>~200 m, except over the built-up regions in the domain where blt is still shallow, which is highly conditioned by UHI effect. The effect of Cartosat-1 in VI forecast is visible in Figure 6 *c*, except that the southern ridge dipole nature of index is visible in the nearby grids and majority of the grid points in the domain give reduced values in VI forecast.

In summary, the use of Cartosat-1 satellite DEM to generate orography for the DM model and its impact on the model forecast of fog/visibility-related parameters are examined. The effect of Cartosat-1 DEM through changes in the mean orography is felt at the lowest boundary layer through enhanced downdraft, and the associated push down of the boundary. In addition, the surface winds are weakened in most areas, though they are highly variable and turbulent in nature. Histogram analysis revealed enhanced fog growth through the formation of shallow boundary layer and reduced surface wind speed in the Cartosat-run. The Cartosat orography has been operationalized in the DM model since the winter season of 2018. Besides the daily operational fog/visibility forecast, the forecasting of VI from DM can serve as a potential proxy for short-range air-quality monitoring. The results presented here could be beneficial to improved air-quality risk monitoring, management and strategic planning, especially over the Delhi region.

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Hydrocarbon generation potential of source rocks in Jaisalmer Basin, Rajasthan, India

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Geochemical and statistical analyses have been carried out for the evaluation of source rocks characteristics of Jaisalmer Basin, Rajasthan, India. The geochemical analysis includes pyrolysis data, total organic carbon, oxygen and hydrogen indices. The analysis suggests that Cretaceous source rocks are poor to fair with kerogen of types III–II and have the capability of generating gas and oil whereas the Jurassic source rocks are poor with kerogen of type III and have the capability of generating gas. The Tertiary sources of rocks however have poor potential and are immature. The Jaisalmer Basin has gas-rich petroleum system, whereas the Baisakhi–Badesir and Pariwar sources have oil generation capability. The presence of higher concentration of N_2 and CO_2 in the gas suggests the over-maturation and residual accumulation of N_2 and CO_2 in the natural gases.

Keywords: Jaisalmer Basin, kerogen, pyrolysis data, source rock.

JAISALMER Basin in the eastern part of Indus Basin has commercial production of gas in India. The available data of four tectonic units, viz. Kishangarh shelf, Jaisalmer-Mari high, Shahgarh low and Miajalar low are integrated. Maximum source rock data is available from Jaisalmer-Mari High followed by Shahgarh low and Miajlar low, while sparse data is available from Kishangarh shelf. Jaisalmer-Mari High area is operated by M/s Oil and Natural Gas Corporation (ONGC), Shahgarh low is operated by M/s Focus Energy Ltd. with ONGC as joint venture partner. Miajalar depression was operated by M/s Ente Nazionale Idrocarburi (ENI) and ONGC (now relinquished) and Kishangarh Shelf by Oil India Limited (OIL) independently.

In general, petroleum source rocks are fine-grained, organic-rich sediments that could either generate or have already generated and expelled significant amounts of petroleum[1]. The source rock potential of the basin is to be evaluated initially for assessing hydrocarbon prospectivity of the basin in terms of oil and gas. The present paper has brought out source rock geochemistry and maturity based on a compilation of studies carried out by

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various workers on total organic carbon (TOC), Rock-Eval pyrolysis, vitrinite reflectance, isotopic data along with gas composition. The geochemical analysis includes pyrolysis data as total organic carbon (TOC %), oxygen and hydrogen indices (OI, HI), generating source potential ($S1$, $S2$ and $S3$) and T_{max} (ref. 2).

Analysis of source rock data has been carried out for the important source rocks to estimate the potential of oil and gas generation from Jurassic (Lathi Formation) to Palaeocene (Sanu Formation) sequences. Based on detailed studies, source rocks within Baishakhi–Badesir and Pariwar formations appear to be the main for generation of gas and associated liquid hydrocarbons.

Jaisalmer Basin is a pericratonic basin in the north-western part of India, known as western Rajasthan shelf[3]. The basin situated on the eastern shelf of part large Indus Basin and is characterized by thick sedimentary alternating sequences of clastics and carbonates. It is a late Palaeozoic–Mesozoic basin with gentle westerly slope (dip 3° to 5°) and comprises rocks of Permian age which unconformably overlie the Proterozoic basement. The rocks of Tertiary and Mesozoic age are well exposed in this basin and represented mainly by limestone, shale, siltstone and sandstone[4].

