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Shale Oil Plays of Cambay Shale Formation, Cambay Basin, India

Abstract

The objective of this paper is to explore shale oil plays of Cambay Shale Formation in Ahmedabad sub-block of Ahmedabad-Mehsana block of Cambay Basin, India. Oil and gas shows observed while drilling through Cambay Shale Formation, particularly in mature oilfields of Nawagam, South Kadi, Ahmedabad, Wadu, Kalol and small fields like, Naika, Walod and Mahelaj fields are corroborated with laboratory and geophysical data. Identified sweet zones of the shale reservoirs within oil window were taken up for deliberate exploration, as low cost exploration, in idle/low producing wells of Nawagam and South Kadi fields. Silty shale intervals in these conventional oil wells have yielded encouraging results on testing and frac job in vertical/deviated wells.

Potential zones are identified and correlated on the basis of electro-log characteristics. Some of these shales in Younger Cambay Shale formation are exploited as conventional oil which typically show low production rate in existing vertical wells. The conventional reservoirs that are found in some areas within abnormally pressured Older cambay Shale are currently being exploited, but these encapsulating shale zones have also been proved to be low rate oil producers after frac jobs, in vertical wells.

These shale/tight reservoirs within both Older Cambay Shale and Younger Cambay Shale have wide areal extent, adequate TOC and maturity to produce oil and gas. Poor permeability aided to retain insitu oil and gas. Priliminary testing in conventional wells proved producibility of shale oil in Cambay Shale, but true potential can be realised through application of accepted shale oil and gas well technology.

Introduction

The intra-cratonic Cambay rift basin is mature and prolific oil and gas producer from Tertiary deposits. The NNW-SSE elongated Cambay Basin is divided into five different blocks by major cross faults. The study area is located at the central part of the basin in the Ahmedabad sub-block (Figure 1).

This study is carried out to explore the plays of Tight Oil and Shale Oil/ Shale gas of the Cambay Shale Formation based on leads obtained during exploration and exploitaion of conventional reservoirs in some of the producing oil fields. This paper attempted to explore the hydrocarbon potential of Late Paleocene transgressive Older Cambay Shale (OCS) formation which was deposited in late-rift stage of the basin and Early Eocene shallow marine to transitional environment Younger Cambay Shale (YCS) deposited in post-rift thermal subsidence stage. Cambay Shale formation is well established as basin -wide source rock of almost all conventional hydrocarbon reserves.

However, other than exploration and exploitation of few conventional hydrocarbon reservoirs discovered within the Cambay Shale Formation, exploration of thick argillaceous section within Cambay Shale formation is in nascent stage. Few wells that have been tested for Shale oil/gas potential in Nawagam, South Kadi and Walod field either produced oil at low rate or proved to be oil bearing in shale and siltyshale in conventional vertical oil wells. This study tries to corroborate all the data concerned to shale/tight oil exploration that are available to facilitate better understanding of shale/tight oil potential in the study area.There is scope for more elaborate study that requires extensive shale-specific data acquisition.

