Fine Tuning the Petroleum Systems in Western Onshore Basin through Re-evaluation of Source Organics, Depositional Environments and Thermal Maturities of the Oils and Source Rocks*

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Abstract

The Western Onshore Basin is located on the western margin of the Indian craton and covers an area of approximately 56000 sq. km. From north to south, the basin is divided into five blocks, Sanchor-Patan, Mehsana-Ahmedabad, Tarapur-Cambay, Broach-Jambusar and Narmada-Tapti blocks. Western Onshore Basin has been divided in two sub-basins, namely, North Cambay and South Cambay. The salient aspects of the geology of Western Onshore has been discussed by Pandey et al., (1993) and Kundu and Wani (1992). The basin came into existence during Late Mesozoic era with the development of major tensional faults along pre-existing basement trends following widespread extrusion of Deccan trap basalt. This basaltic floor formed the basement for the deposition of a huge thickness of Tertiary-Quaternary sediments in the basin. The non-marine to marginal marine Olpad Formation was deposited over basement, which is several hundred meters thick and has been observed to possess fair to good hydrocarbon potential in certain areas. The Cambay Shale Formation unconformably overlays the Olpad Formation and it represents the first major transgressive episode in the basin. The shale is grey to dark, fissile, often carbonaceous and rich in disseminated organic matter. Geochemical studies have established the Eocene Cambay Shale as the regional major source rock. The Kalol Formation in the north and its equivalent Hazad Formation in the south conformably overlies the Cambay Shale. Kalol and Hazad are the major reservoirs in the Cambay Basin and are inferred to pinching out towards the basin margin areas. The Kalol Formation is mainly sandstone/siltstone with alternations of shale and coal while Hazad Formation is mainly sandstone. Both these time equivalents were deposited in a prograding deltaic facies. Kalol and Hazad reservoirs are effectively capped by the marine transgressive Tarapur Shale of Late Eocene- Early Oligocene age. The Early Oligocene is followed by a hiatus due to complete withdrawal of the sea from the basin. Marine to fluviodeltaic interbedded shale represents the Neogene section and sandstone and it includes the Miocene Tarkeshwar, Babaguru, Khand and Jhagadia

formations. Pliocene-Pleistocene sedimentary rocks are represented by Broach and Jambusar formations consisting of claystone and sandstone. Recent alluvium covers the entire basinal area except the outcrops along the eastern margin. The entire Neogene section is immature for hydrocarbon generation but is a part of overburden rocks necessary to create thermal maturity in the Cambay Shale and Olpad formations.

Samples and Methodology

In the present study, an effort is made to integrate the freshly generated data on biomarkers on 70 oils and 30 source rocks samples in the gap areas with old data on more than 400 oils/bitumens covering the entire basin to bring out the paleoenvironment, source organics and maturity of oils and source rocks to decipher the oil-oil and oil-source correlations in regional framework and establish the petroleum systems. Extractable organic matter (EOM) and crude oil samples were fractionated into saturate, aromatic and NSO fractions following the standard ASTM procedures. Saturate and aromatic fractions were analyzed on Perkin Elmer GC-MS using DB-1 and DB-5 columns respectively. Stable carbon isotopic study is carried out on VG Iso-Prime CF-IRMS.

Results and Discussion

Gross and bulk parameters of oils: The relative abundance of saturated hydrocarbons and saturate/aromatic (sat/aro) ratio >1 indicates that most of the oils of Western Onshore Basin are predominantly aliphatic in nature. Oils of Jotana, Linch, Sobhasan, North Kadi, Mewad, Khambel and West Patan fields are normal oils while oils from Bechraji, Lanwa and Santhal are asphaltic biodegraded oils in Mehasana block. Most of the oils of Ahmedabad block in North Cambay and Broach and Anklesvar blocks in South Cambay are normal oils except Padra oils, which are partially biodegraded.

Variation in organofacies from north to south in Western Onshore Basin: Gammacerane a saline water indicator biomarker is present in Mehasna block and found up to western flank of Ahmedabad block covering oil fields of S. Kadi, Viraj and Jhalora. It is absent in other parts of Ahmedabad block and entire South Cambay. Similarly, C30steranes, the marine indicators are present in high concentration in Patan-Khambel area of Mehsana block and its concentration decreases slowly towards south and is comparatively much low in South Cambay. Oleanane and bicadinanes are present in high concentration in South Cambay. Oleanane is present in very low concentration while bicadinanes are absent in North Cambay. Similarly, bisnorhopane and dihopanes are present in South Cambay and are absent in North Cambay. Variation in distribution of these biomarkers along with isotopic data suggests source input is predominantly terrestrial mixed organics in the entire basin (Peters and Moldwan, 2004). Paleoenvironment of the source rocks of oils varies from saline/marine in stratified water column in the far north to lacustrine-marine in middle to sub-oxic with comparatively

