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Author **sukumar pahari , KDMIPE, ONGC, Dehradun , India**
Co-Authors **M. Purkait, Neha Rawat and Sweta Singh**

Assessment of origin, timing and extent of hydrocarbon generation in Kutch Offshore Basin through kerogen kinetic study

Abstract

Source rock kinetics reflects kerogen reactivity that controls the onset and rate of hydrocarbon generation as well as the depth and temperature of hydrocarbon generation windows. The present study determines custom kinetics of immature Mesozoic and Tertiary source rocks in Kutch Offshore Basin to examine the accurate timing and extent of hydrocarbon generation.
The study reveals that the Early Eocene source rocks of K and G3 area and Paleocene source rocks of G42 area possess labile (kinetically reactive) kerogen and can transform into hydrocarbons at lower thermal stress with activation energy maxima (Ea max) and frequency factor (A) of 46-48 Kcal/mole and 10^{11} -10^{12} s^{-1} respectively corresponding to burial depth ~2500m and maturity 0.55 VRo. However, Mesozoic and rest of Tertiary source rocks in study area are kinetically less reactive and needs higher thermal stress for conversion into hydrocarbons with Ea max and A of 50-60 Kcal/mole and 10^{13} -10^{15} s^{-1} respectively.
Cretaceous (Coniacian and older) to Jurassic source rocks have mostly contributed towards hydrocarbon accumulation with hydrocarbon expulsion window at ≥ 4400m burial depth. These sediments started generating hydrocarbons since 80-88ma. Additionally, some oil expulsion observed from Eocene source in low of KI area only. This study provides critical input for realistic resource assessment of the area.

Introduction

Knowledge of the kinetics of kerogen degradation of various source rock facies deposited in a petroliferous basin is necessary for understanding evolution of hydrocarbon (HC) on a geological time scale. Hydrocarbon generation depends on both the thermal-burial history of a source rock and the kinetics of hydrocarbon generation from the associated kerogen. Laboratory determined customized kinetics is the representative kinetic data for accurate estimation of timings and extent of hydrocarbon generation in a petroliferous basin. The present study determines custom kinetics of immature Mesozoic and Tertiary source rocks of Eocene to Jurassic age in Kutch Offshore Basin and examines the timing and extent of hydrocarbon generation using custom kinetics from source rocks of Eocene to Jurassic age. The study further correlates kerogen transformation with maturity of the source rocks.

Geological setting of the study area

The Kutch–Saurashtra basin is a part of the three marginal rift basins that have formed at different times since the late Triassic at the northwest coast of India. During the course of evolution of Indian Plate, three prominent pericratonic rift basins (Kutch-Saurashtra, Cambay and Narmada) developed on the periphery of the Indian Peninsula. Rifting along Precambrian tectonic trends formed these basins (Biswas, 1982, Zutshi et al, 1993). The Kutch Offshore Basin (Figure 1), a Mesozoic basin is a south-western continuation of the Rajasthan Basin, extending into the offshore with a wide shelf platform. The basin contains substantial offshore part characterized by the presence of shelf around 160 km wide in Kutch offshore and slightly lesser along the Saurashtra offshore with shelf break occurring at 200 m bathymetry. The entire basin is important from the point of petroleum prospect as it is surrounded by the basins having prolific oil and gas discoveries such as the south Indus basin of Pakistan in west, Cambay basin in east, and the Mumbai offshore basin in south.

Kinetics of kerogen decomposition

It is established that thermal evolution of petroleum is controlled by the kinetics of cracking reactions of organic matter that occur in sedimentary basins at temperature of 100–200^{0}C over time and buried typically for a few million years (Tissot and Welte, 1984). Knowledge of the timing and location of petroleum generation can be predicted from the thermal and burial history of the basin and the kinetic parameters that characterize the thermal breakdown of kerogen in source rocks. The theory of kinetic model of Tissot and Espitalié (1975) predicts the amount of hydrocarbon generated by primary cracking of kerogen in a source rock when temperature increases through time. The degradation of kerogen into hydrocarbon is described by a series of number of parallel chemical reactions and each chemical reaction follows a first order kinetics which is characterized by the Arrhenius Law:

$$K=A*e^{(-Ea / RT)}$$

Where, ^{K} = reaction rate parameter, A = frequency factor (in s^{-1}), Ea = activation energy (Kcal/mole), R = molar gas constant and T = absolute temperature (^{o}K).
The kinetic approach resolves the problem of the multitude of chemical reactions involved during oil and gas generation and also provides the link between the short-time high temperature reactions in the laboratory and the long-time low temperature reactions in sedimentary basins.