The basin covers an area of 45,000 sq. km and is contiguous with the gas-rich area of Middle Indus Basin of Pakistan. The Basin is subdivided into four tectonic blocks, viz. Kishangarh shelf, Jaisalmer-Mari high, Shahgarh low and Miajlar low. The NNW–SSE trending regional step-faulted Jaisalmer-Mari High zone occurs at the centre of the basin. The structural trend in the basin is regionally considered to be two-fold – a NNW–SSE trend corresponding to Dharwarian trend and a NE–SW trend parallel to the Aravalli range (Figure 1).

The stratigraphy of Jaisalmer Basin was first established by Blanford[5], followed by Oldham[6]. Subsequently, the ONGC revised the stratigraphy of the basin (Table 1)[7].

A number of gas fields such as Manhera Tibba, Bankia, Ghotaru, Kharatar, Sadewala, Chinnewala Tibba and Bakhri Tibba have been established so far by ONGC in the Jaisalmer Basin (Figure 2). Currently gas is produced

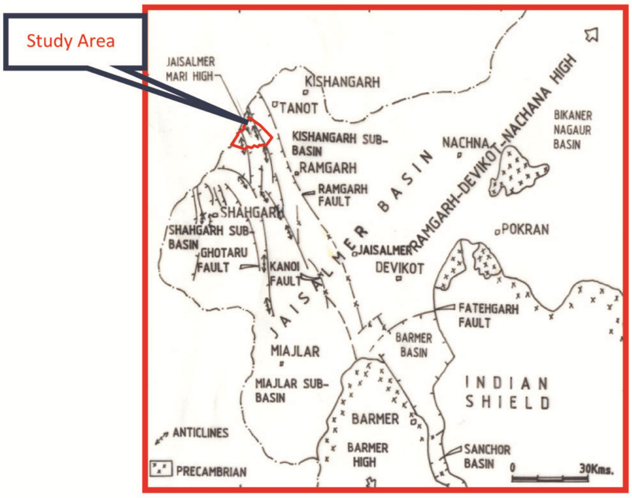

Figure 1. Structural elements of Jaisalmer Basin, Rajasthan, India.

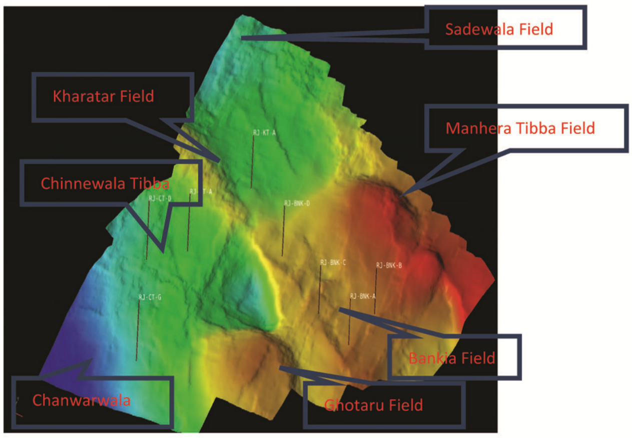

Figure 2. Spatial distribution of different gas fields in ONGC acreage.

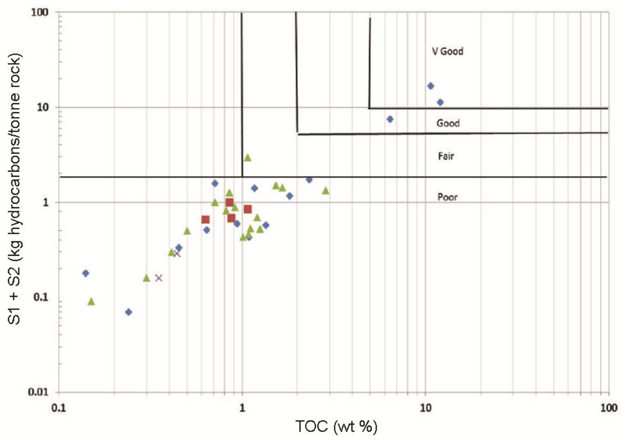

Figure 3. $S1 + S2$ versus total organic carbon (TOC) plot for Lathi Formation.