less marine influence in the south of Western Onshore Basin. Oils are low to moderately mature in the north while moderate to peak oil maturity is observed in the south. Further variation in these biomarker parameters in each block has given rise to oil families. Two oil families in Mehsana block and three families in Ahmedabad block have been identified in North Cambay while three oil families have been identified in South Cambay. Schematic presentation of variation in molecular parameters of oils for their source rock facies in Older Cambay Shale (OCS) and top of Olpad in North Cambay and South Cambay basins is presented in Figure 1. Variation in depositional environments of source rocks of oils from North to South in Western Onshore Basin is shown in Figure 2. Source inputs for the source rocks of oils in North Cambay are predominantly terrestrial to mixed organics while it is mainly mixed source input in South Cambay (Figure 3).

Oil-oil and oil-source correlations: Genetic oil-oil and oil-source rock correlations are based on the assumption that specific components in a source rock are transmitted to the expelled oils. This “similarity through heritage” can range from bulk properties to such as carbon isotopic data and the presence of selected source related biomarkers.

Oil-oil and oil-source correlations in Mehasana block of Western Onshore Basin: The molecular evidences clearly indicate a genetic relationship among various oils of Mehsana block producing from different fields. These oils have been generated from the source rocks containing predominantly terrestrial mixed source organics. However, the significant variation in gammacerane and 4-methyl steranes of these oils indicate varying degree of salinity experienced by the organic matter during deposition and also differentiate them into two groups. The group-1 oils of Mehsana block have relatively high concentration of gammacerane, which is an indicator of salinity of the source rock depositional environment. This indicates that these oils have been generated from organofacies deposited in stratified/ high saline water condition (Damaste et al., 1995) whereas the group-2 oils are characterized by relatively low concentration of gammacerane suggesting that the source rocks of these oils were deposited in relatively low saline or unstratified condition. Both the groups of oils are distributed in all the main oil fields of Mehsana block. These two groups of oils exist in Mehsana block of Western Onshore Basin in Mandhali as well as Linch pay horizons of Kadi Formation. Khambel and Patan oils do not correlate and may have been generated locally. The group-1 oils of Jotana, Linch, N. Kadi, Mewad and Sobhasan show close similarity in biomarker and isotopic characteristics with the Older Cambay Shale source sequences from Linch, N. Kadi and probably deeper sediments from Warosan area having similar organofacies of high gammacerane. The group-2 oils from these fields have similar fingerprints show close similarity with relatively low concentration of gammacerane organofacies from Linch, Jotana and Warosan low areas (Figure 4). The oils of Lanwa, Balol, Santhal and Bechraji are genetically similar and are sourced from significant presence of oleanane and high gammacerane organofacies from deeper OCS/Olpad sediments from nearby Jotana-Warosan Low area. These oils are different from oils of Khambel as well as Patan area. The oils of Khambel has been derived from nearby OCS of Khambel-B & D area having organofacies with almost absence of oleanane, low gammacerane and presence of C30 4-methyl steranes while oil of

west Patan is derived from presence of oleanane, low gammacerane and significant presence of C30 4-methyl steranes similar to OCS of W. Patan-C. Oils in western and central oilfields were derived from two types of organofacies. Group-1 oils are generated from predominantly terrestrial source organofacies, which were deposited in stratified saline water column in marine environment. The source rocks for group-2 oils having predominantly terrestrial source organofacies were deposited in less saline-marine environment. The source rocks for oils from eastern oil fields having mixed source input were deposited in marine-lacustrine environment.

Oil-oil and oil-source correlations in Ahmedabad Block of Western Onshore Basin: The oils of Kalol, Limbodra, Halisa, Wadu, Paliyad and Motera show similar gas chromatographic, triterpanes and steranes fingerprints. Various biomarker parameters also show similarity in these oils. Various cross plots of biomarker parameters show mainly three groups of oils in Ahmedabad block. The Group-1 oils are from Kalol, Wadu, Paliyad, Limbodra, Halisa and Motera oil fields. The group-2 oils are from western margin oil fields of Sanand, Viraj, South Kadi and Jhalora having similar molecular parameters and were derived from predominantly terrestrial mixed source organics deposited in restricted marine environment. The oils from Nawagam, Gamij, Wasna, Nandej and Ahmedabad shows similar characteristics and were derived from predominantly terrestrial source rocks deposited in sub-oxic marine environment forming group-3 oils in this block. The group-1 oils of Kalol, Limbodra, Halisa, Wadu, Paliyad and Motera show close similarity in biomarker and isotopic characteristics with the Older Cambay Shale and top of Olpad source sequences from Kalol-Wadu-Paliyad area of central axial depressions (Wamaj and Nardipur Lows). The group-2 oils of Sanand, Viraj, South Kadi and Jhalora have similar fingerprints and have been sourced from similar gammacerane organofacies of OCS/Olpad sediments from western flank lows since they do not show similarity with Olpad sediments from Sanand area. Similarly, group-3 oils from Nawagam, Gamij, Wasna, Nandej and Ahmedabad show close similarity with source sediments from Indrora-Gamij- Nawagam area (Figure 5).