Hydrocarbon occurrences

The early discoveries in Tertiary reservoirs of Kutch Offshore include oil in Eocene limestone and calcareous sandstone from K area, and Paleocene sands in G29 area (Figure 1). The occurrence of hydrocarbons below Deccan trap in the Mesozoic sequence has been established through gas finds in G22, G28, SN4 (Figure 1) and has given fillip to Mesozoic exploration. Oil has also been discovered for the first time in the sub-trappean Cretaceous reservoirs in G28. Presence of oil and gas in several Tertiary and Mesozoic reservoirs proves the hydrocarbon generation and entrapment process in the Kutch offshore basin.

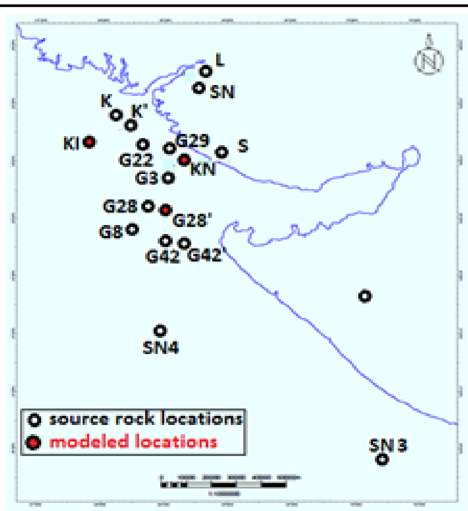

Figure 1: Map of studied locations

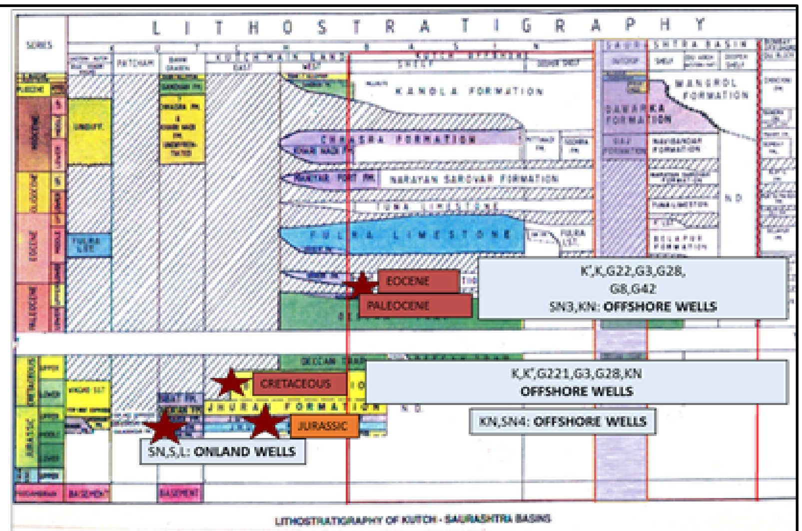

Figure 2: Distribution of samples in stratigraphy

Source Rocks

Studies indicate that TOC and HI values of Paleocene-Early Eocene source rocks in shallow offshore of Kutch Basin are in the range of 3.19-7.44% and 140-257 mg HC /g TOC, respectively and are not in oil window zone in the drilled locations. The late Paleocene-Early Eocene finer clastics host good source facies and are likely to continue in the deeper part of the basin.
In the Offshore Kutch Basin, Late Jurassic to Early Cretaceous source rocks represent the oldest tested source rocks on the Western India margin. Mesozoic source sequences have been identified in 9 exploratory wells located mostly in the shallow offshore part. The Mesozoic sediments possess adequate organic matter richness (TOC: 1.47 - 4.36%) coupled with oil and gas prone Type II and Type III organic matter as evident from Hydrogen index values (HI: 145-368 mg HC/g TOC). Vitrinite reflectance studies of the sediments (Table-1) indicate that Mesozoic sediments of the wells K, KI, SN3, G28, G3, L and S are in oil window zone (VRo: ≥0.6%).