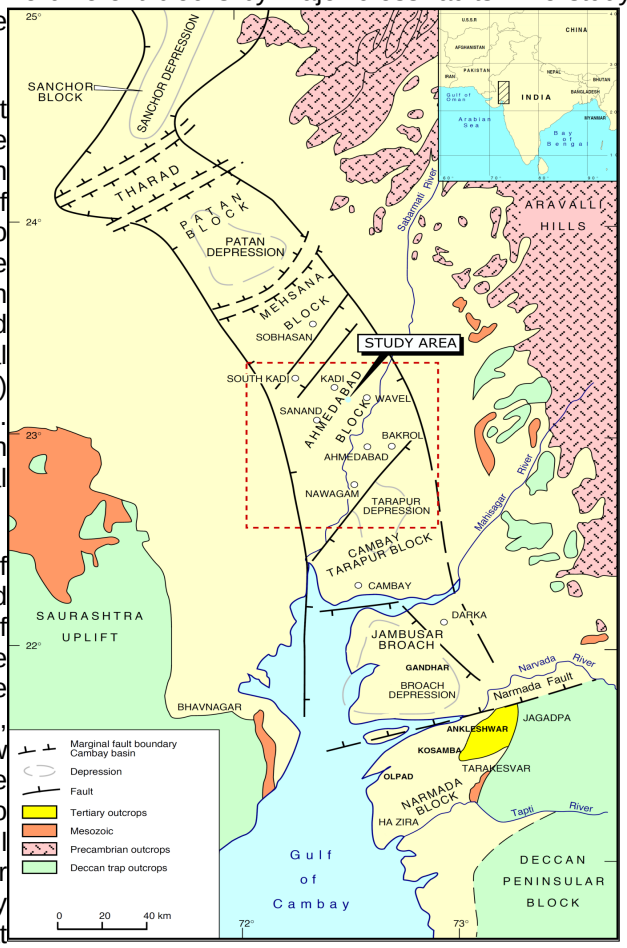


Figure 1: Study area in the regional map of Cambay basin (modified after Raju and Srinivasan, 1993)

General Geology and Stratigraphy

Ahmedabad sub-block of Cambay Basin, Gujarat covers an area of about 14000 sq km (Figure 1), occupies the area between Kadi town and Paliyad village in north and Kheda town and Nawagam in south. Stratigraphy of the area is well established (Figure 2). The rift fill sequence, Olpad Formation lies unconformably above the technical basement of Deccan Trap basalt. The Olpad formation consists of trapwash with trap conglomerates deposited as fanglomates to lacustrine deposits in syn-rift phase. Olpad Formation is overlain unconformably by Late Paleocene to Early Middle Eocene transgressive shale, represented as Cambay Shale Formation. The entire basin was engulfed by rising sea level from south.

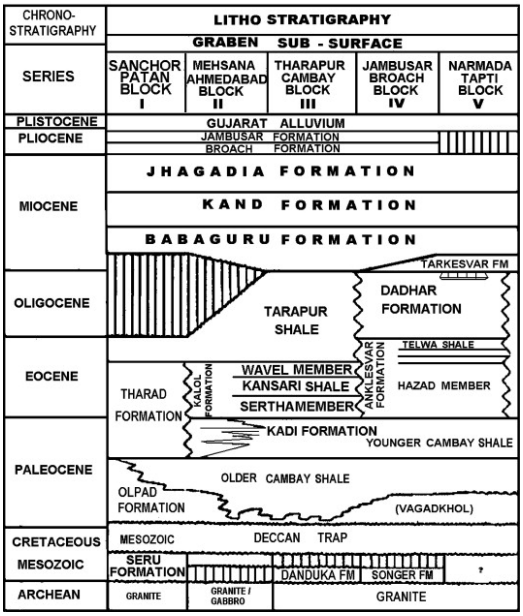


Figure 2: General Stratigraphy of Cambay Basin

Based on fauna and flora noted in two southern blocks, Cambay Shale Formation is divided into underlying Older Cambay Shale (OCS) and overlying Younger Cambay Shale (YCS). In Ahmedabad-Mehsana Block, Younger Cambay Shale is represented by regressive phases of Mandhali, Mehasana and Chhatral members with shallow marine shales in between. Chhatral, Mehsana and Mandhali members having type area in Mehsana Sub-Block grades to shale in the northern part of Ahmedabad Block (Kalol and Sanand). Further south, it is deposited in tidal environment having litho-associations like sideritic siltstones, ash grey to medium sandstone and carbonaceous pyritic shale. Overlying regressive cycle in

Middle Eocene represented by Kalol Formation, deposited in deltaic to intertidal mud flats. South of Ahmedabad city, the Kalol Formation is possibly deposited as tidal delta deposits (Raju and Srinivasan, 1993). Late Eocene-Oligocene transgressive cycle is represented by Tarapur Formation which acts as a regional seal. The Neogene section is dominantly fluvial deposits.

Characteristics of shale oil reservoirs

The shale reservoirs are classified as unconventional reservoirs (reservoirs with permeability less than 0.1mD) (Boyer et al., 2011). Such reservoirs can be exploited economically after they are hydro-fractured. Unlike conventional plays, these resource plays cover a wide areal extent and are not typically confined to geologic structure. Typical shale gas/oil plays have TOC more than 2% with type I, II or III kerogen and vitrinite reflectance between 0.6 to 3.0. Other desirable factor is shale brittleness which is directly proportional to quartz concentration. The most productive shale gas and shale oil have Poisson's Ratio <0.3 and Young's Modulus >2.0. Shale gas may grade into tight gas with increase of quartz fraction or carbonate fraction.