Oil-oil and oil-source correlations in Broach and Narmada blocks of Western Onshore Basin: The distribution of biomarker and isotopic data in South Cambay shows that oils of Narmada block are genetically correlatable. Three groups of oils in Broach block have been identified. The cross plots of Oleanane versus bicadinane clearly brought out genetic relationship in these three groups of oils of Broach block (Figure 6). Ankleshvar and Kosamba oils of Narmada block show genetic relationship with oils of Gandhar, Dahej, Pakhajan, Dabka and Padra of Broach block (Group-1) which show low to moderate oleanane and bicadinanes. Group-II oils form from western flank of Broach block (Nada and S. Malpur) having much higher oleanane, bicadinane and dihopane. Group-III oils are from Jambusar area, which are characterized by high Oleanane and bicadinane but low dihopane and are different from group-1 and group-2 oils. It is found that the oils of Ankleshwar, Kosamba, Gandhar, Dahej, Pakhajan, Dabka and Padra shows close similarity with Cambay Shale sediments of Gandhar-Dahej area. These sequences have source characteristics similar to the oils of above basinal and eastern margin fields of Broach block as well as oils of Narmada block, like Pr/Ph, Pr/nC_{17} and $(Pr+nC_{17})/(Ph+nC_{18})$ ratios and carbon isotopic composition. Similar to these oils, these sediments are also characterized by low

oleanane (<12%), bicadinane (<15%), dihopane/C_{29}Ts ratio (<10%) and presence of C30steranes. It has been observed that oils of Nada and S. Malapur matches with Older Cambay Shale and Olpad sediments from Nada and Barkhodra area. These sequences have source characteristics similar to Nada and S. Malapur oils like Pr/Ph, Pr/nC_{17} and (Pr+nC_{17})/ (Ph+nC_{18}) ratios, carbon isotopic composition and comparatively high values of oleanane (>10%), bicadinane (>20%), dihopane/C_{29}Ts ratio (>1), C_{27} regular steranes (>25%) and significant presence of bisnorhopane and C_{30}steranes. Jambusar oils of basinal areas of Broach block have intermediate values of source specific biomarkers and do not match with the basinal sediments of Gandhar area as well as western flank sediments of Nada-Barkhodra area. They form a separate group of oils. Oils of Ankleshvar and Kosamba fields of Narmada block do not show any correlation with the Cambay Shale and Olpad sediments from Panoli depression of Narmada block. This may be due to the depocenters in northern part of Narmada block, which are relatively small and have not shown good source rock development. They show very good correlation with oils and source rock extracts from Broach block. Hence, oils in Narmada block reservoirs were charged from Broach and Tankari depressions of Broach block as revealed by geochemical studies. Although, potential source rock development (Type III) has been observed in Tapti area, which may have generated gaseous hydrocarbons of Olpad and other nearby fields in southern & middle part of Narmada block.

Conclusions

Early Eocene Cambay Shale and top of Paleocene Olpad formations have good to excellent source rock characteristics in the basinal part of each block in the Western Onshore Basin except Narmada block. Source input is predominantly terrestrial mixed organics in the entire basin. Paleoenvironment of the source rocks of oils varies from saline/marine in stratified water column in the far north to lacustrine-marine in middle to sub-oxic marine in the south. Oils are low to moderately mature in the north while moderate to peak oil maturity is observed in the south. Two oil families in Mehsana block and three families in Ahmedabad block have been identified while three oil families have been identified in Broach block. Oils of Ankleshvar and Kosamba fields of Narmada block do not show any correlation with the Cambay Shale/Olpad sediments of Panoli depression of Narmada block. They show very good correlation with oils and source rock extracts from Broach block. Hence, oils in Narmada block reservoirs were charged from Broach and Tankari depressions of Broach block as revealed by geochemical studies. Two major petroleum systems in the north and one in South Cambay have been identified in the Western Onshore Basin. They are top of Olpad/Cambay Shale-Hazad (!) petroleum system in the South Cambay and top of Olpad/Cambay Shale-Kalol (!) and Olpad/Cambay Shale-Kadi (!) petroleum systems in the north Cambay. The oil-oil and oil-source correlation studies suggest that areas between Jotana-Linch-Sobhasan-Mewad-Warosan, around Khambel and west Patan in Mehsana block and between Kalol, Halisa and Limbodra and north northeast of Wadu-Paliyad in Ahmedabad block are prospective for future exploration. Eastern margin oil fields in Broach block were charged by the Broach-Tankari depression; hence,

the area around Padra, Dabka, Karjan, Pramoda and east- north east of Gandhar field should be explored for new structures and stratigraphic traps having better reservoir facies.

