Total carbon.

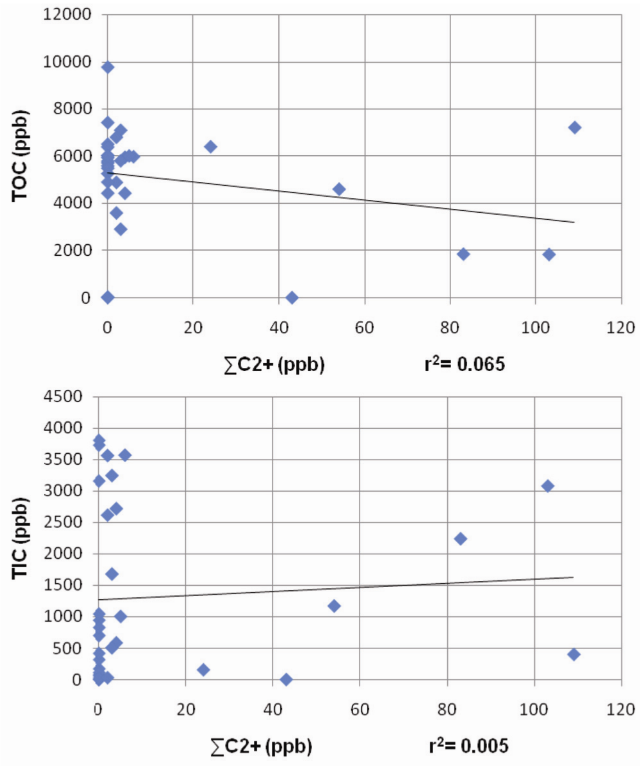

Figure 6. Scatter plots of $\sum C_{2+}$–TOC and $\sum C_{2+}$–TIC.

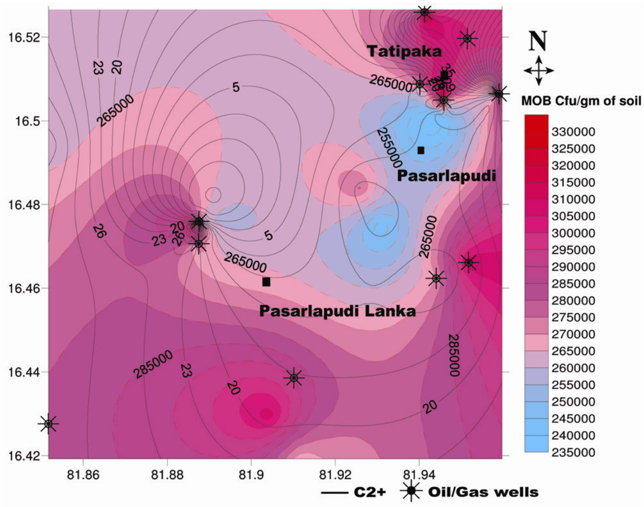

Figure 7. Composite anomaly map of methane oxidizing bacteria and adsorbed methane in the Krishna–Godavari Basin.

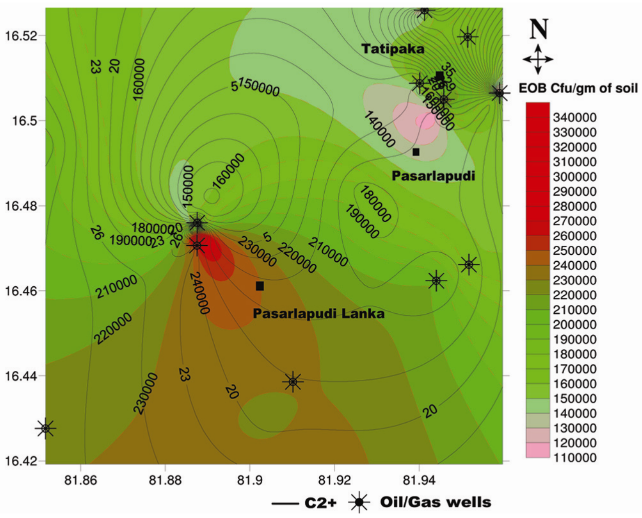

Figure 8. Composite anomaly map of ethane oxidizing bacteria and adsorbed ethane in the Krishna–Godavari Basin.

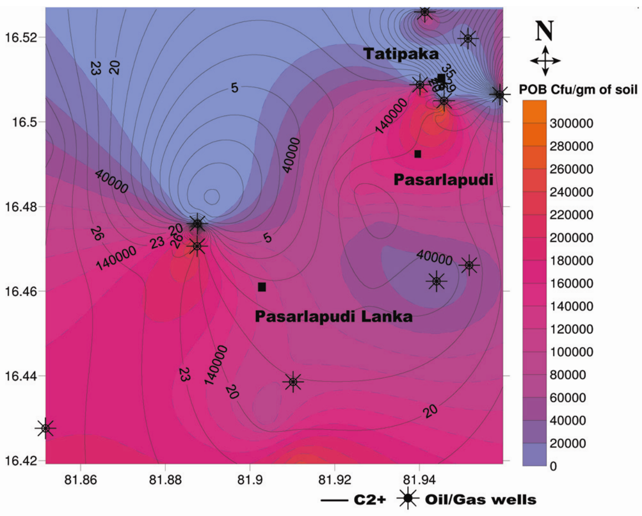

Figure 9. Composite anomaly map of propane oxidizing bacteria and adsorbed propane in the Krishna–Godavari Basin.

Integration with adsorbed soil gas studies

Integrated anomaly maps of adsorbed light hydrocarbons (C_1–C_3) and hydrocarbon oxidizing bacteria MOB, EOB and POB (Figures 7–9) show composite anomalies for light gaseous hydrocarbons and hydrocarbon oxidizers anomalies that follow the natural model depicting 'Halo' pattern[14,19,35,37,40]. The study reveals a good correlation between the hydrocarbon utilizing bacteria and adsorbed hydrocarbon. These observations indicate that the micro-seepages of hydrocarbon gases may become scanty or may be undetected by geochemical means in areas where high soil microbial activity exists, resulting in moderate utilization of soil gases by microbes. These microbes can survive even at low concentration of hydrocarbons of about 10^{-6} vol.% or higher and significantly reach a bacterial count of 10^3 to 10^6 cells per gram of soils or sediments[26].

Conclusion

The present study shows that microbial presence has a direct bearing with the accumulation of hydrocarbons in sub-surface regions. The microbial prospecting and adsorbed soil gas studies together indicate that hydrocarbon micro-seepage exists in the area under review. Finally, the study highlights the corroboration of adsorbed light gaseous hydrocarbons and hydrocarbon oxidizing bacteria. We infer that this approach is one of the potential tools for surface geochemical prospecting of hydrocarbons that can be applied in other basins prior to seismic and other applications. However, the findings when integrated with available field data may bring a holistic picture of locating the possible zones of interest.

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