Shale is classified into three types on the basis of dominant organic and lithological characteristics: (1) Tight Shale: organic-rich mudstones with predominantly healed fractures; (2) Fractured Shale: organic-rich mudstones with open fractures; and (3) Hybrid Shale: hybrid systems with a combination of juxtaposed organic-rich and organic-lean intervals (Fig. 3) (Jarvie, 2012). Producible oil from shales is closely associated with organic-lean intra-formational lithofacies: in case of Cambay Shale these are such as siltstone and siltyshale. Resource system of Cambay Shale may be termed as hybrid-type. In general shale of Cambay Shale Formation have low quartz content. These grey to dark grey colour shale are, moderately fissile and have carbonaceous, pyritic and silty bands and laminations. The silty bands give away to conventional reservoirs at places in north western part of the block (South Kadi area) due to favourable tectono-sedimentary condition at the time of deposition. The x-ray diffraction analysis of Cambay Shale of Sanand area shows that the clays are composed of kaolinite and chlorite (Table 1) (Gangwar and Sircar, 2013). Quartz and pyrite are other mineral constituents. The formation is composed of bituminous shale with occasional bands of sandstones and siltstones. Oolitic claystones and glauconitic clay are recorded in the lower part of YCS in Nawagam area.

Table 1: Density & mineral composition (weight fraction) of shale, Sanand area (Gangwar and Sircar, 2013)

Sample	Density (g/cm3)	Weight fractions (%)				
		Illite/Smectite	Kaolinite	Quartz	Siderite	Feldspar
YCS	2.21	35	44	14.2	4.6	1.8
OCS	2.16	32	38	11.2	5.6	3.5

A comparative study of Cambay Shale with some of the major shale gas and shale oil fields show remarkable correlability in most of the major criteria except in age and maturity of organic matter (Table 2). However Clay mineral assemblage typing, reservoir parameters, quartz content and mechanical properties need more data to define the shales.

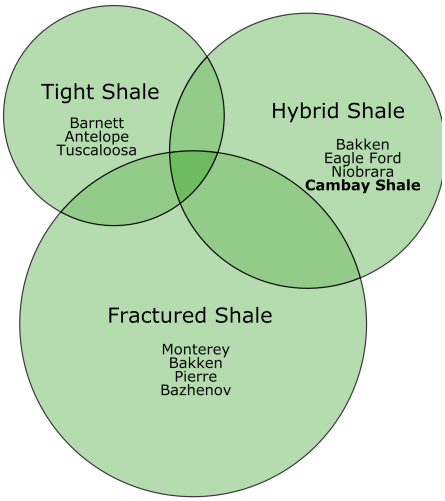


Figure 3: Classification of shale types and position of global major shale gas/oil plays (modified after Jarvie, 2012).

Table 2: Comparison chart of Cambay basin with major global shale oil/gas producing basins

Criteria	Barnett	Eagle Ford	Bakken	Haynesville	Horn River	Cambay
Age	Mississippian	Cretaceous	Mississipian	Up. Jurassic	Up. Devonian	Paleocene-Eocene
Depth	2286m	3505m	2800m	3657m	2682m	1525-3050m
Area	129500 sq.km	3500 sq.km	Not available	23310 sq.km	12950 sq.km	2590 sq.km (prospective)
Thickness	91m	76m	20m	69m	137m	180-300m
TOC avg.	4.5%	4.5%	13.0%	3.0%	3.0%	1.6-8.0+%
Tmax	200°F	Not available	Not available	340°F	160°F	160-320°F
VRo	1.1-2.1 %	1.5 %	0.9-1.1%	2.2 %	2.5 %	0.5-1.25 %
Porosity	2-6%	11%	3-12%	10%	3%	Not available
K_{matrix}	250 nD	1100 nD	600 nD	660 nD	230 nD	Not Available
Pressure	4000 psi	5200 psi	6930 psi	8500 psi	Not available	2500-8000 psi
Pr. Grad	0.53 psi/ft	0.65 psi/ft	0.75 psi/ft	0.95 psi/ft	0.6 psi/ft	0.61-0.91 psi/ft