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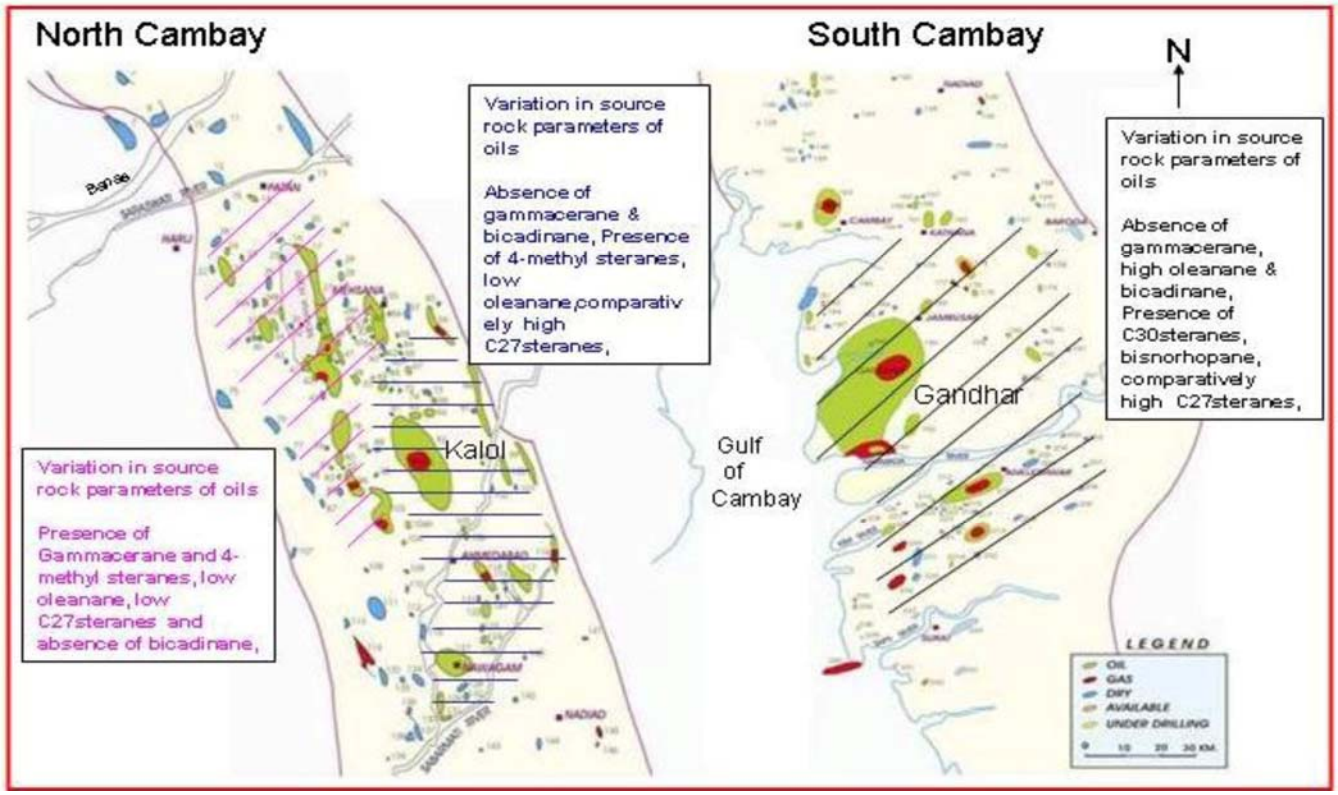

Figure 1. Schematic presentation of variation in molecular parameters of oils for their source rock facies in OCS & top of Olpad in North Cambay and South Cambay sub-basins of Western Onshore Basin. Further variation in these parameters in each block has given rise to oil families. Two oil families in Mehsana block and three families in Ahmedabad block have been identified in N. Cambay while three oil families have been identified in S. Cambay.