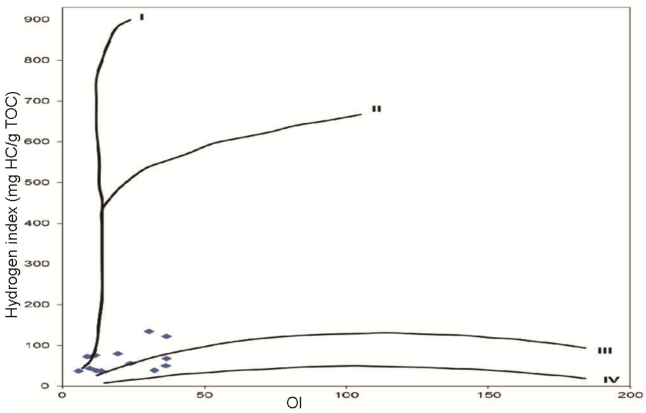

Figure 4. HI versus OI plot for Lathi Formation.

Table 1. Generalized stratigraphy of Jaisalmer Basin, Rajasthan

Eon/era	Period/epoch	Formation	Lithology
Cenozoic	Holocene	Wind-blown sand/alluvium	Loose sand and alluvial materials
	Holocene to Pleistocene	Shumar	Dune sands, gravels with ferruginous nodules
	Middle Eocene	Bandha	Foraminiferal limestone clayey at the base
	Early Eocene	Khuiala	Shales with limestone beds and calcareous silt
	Palaeocene	Sanu	Sandstone with minor clays
Mesozoic	Late Cretaceous	Parh	Marls and arenaceous limestone
	Middle-Early Cretaceous	Goru	Arenaceous limestones and calcareous sandstones
	Early Cretaceous	Pariwar	Sandstone, shale, lignite
	Late Jurassic	Baisakhi/Bhadesar	Sandstone and shale
	Middle Jurassic	Jaisalmer	Limestone and Sandstone
	Early Jurassic	Lathi	Sandstone, shale and lignite
	Triassic	Sumarwali	Sandstone and clay stone
Palaeozoic	Permian	Karampur	Shale and sandstone
	Cambrian	Birmania	Sandstone and shale
Neoproterozoic	Tonian/Cryogenian	Randha	Sandstone and shale
		Basement	Malani igneous suite/metamorphic basement

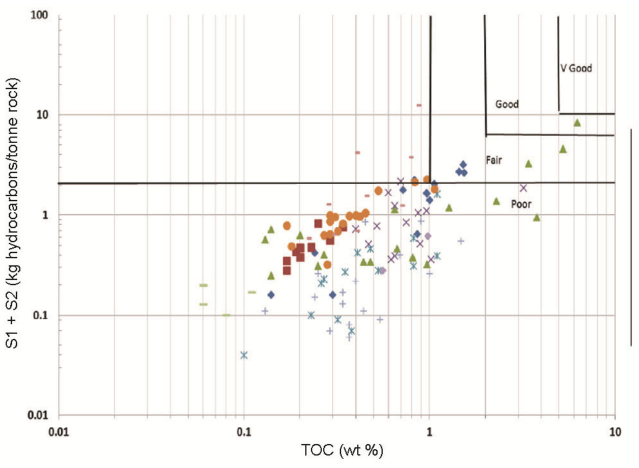

Figure 5. $S1 + S2$ versus TOC plot for Jaisalmer Formation.