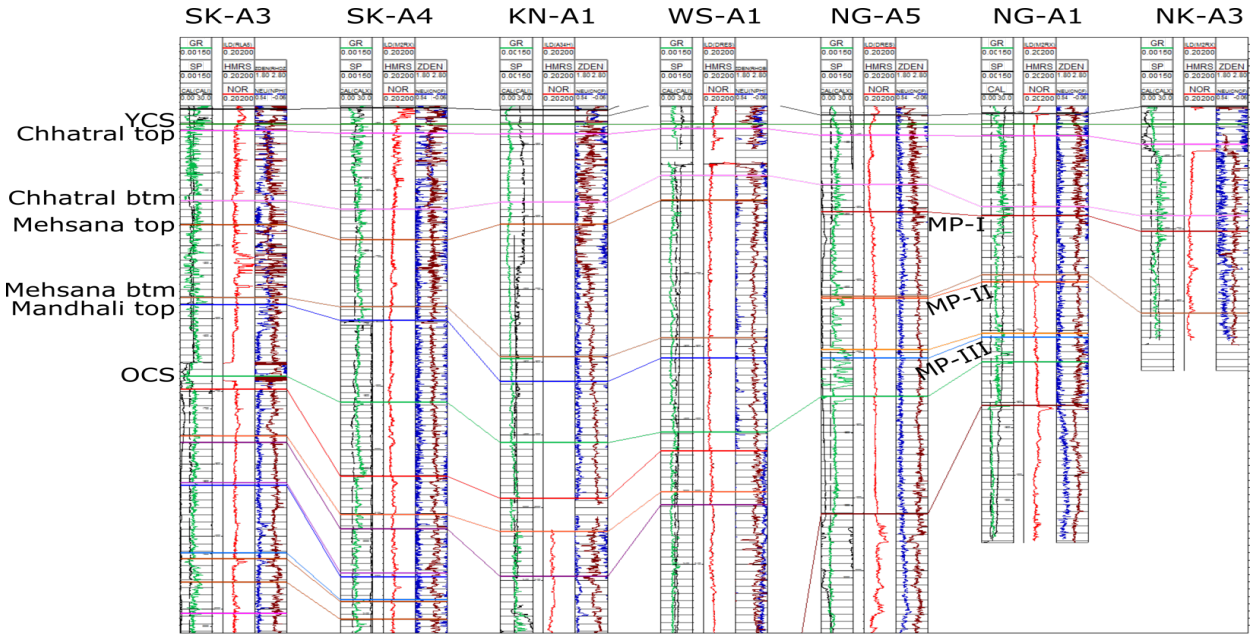


Figure 4: North to south correlation between wells from fields South Kadi, Karan Nagar, Wasna, Nawagam and Naika. Middle Pays of southern fields are equivalent to Mehsana and Mandhali members of northern fields.

Hydrocarbon shows during drilling corroborates electrolog correlation

Direct evidences like gas cut mud, flow of oil and gas observed during drilling are indicators of presence of oil and gas reservoirs. Wells in various fields in the study area have shown such indications. Such activities were correlated to conventional electrolog signatures of the wells. Almost all wells drilled in Nawagam field for development of conventional pays experienced well activities, while drilling through Cambay Shale, in the depth range from 1500-1750m (Figure 4). These well activities are controlled by increasing mud weight to 1.44-1.53 gpl. Formation pressure varies from 210-250ksc as observed from long shut-in studies in few such tested wells. Similar evidences are found in South Kadi field, whrere the minimum mud weight required to drill OCS shale is 1.45-1.75 gpl in the depth range 1750-2400 above hydrostatic pressure.

Pro-deltaic regressive phases of YCS in Ahmedabad-Mehsana Block gradually grade to siltyshale and shale in the southern and eastern parts of the block. Multiple well activities observed in many wells within YCS of Nawagam, Wadu, Kalol, Nava, Ahmedabad, Naika, Mahelaj and Sadra fields correlate easily with electrolog characteristics of wells across the block (Figure 4 & 5). Three units, Middle Pay-I (MP-I), Middle Pay-II (MP-II) and Middle Pay-III (MP-III) were identified within YCS in Nawagam field on the basis of correlative shale layers in the field (Ghosh et al., 2015). Subsequently these were extended to nearby oil fields of Naika, Sadra Ahmedabad and Wasna in southern part of the block. The three units were found to be both correlative and mappable. Total seven sweet spots were identified in the Middle Pays within Nawagam field on the basis of comparatively low bulk density. However, these sweet zones showed varying degree of development in nearby fields like Naika and Sadra. Till date six of these low bulk density intervals were tested in eight vertical and inclined wells and proved to be oil producers/ oil bearing. Apart form these, shale sections within YCS of Wadu field in north have produced oil and gas.