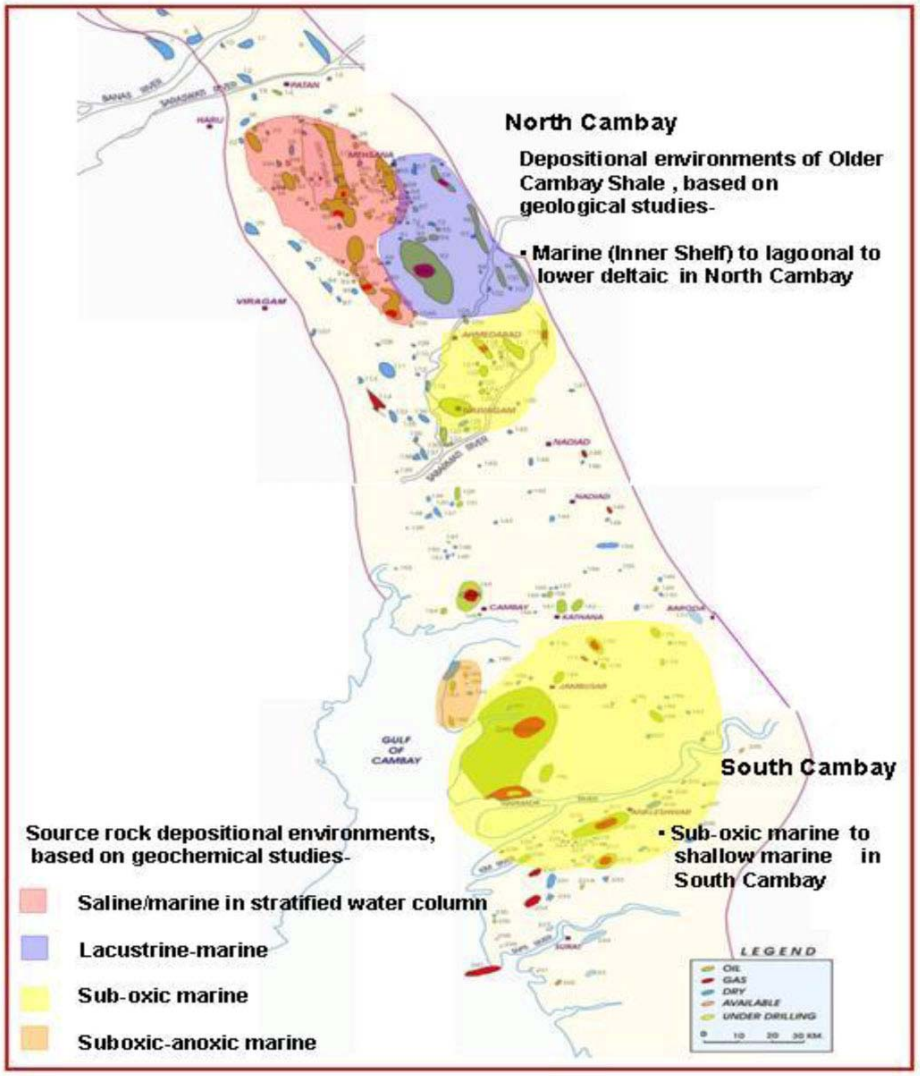

Figure 2. Variation in depositional environments of source rocks of oils from north to south in Western Onshore Basin.