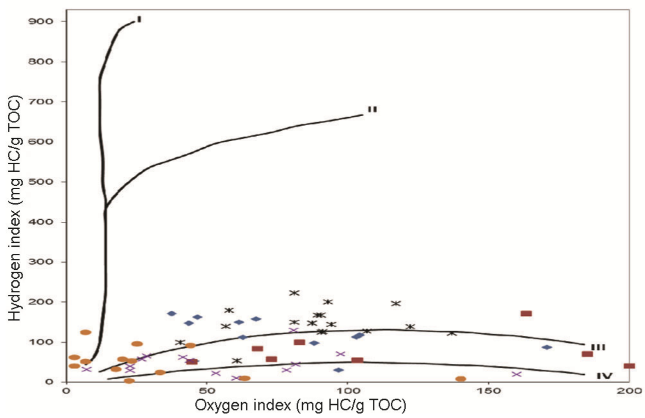

Figure 6. HI versus OI plot for Jaisalmer Formation.

primarily from C2–C4 and B4 reservoirs of Khuiala Formation (Palaeocene to Lower Eocene) from Manhera Tibba Field. Besides, Sanu (Palaeocene), Lower Goru and Pariwar formations (Lower Cretaceous) have been found to be gas-bearing. Presence of minor oil within Lower Goru and Pariwar formations in Chinnewala Tibba, Ghotaru and Bankia fields has been proved during production testing of a few wells. Gas from Manhera Tibba field is supplied to M/s GAIL at GCS Gamnewala which in turn supplies to RRVNL at Ramgarh. Commercial gas is produced by M/s OIL in Tanot area, and in SGL field by M/s Focus Energy Ltd towards the southwest.

There are a number of gas and oil fields in Middle Indus Basin, Pakistan and producing from Paleocene (Dunghan), Lower Eocene (Sui Main) and Middle Eocene (Habib Rahi) shelf carbonates. At deeper stratigraphic levels, production comes from subtle structural closures in the distal Cretaceous siliciclastic low stands of the Sembar and Lower Goru formations. Sui and Mari are important gas fields with commercial production whereas Lagheri and Khaskeli are the oil producing fields in Pakistan.

The composition of gas varies from one field to another also from deeper stratigraphic levels to shallower stratigraphic levels in the basin (Table 2).

In the deeper parts of basin in Pakistan, N_2 and CO_2% are observed to decrease in NW and western directions[8].

The distribution, thickness, quality and thermal maturity of the organic matter are described for units of the drilled formations of the basin. Standard plots of the TOC and Rock-Eval pyrolysis data are used to understand source rock richness, quality, maturity and kerogen type. Original HI values for each formation and lithology are determined through the analysis. Where data density permits, maps of the present-day TOC and HI are prepared, for spatial variation in the amount and quality of

Table 2. Gas composition of different discovered gas fields on Jaisalmer Mari High

Field	C1 (%)	C2 (%)	CO_2 (%)	N_2 (%)
Manhera Tibba (Cretaceous reservoir)	20–25	0.6–0.8	5–8	60–70
Manhera Tibba (Tertiary reservoir)	40–50	0.1–0.04	1–5	50–60
Kharatar	10–35	0.05	5–10	65–70
Bankia	20–30	0.3–0.5	2–10	70–80
Ghotaru	20–30	0.3–0.5	5–10	70–80
Chinnewala Tibba	60–70	3-8	2–8	20–25
Chanwarwala Dara	60–80	12.43	0.01	23.01

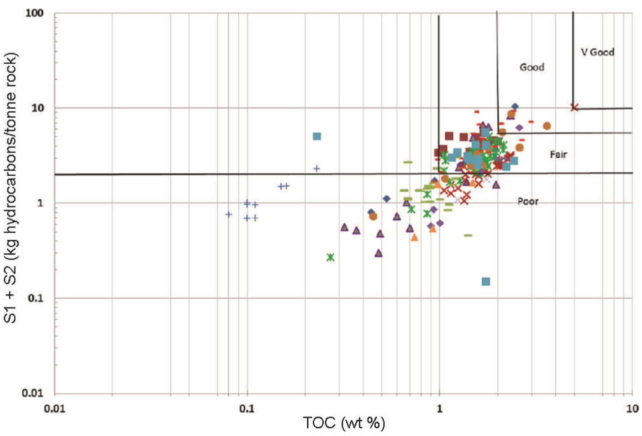

Figure 7. $S1 + S2$ versus TOC plot for Baisakhi–Badesir Formation.