These three correlative units of YCS are extended to Wadu, Kalol, Jhalora, South Kadi, Viraj and Walod oil fields in northern part of the block (Figure 4). Top of MP-I unit correlates to Mehsana Member top. Mehsana Member is represented in South Kadi, Viraj and Jhalora fields (northern-western part of study area) as alternation of sandstone, shale and thin coal beds. In the north-eastern part in Kalol, Wadu and Palyad fields Mehsana Member (and the underlying Mandhali member) is mostly siltyshale and shale, formally named as Wadu Pays. Wadu pay is typically low density oil bearing silty shale that is only confined to the NW part of the study area. MP-I bottom is marked by a correlatable and mappable shale homotaxial to shale between Upper Mehasana and Lower Mehsana as established in Mehsana sub-block. Oil producer siltyshale layer at the top of MP-II appears to be homotaxial to coal top of Lower Mehsana. Bottom of MP-II correlates to bottom of Mehsana Member. Mandhali Member in the northern part of the block correlates with MP-III unit of Nawagam area. MP-III bottom is correlatable to Mandhali Member bottom, both of which overlies OCS.

Similar incidents of well activities are observed while drilling OCS section in South Kadi, Kalol, Wadu and Walod areas. The Kadi pays are discreet lensoid sand bodies encapsulated in shale within OCS in South Kadi field. These conventional reservoirs are prolific oil producers. Some of these conventional reservoirs grade to tight reservoirs laterally. The enclosing thick shale/ silty shale layers are also highly charged. Similar low density shale layers within OCS in Walod and Kalol fields, on the eastern and central part of the block showed well activities during drilling (Figure 5) need intregated study and effective well testing.

Analysis of wells producing hydrocarbon from Cambay Shale

Few existing conventional vertical/incline wells, having only conventional electrologs,within the study area were tested for shale/ tight oil. In well NG-A1 four of the five identified objects in Middle Pays were tested and all of them yielded oil (FIgure 6). Recorded influx rates are 38.0 bbl/day in MP-IIIB after fracking and 7.6 bbl/day in MP - IIIA without fracking. Well NG-A1 produced oil from MP-IIB and MP-IIA at the rate of 7.2 and 15.7 bbl/d respectively after fracking. Wells NG-A4, NG-A5 and NG-A6 were also tested and are producing oil from different Middle Pay layers. After fracking these wells produced oil at rates of 33.0, 75.0 and 67.0 bbl/day respectively (Figure 6). Shale zone in Naika field (NK-A2) also showed influx of oil post fracking. Wadu pays within YCS in Wadu-Palyad field are known producers. Initially these wells produced oil at the rate of 113-133 bbl/day (WD-A1, WD-A2) (Figure 7). But the rate of production decreases rapidly since permeability in these pays are very low.

In South-Kadi area the discreet lensoid sand bodies of Kadi Pays are sandwiched between low permeability but overpressured shale. Such shale was tested in well SK-A1 which, after fracking, flowed 20 bbl/day on artificial lift. Similar objects in Walod area (WL-A1) also gave influx of 16 bbl/day pre-fracking and 53.3bbl/day post-fracking activation in two separate zones within OCS (Figure 8).

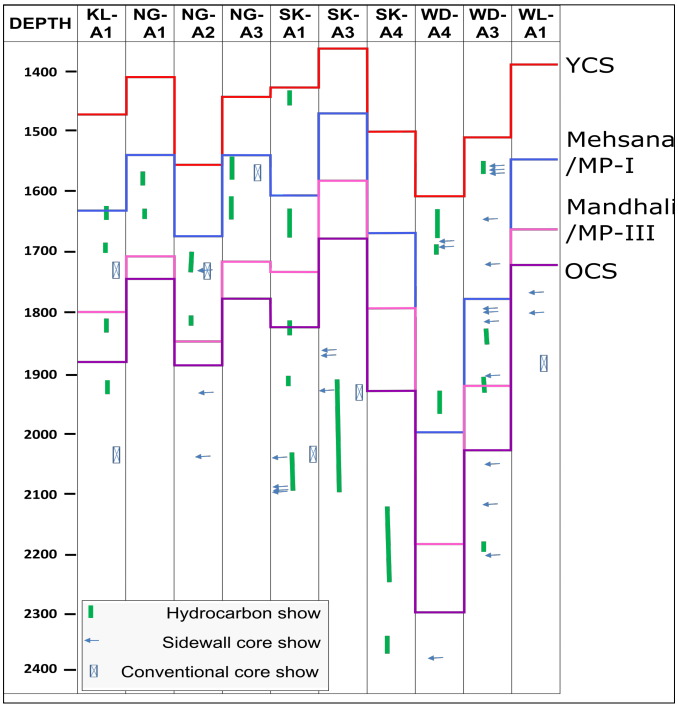
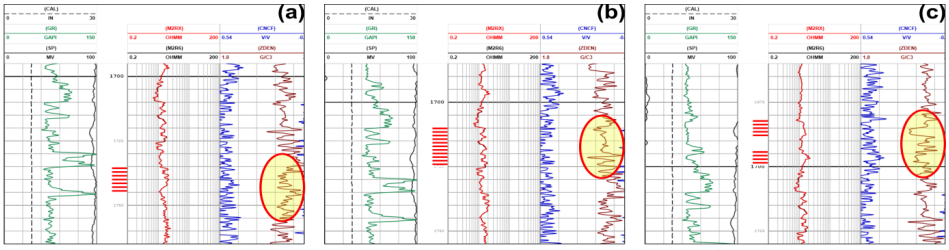