SLNo.	Well name	Depth (m)	Age/ Formation	VRo range	Average VRo (%)
1	G3	2860-65	Early Cretaceous	0.651-0.858	0.76
2	G28	3540	Jurassic	0.52-0.80	0.61
3	G28	3610	Jurassic	0.52-0.78	0.64
4	G28	3730	Jurassic	0.55-0.80	0.7
5	G28	4070	Jurassic	0.61-0.88	0.78
6	K'	2970	L.Turonian	0.58-0.84	0.71
7	K'	3075	L.Turonian	0.58-0.84	0.75
8	K	3825-28	Coniacian	0.851-0.979	0.92
9	K	4011-14	Coniacian	0.926-1.109	0.99
10	K	4263-66	Coniacian	0.956-1.179	1.09
11	L	2441-44	Upper and Middle Jurassic	0.53-0.70	0.62
12	S	1970-75	Upper and Middle Jurassic	0.533-0.74	0.64

Table 1: VRo data of Mesozoic sediments

Samples and Experimental

Total 59 immature (Tmax<$435^{o}C$) source rock samples of Jurassic to Eocene age from fifteen exploratory wells of study area (Figure 1 and Figure 2) have been taken up for the present study having good organic matter richness and hydrogen index values more than 100 mg HC/g TOC. Source rock evaluation has been done based on the geochemical data obtained from 15 wells comprising total organic carbon, Rock-Eval pyrolysis, vitrinite reflectance (Peters, 1986; Stach et al., 1982). The study has used GENEX (from Beicip-Franlab, France) software for 1-D modeling. Bottom hole temperature from wells available (K', G28 and KN) were used to calibrate the thermal model. A heat flow value ~ 56 mW/m2 is obtained at the bottom of the sedimentary column.
Kinetic parameters (Ea, the activation energies and 'A', the frequency factor) of a source rock are measured in laboratory through pyrolysis in Rock-Eval 6 at four different heating rates ($1^{o}C$, $5^{o}C$, $10^{o}C$ and $25^{o}C$/min). in the temperature range $300^{o}C$-$650^{o}C$ followed by mathematical optimisation of best fitted experimental data by Optkin software.

Kinetic studies on source rocks

Kinetic study reveals that the kerogen in Early Eocene source rocks of K and G3 area and Paleocene source rocks of G42 area are very kinetically reactive and can transform into hydrocarbons at lower thermal stress with activation energy maxima (Ea max) and frequency factor (A) of 46-48 Kcal/mole and 10^{11} -10^{12} s^{-1} . However, rest of Tertiary source rocks in study area are kinetically less reactive and needs higher thermal stress for conversion into hydrocarbons with Ea max and A of 50-58 Kcal/mole and 10^{13} -10^{15} s^{-1} respectively. Cretaceous source rocks are found to possess kinetics of late hydrocarbon generating characteristics (Ea max: 54-60 Kcal/mole, A: 10^{14} to 10^{15} s^{-1}). Jurassic source rocks exhibit late hydrocarbon generating characteristics (Ea max: 54-58 Kcal/mole, A: 10^{13} to 10^{15} s^{-1}).

Petroleum generation and expulsion studies

1-D modeling has been carried out in order to assess the timing of hydrocarbon generation and expulsion for four main potential source rock horizons (the Late and Middle Jurassic, the Early and Late Cretaceous, the Paleocene and Eocene) at drilled wells KI, G28 and KN in the Kutch Basin. Stratigraphic depth for pre Albian at KI location and pre Late mid Jurassic at other two locations are estimated from available isopach map of

Figure 3: Distribution of activation energies of Mesozoic and Tertiary source rocks

Mesozoic. The model included basin history viz. depositional, non-depositional and erosional events which are specific with respect to time and space. Similarly, structural and tectonic events such as faulting, rifting and volcanic eruptions have been included. Information available on geometry, lithology, stratigraphy and source rock data was used as input data for the conceptual model of the basin. Each formation/layer is assigned with its pertinent lithology and facies. Heat flow (56 mW/m2), paleo latitude, sediment water interface temperatures and Paleo water depths of the basin are defined according to tectonic events and change in sea level. The kerogen-hydrocarbon kinetics used in the model for Mesozoic and Tertiary source rocks is based upon measured kinetics shown in Figure 3. Kinetic data of Jurassic source rock for on land wells L, S, and SN has been used for modeling of Jurassic source rocks.
The BHT and VRo data are used for calibration of the thermal model. A heat flow value ~ 56 mW/m2 is obtained at the bottom of the sedimentary column. After calibration, and simulation with input data the model determines generation and expulsion history of the source rocks.