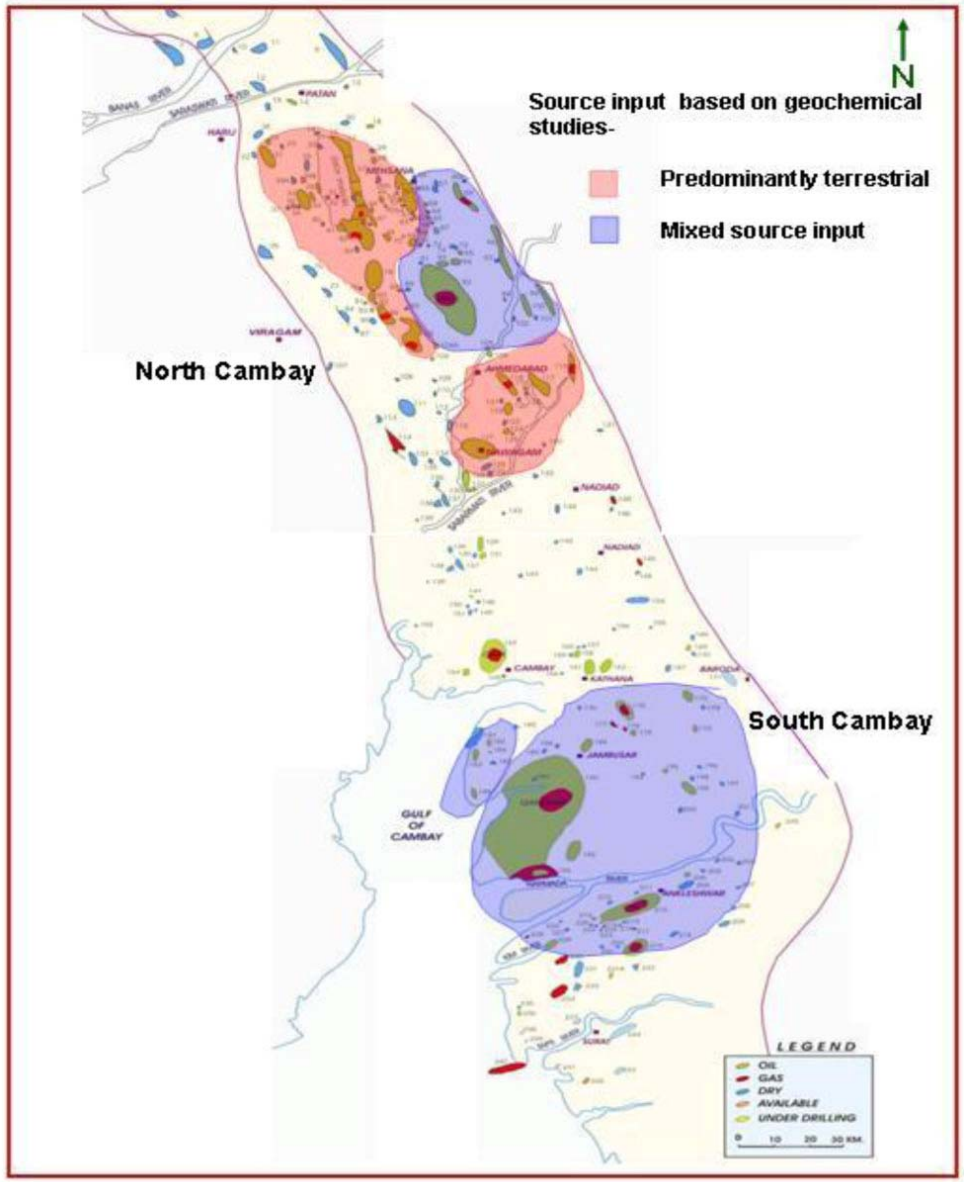

Figure 3. Variation in source organics of oils in from north to south in Western Onshore Basin