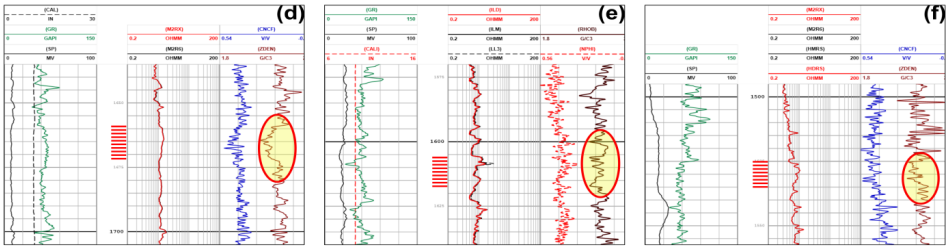
Figure 5: Direct observations of occurrences of oil and gas (during drilling) within YCS and OCS of study area in Ahmedabad sub-block



NG-A1: Object-II (1744-1735m), MP-IIIB: After fracking influx rate 38 bbl/d oil

NG-A1: Object-III (1725-1710m), MP-IIIA: Without fracking Influx 7.6 bbl/d oil (initial rate)

NG-A1: Object-IV (1699-1694, 1688 -1682m), MP-IIB: After fracking 7.2 bbl/day oil flowed on artificial lift

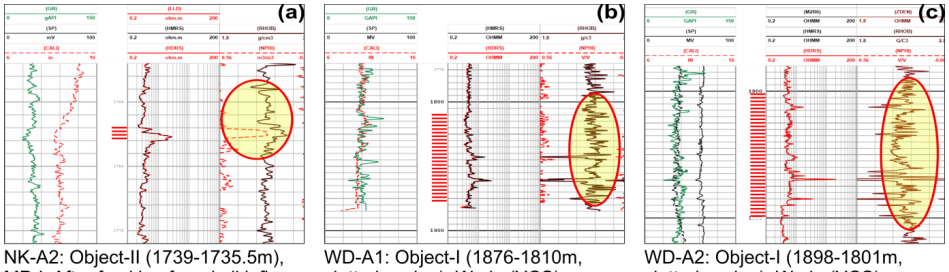


NG-A4: Object-III (1672-1659m), MP-IIA: After fracking Influx 33 bbl/d

NG-A6: Object-II (1606-1617m), MP-IB: After fracking, well flowed on self @ 75 bbl/d (initial rate)

NG-A5: Object-II (1525-1535m), MP-IA: After fracking, well flowed on self @ 67 bbl/d

Figure 6: Log motifs of six producing sweet zones within YCS in Nawagam area with initial production data.