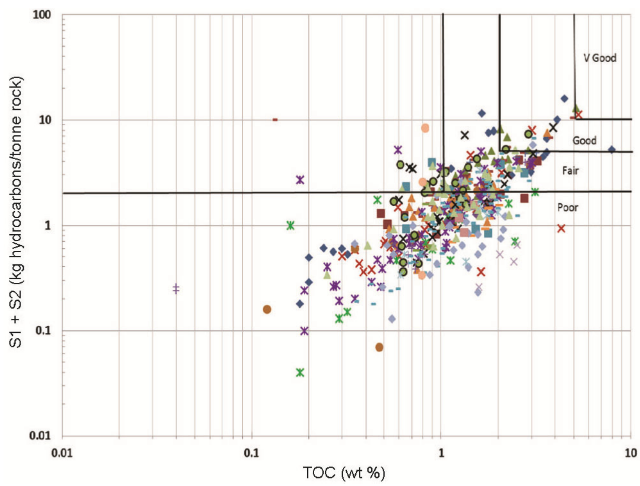

Figure 9. $S1 + S2$ versus TOC plot for Pariwar Formation.

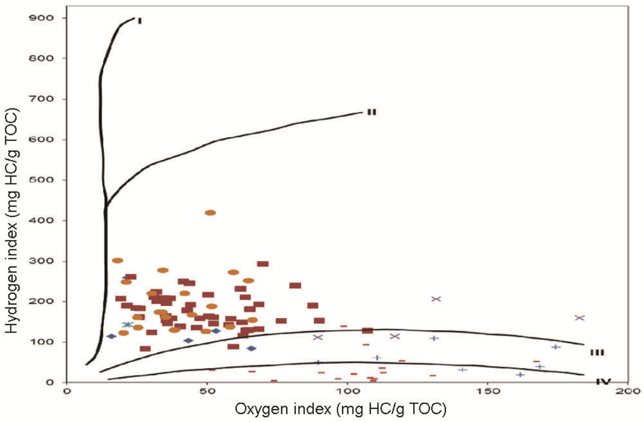

Figure 8. HI versus OI plot for Baisakhi–Badesir Formation.

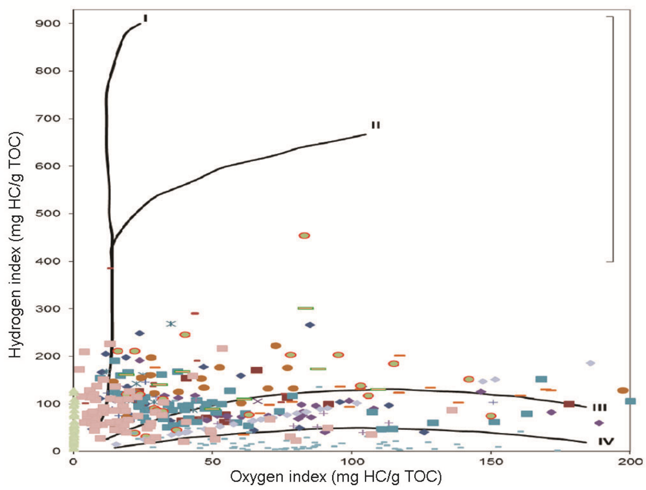

Figure 10. HI versus OI plot for Pariwar Formation.

the source rock present now and prior to the onset of hydrocarbon generation.

The data availability is poor for deeper stratigraphic units and it is fair for shallower stratigraphic units. The deepest stratigraphic level considered in the present study is Lathi Formation (Early Jurassic age).

The generation potential of a source rock is identified using the results of pyrolysis data. The generation potential (GP) is the sum of $S1$ and $S2$ values. According to Hunt[9], source rocks with GP <2, 2 to 5, 5 to 10 and >10 are considered to be poor, fair, good and very good respectively[10]. The kerogen type and maturity were determined based on pyrolysis data. Kerogen classification diagrams were prepared using the HI versus T_{max} plot[11].