Results of modeling

At KI location, Late Cretaceous source rocks starting from Maastrichtian to Cenomanian age started generating hydrocarbons from 20-85 Ma. At present day, Turonian and Cenomanian source rocks transformed fully to enter into dry gas zone (VRo>2%) whereas Campanian, Santonian, and Coniacian source rocks have undergone 40-90% kerogen transformation. The Turonian and Cenomanian source rocks were at peak oil generation stage (VRo upto 1%) during Early Eocene (~70% transformation, 52Ma) and Maastrichtian age (~74% transformation, 68Ma) respectively. At present day, younger source rocks of Maastrichtian, Campanian, Santonian source rocks are in Peak oil generation stage (VRo% 0.7-1.0) and Coniacian source rocks are at late oil stage (VRo%1.25). Expulsion of hydrocarbons from the Turonian and Cenomanian source rocks started from ~35 Ma, Late Eocene and ~58 Ma, Late Paleocene age respectively. Early Cretaceous, Albian source rocks started generating hydrocarbon from 88Ma during Coniacian and at present day it has entered dry gas generation stage (VRo %> 2.5). Peak oil generation stage for Albian occurred during Campanian age with upto 72% Kerogen conversion. Expulsion of oil and gas occurred during Early Paleocene, 62Ma from Albian. Late Jurassic source rock started generating hydrocarbon from 89Ma during Coniacian and at present day it is under dry gas window zone. Oil Expulsion from the Jurassic source rocks started during Campanian, 80 Ma. Figure 4 presents hydrocarbon window geo history of the K' at present day indicating Early Eocene (at 2550m) to Santonian (at 3450m) sediments are in oil window zone whereas Coniacian sediments(at 4400m) are in late oil window zone. Turonian to Jurassic source rocks (5700m onwards) are presently at dry gas zone. Hydrocarbon expulsion status at present day indicates some oil expulsion from Eocene source rocks due to its early generating kinetic characteristics. Otherwise, Late Cretaceous, Coniacian to Jurassic source rocks, from 4400m onwards have generated and expelled most of hydrocarbons in study area.
Present day maturity of Jurrasic, Cretaceous, Paleocene and Eocene source rocks at KI location are computed to be ~4.0, 0.66-2.4, 0.61 and 0.58 VRo respectively corresponding to kerogen transformation (KT) ~100%, 25-98%, 9.2% and 30% respectively.

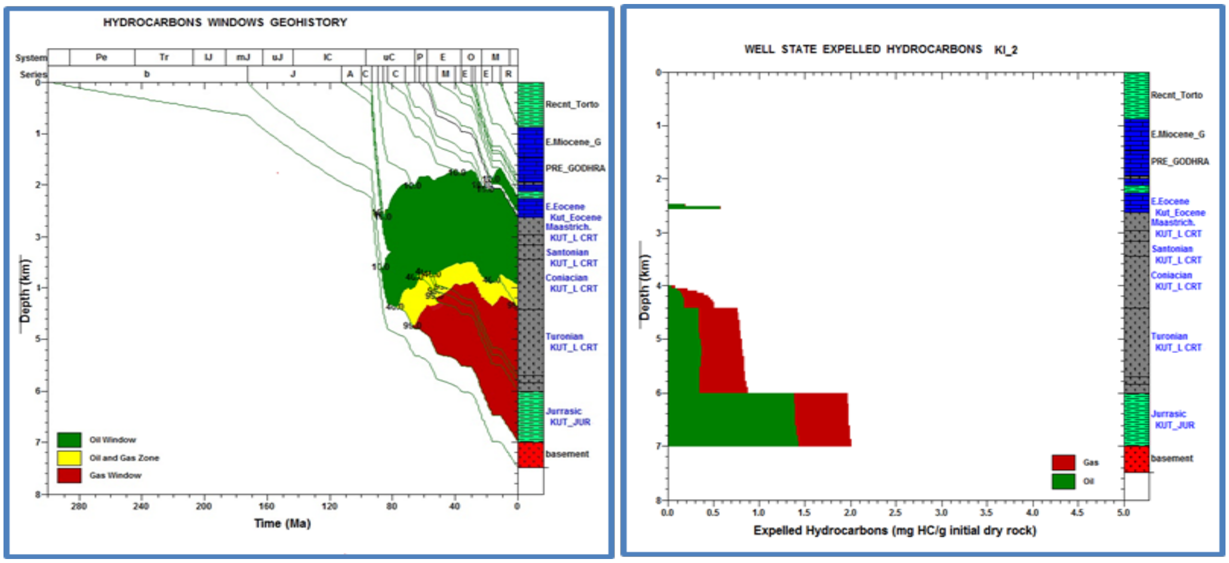

Figure 4: Hydrocarbons windows geo history and hydrocarbon expulsion status at KI location