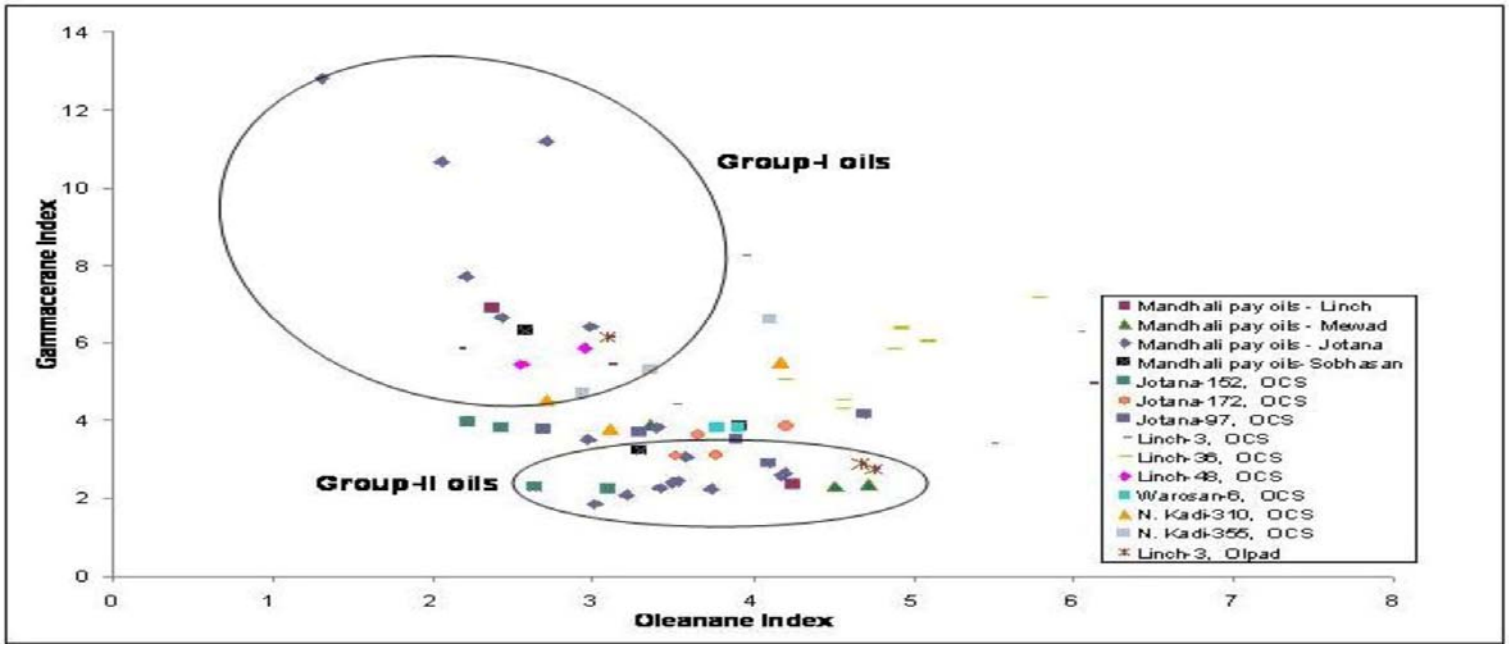

Figure 4. Group-II oils are generated from the organofacies of OCS source rocks from the area near Linch, Jotana, North Kadi and Warosan area having predominantly terrestrial mixed source organics deposited in less marine/saline conditions in stratified water columns. Source for group-I oils were deposited in saline/stratified water conditions from the area Linch, North Kadi and probably deeper sediments from Warosan area, having predominantly terrestrial mixed source organics.