The statistical analysis of Lathi Formation includes samples from four wells with TOC values and complete

Rock-Eval pyrolysis data. The majority of sample points are located in the eastern flank of the basin. The principal source rocks are shales, and analysis indicates that the formation has poor potential (Figure 3) with Type III source rock (Figure 4). The maximum TOC value for the formation is 1.2% and HI value is <150 mg HC/g TOC and OI < 50 mg HC/g TOC. Jaisalmer Formation has been penetrated in a few wells across the basin. Available samples were studied along with complete Rock-Eval pyrolysis data (very few drilled wells have gone up to Jaisalmer Formation and the samples from those wells have been used for geochemical analysis). The formation suggests fair to poor source rock potential (Figure 5) and dominantly Type III source rock (Figure 6). TOC value ranges between 0.1% and 1% and HI and OI values are up to 200 mg HC/g TOC. TOC or HI maps were not are prepared due to the limited data. Similar analyses were carried out for Baisakhi–Badesir, Pariwar and Goru formations. The source rock potential plot ($S1 + S2$ versus TOC) suggests these formations have fair to good generation potential of hydrocarbons and dominantly type-II and type-III kerogen (Figures 7–12). Sanu Formation shows poor potential, type-III source rock.

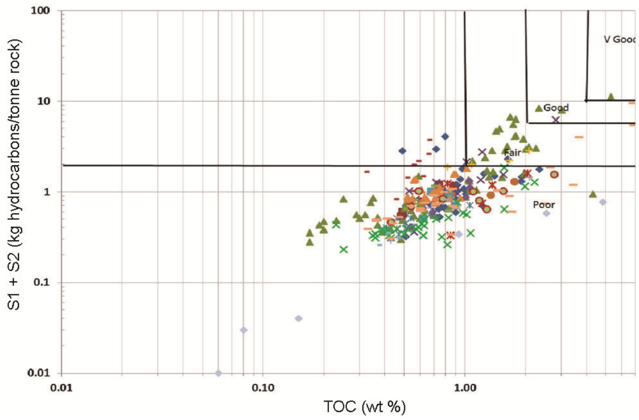

Figure 11. $S1 + S2$ versus TOC plot for Goru Formation.

TOC and HI maps were generated for best source rocks, i.e. Baisakhi–Badesir and Pariwar formations. The spatial distribution of Baisakhi–Badesir suggests that in Shahgarh and Miajalar sub-basin, the organic richness is good to very good (TOC 1.57–2.5%) and the Hydrogen Index (HI) of the kerogen is in the range 163–204 mg HC/g TOC, which is wet gas prone Type-III in the southern part. In Jaisalmer-Mari high the source rock data indicates good organic richness (TOC 1.63–5.3%) and Type–II/III source rock indicates Oil and Gas prone kerogen (HI–240–260 mg HC/g TOC). The HI is found to be increasing from Manhera Tibba to Sadewala and Manhera Tibba to Shahgarh. Towards the south-western margin, best source rock is found in Shagarh low with high TOC and HI values.

The spatial distribution of TOC in Pariwar Formation suggests maximum TOC value at Jaisalmer Mari High near Kharatar Gas Field and minimum TOC value in Shahgarh depression. HI value decreases from SW to NE direction. Espitalie *et al.*[11] reported that oil generation from source rocks began at $T_{\max} = 435–465°C$ and production index ‘PI’ between 0.2 and 0.4. The source rock analysis indicates that Baisakhi–Badesir and Pariwar formations have capacity to generate liquid hydrocarbons (Figures 13 and 14).

Pariwar and Basisakhi–Badesir formations have Type-II kerogen along with Type-III and indicate the presence of gas rich source potential with potential generation of oil. The shales of Baisakhi–Bhadesir and Pariwar formations as well as shales of Lower Goru Formation have been identified as major source rock units. Source rock richness increases towards west and south-west along the basinal slope. Top of oil window in the basin, ranges

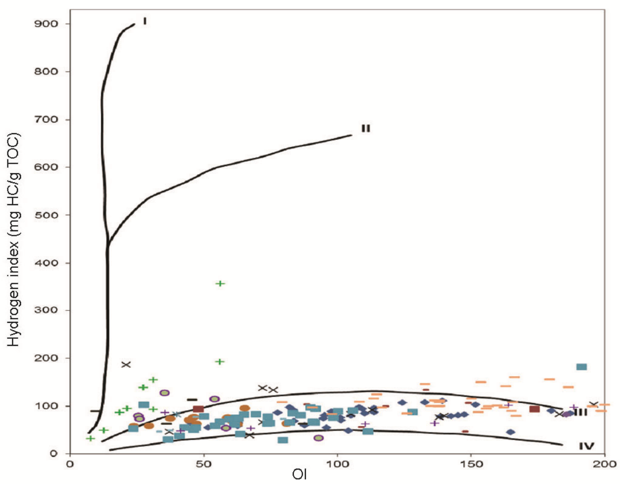

Figure 12. HI versus OI plot for Goru Formation.