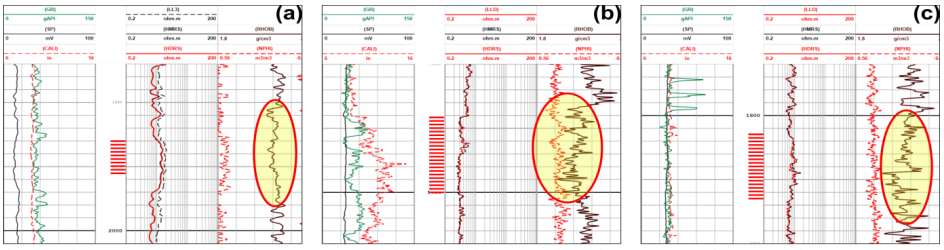


NK-A2: Object-II (1739-1735.5m), MP-I: After fracking found oil influx

WD-A1: Object-I (1876-1810m, slotted casing), Wadu (YCS) pay: Well flowed on self 113 bbl/d oil

WD-A2: Object-I (1898-1801m, slotted casing), Wadu (YCS) pay: On activaiton well flowed on self

Figure 7: Log motifs of six producing sweet zones within YCS in Naika & Wadu area with initial production data.



SK-A1: Object-II (1965-1977m), OCS: After fracking flowed 20 bbl/d oil on artificial lift

WL-A1: Object-VI (1870.5-1900m), OCS: After fracking got approx. 53.5bbl/d oil on activations

WL-A1: Object-VII (1807-1833m), OCS: On activation got influx of 16 bbl/d oil

Figure 8: Log motifs of producing zones within OCS in South Kadi and Walod areas.

It is to be noted that all these wells that are tested for shale/ tight oil are vertical wells. So exposure to target reservoir is very small and conventional fracking has also minimal volume impact, thus the area of influence for shale/tight oil production is significantly small compared to horizontal drilling and multi-stage fracking practice in case of such unconventional reservoirs.

Discussion

Cambay shale is rich in organic matter (~1.6-8% on average) with average T_{MAX} ranging from 160°F to 320°F. There are 4 to 5 organic rich layers within Cambay Shale Formation (Banerjee & Rao, 1993). Average maturity (VR_O) of organic matter varies between 0.5-1.1 (Figure 9). Areas having organic matter with higher maturity are limited to greater depth. These area may not be suitable for exploiting shale oil. Another favourable aspect of Cambay shale Formation is its high temperature gradient. Temperature gradient varies from 4.1°C to 5.3°C/100m in Ahmedabad-Mehsana block.

Sustained producibility of shale/ tight oil within YCS in Nawagam area was established (Ghosh et al., 2015). Few wells that have been tested for shale/tight oil produced hydrocarbon at a decent rate through conventional well testing and completion. Presence of hydrocarbon in YCS shale in other fields like Naika and Wadu and in OCS shale in fields like South Kadi, the total potential of Cambay shale is increased many times.

These zones need to be targetted with specific objective to explore unconventional tight reservoirs. These zones thus warrant a better exploratory approach to truly reach its potential.

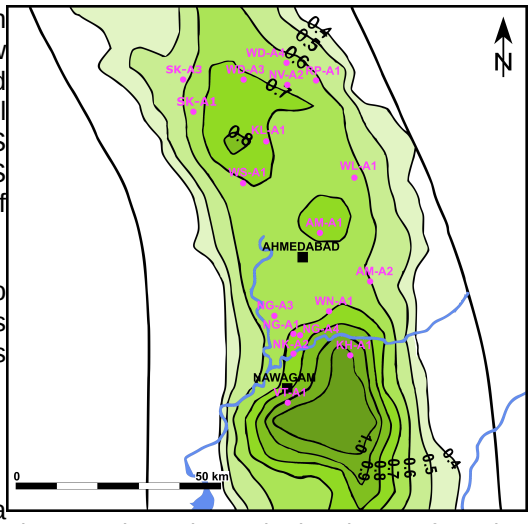


Figure 9: Thermal maturity (VR_O) map of Cambay Shale of the study area in Cambay Basin (Modified after Raju & Srinivasan, 1993)

Conclusion

1. Correlative study across various fields in the study area has opened up much wider area to explore shale/tight oil and gas in Cambay Shale.
2. Alternations of mature organic rich layers with siltyshale/silt layers, moderate maturity of shale (0.5-1.1), adequate depth of shale formation, considerable shale thickness, high temperature gradient and high pressure gradient offer excellent prospect for Shale Oil in Cambay Basin, in particular Ahmedabad-Mehsana Block.
3. So far the zones tested for shale/tight oil are in vertical and inclined wells. These zones will need technologically advanced approach at par with international practices to realize the true potential.
4. Availabile laboratory data for shale-specific studies are limited. More of such data is required to proper characterization of shale and the sweet spots within them. Since exploration if shale oil in Cambay Basin has just started, it is fair to say that such data will be available in sufficient quantity in years to come.

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