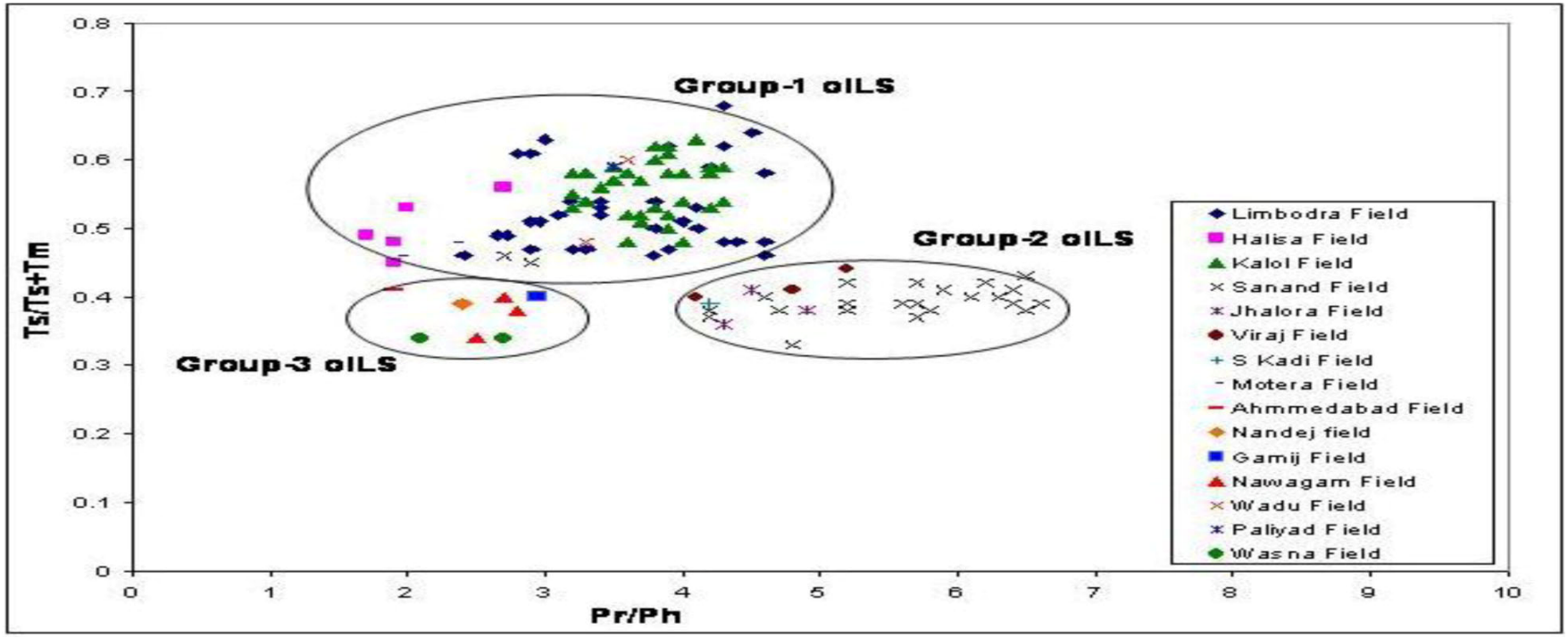

Figure 5. Cross-plots of Ts/Ts+Tm ratio versus Pr/Ph ratio suggest mainly three group of oils exists in the Ahmedabad block of Western Onshore Basin. Group-1 oils are from central axial and eastern margin areas covering fields Kalol, Wadu, Paliyad, Motera, Limbodra and Halisa. They have moderate Pr/Ph ratio and high Ts/Ts+Tm ratio. Group-2 oils have high Pr/Ph ratio and low Ts/Ts+Tm ratio and are from western margin area of Ahmedabad block (S. Kadi, Viraj, Jhalora and Sanand fields). Group-3 oils are from south eastern part of this block covering fields of Gamij, Ahmedabad, Wasna, Nandej and Nawagam having low Pr/Ph and Ts/Ts+Tm ratios.

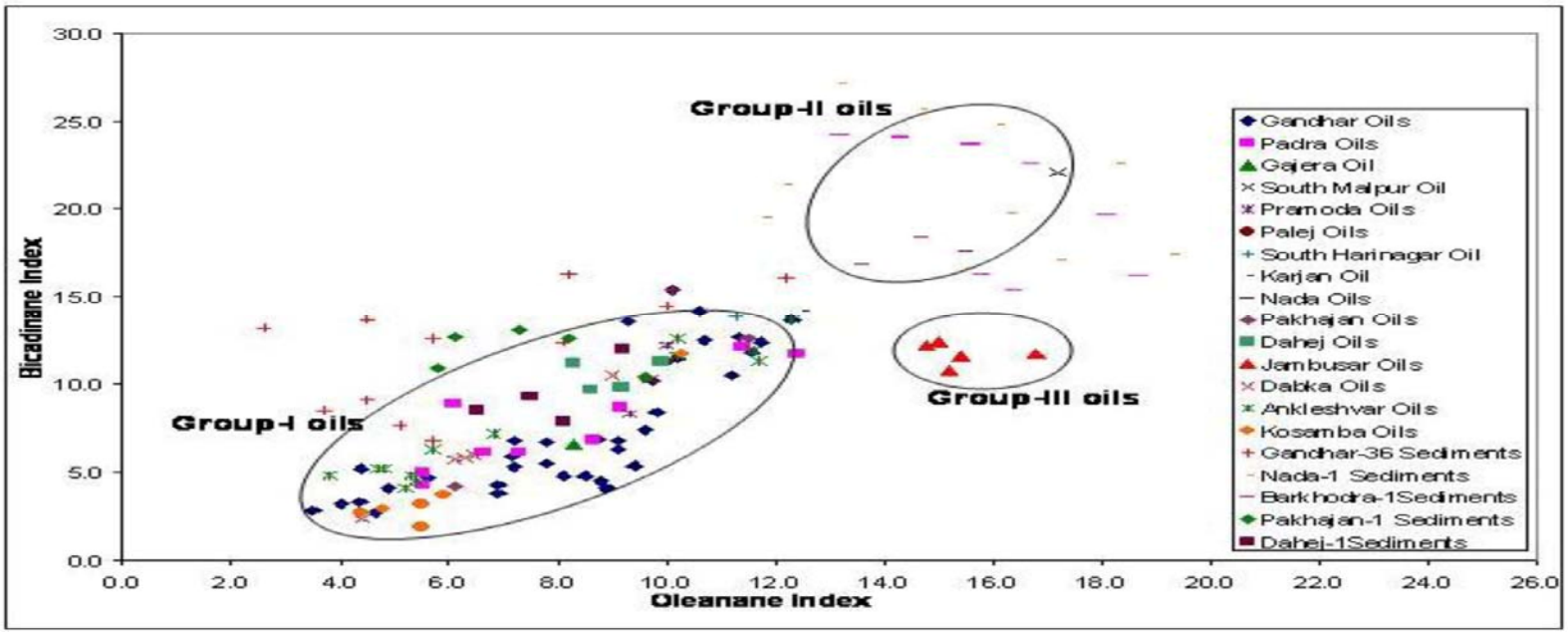

Figure 6. Cross-plots of oleanane index versus bicadinane index of oils and sediments of Broach block of Western Onshore Basin. Oils from Gandhar, Padra, Gajera, Pramoda, Palej, S. Harinagar, Karjan, Pakhajan, Dahej and Dabka area of Broach block and Ankleshvar and Kosamba of Narmada block are showing correlation with Gandhar, Dehaj and Pakhajan Cambay Shale sediments. Oils from western margin area of Nada and S. Malpur are generated from Cambay Shale/Olpad sediments of Nada and Barkhodra area. Jambusar oils may have generated locally having altogether different biomarker characteristics.