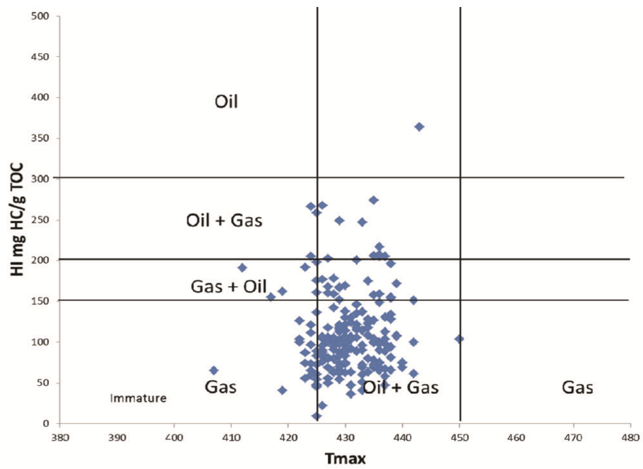

Figure 13. $T_{\max}$ versus HI plot of Pariwar Formation to show generation capabilities of source rock, Jaisalmer Basin.

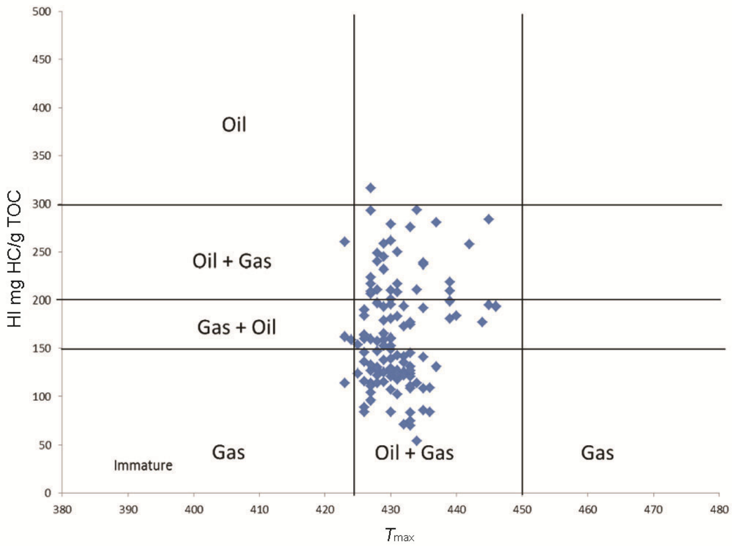

Figure 14. T_{max} versus HI plot of Baisakhi–Badesir Formation to show generation capabilities of source rock, Jaisalmer Basin.

from 1950 to 2800 m in consonance with the basinal geometry where Mesozoic sequences have attained threshold to adequate thermal maturation. The concentration of CO_2 in the gases of the study area is highly variable ranging from 0.73% to 10% in Ghotaru Field, ~70% in Kharatar Field. Similarly, the concentration of N_2 ranges from 33% to 62% in Kharatar, 68% to 75% in Bankia and up to 65.21% to 81.0% in Ghotaru Field. Since mantle-derived helium has not been observed, presence of CO_2 and N_2 is inferred to be of non-mantle origin. Such higher percentages of CO_2 and N_2 are assumed to be because of over-maturation[12].

The source rock maturity is high, but accumulations are relatively small, which suggests early escape of generated hydrocarbons. This is consistent with the late Pliocene trap formation and explains the high N_2 concentrations. Further, N_2 is considered to have evolved as an end-product of organic maturation. It is also inferred that identified source rock units of the basin might have generated and expelled hydrocarbons during Late Eocene due to lack of suitable entrapment condition to accommodate the discharge from these source beds while some may have escaped through the regional faults/erosional surfaces.

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