At location KN, Tertiary source rocks are immature to generate hydrocarbon. Generation of hydrocarbons occurred from the Early Cretaceous, which is now at the peak oil generation stage with 46% Kerogen transformation, started generating hydrocarbons from Early Eocene (~50Ma). Late Jurassic started generating hydrocarbons from Early Eocene (~52Ma) is also at peak generating stage with 66% kerogen transformation. Late Middle Jurassic and Middle Jurassic source rocks started generating hydrocarbons from Late Paleocene (~60Ma) and from Late Cretaceous (~100Ma) are at late and wet gas generation stage, at present, with 80% and 86% kerogen transformation respectively. Hydrocarbon expulsion status at present day indicates some oil expulsion from Early Cretaceous at depth interval ~2750m – 3100m. The Cretaceous and Jurassic source rocks might have generated and expelled hydrocarbons from nearby Mesozoic low, which is more than 7000m deep.

At G28 location, post Coniacian source rocks are immature. Coniacian source rocks started generating HC from Late Eocene (~40Ma) and at present day 32% kerogen transformation took place. Early Cretaceous, Aptian source rocks started generating since Paleocene (60Ma) and presently reached peak generation stage with 70% kerogen transformation. Early Cretaceous (Barremian) and Late Jurassic source rocks reached late oil generation stage with more than 85% kerogen transformation (VRo %> 1-1.35). Late Middle Jurassic which started generating 85Ma, has now reached wet gas generation stage with 86% kerogen transformation (VRo%~1.8). In this location, oil find in the sub-trappean Cretaceous reservoir might have been sourced from the deeper Mesozoic source sequence of nearby low.

Conclusions

- Early Eocene source rocks of K and G3 area and Paleocene source rocks of G42 area are kinetically very reactive and can transform into hydrocarbons at lower thermal stress with activation energy maxima (Ea max) and frequency factor (A) of 46-48 Kcal/mole and 10^{11} -10^{12} s^{-1} . However, rest of Tertiary source rocks in study area are kinetically less reactive and needs higher thermal stress for conversion into hydrocarbons with Ea max and A of 50-58 Kcal/mole and 10^{13} -10^{15} s^{-1} respectively.
- Mesozoic source rocks are found to possess kinetics of late hydrocarbon generating characteristics (Ea max: 54-60 Kcal/mole, A: 10^{13} to 10^{15} s^{-1}).
- Vitrinite reflectance studies of the sediments in wells K, KI, SN3, G28, G3, L and S indicate that Mesozoic sediments of the studied wells are in oil window zone (VRo: ≥0.6%) and hence are capable of generating hydrocarbons.

- In KI location, onset of oil generation starts from Eocene source rocks at 0.55% VRo from Miocene time (~16Ma) with more than 30% Kerogen transformation at present day (~0.58% VRo). In the other two locations viz, G28 and KN, it has not entered oil window zone due to its shallower burial depths (<1500m). Early Eocene (~ 2550m) sediments are in oil window zone only in KI location.
- Onset of oil generation from Paleocene source rocks in KI location has not been initiated due to its late generating kinetic characteristics in the studied locations.
- Peak to late oil generation stage (VRo~0.7-1.3%) with 30-90% kerogen transformation at present day has been observed for the Late Cretaceous source rocks of Maastrichtian, Campanian, Santonian and Coniacian in KI location. The Cretaceous sediments from ≥ 2900m burial started generating hydrocarbons during Miocene to Eocene (20-55 Ma).
- In KI location, Cretaceous source rocks of Turonian, Cenomanian and Albian at ≥ 5500m burial have entered dry gas generation stage (VRo>2.0%) with 99% kerogen transformation. Beginning of oil generation has started from 80-88Ma. Jurassic source rocks at burial depth ~7000m are in dry gas zone with 99% Kerogen transformation.
- Oil and gas from G28 and KN locations evidently has been sourced from the deeper source sequences of nearby Mesozoic low at maturity ~0.9 VRo.
- Further, hydrocarbon expulsion study based on determined kerogen kinetics indicates expulsion of hydrocarbons mostly from Late Cretaceous, Coniacian to Jurassic source rocks with minimum burial depth of 4400m. Some oil expulsion from Eocene source rocks (~2500m) took place only at KI area due to its early generating kinetic characteristics.
- Laboratory determined kinetic data can provide critical input for realistic resource assessment of the area.

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