Journal of Himalayan Earth Sciences Volume 52, No. 2, 2019 pp. 129-144

Hydrocarbon source rock potential of the Early Permian rocks in the Potwar Basin, Salt Range, Pakistan

Faizan Ahmad[1]*, Sajjad Ahmad[1], Suleman Khan[1], Qi Fu[2], Irfan U. Jan[3], Rafiq Ali Khan[1] Shehla Gul[4] and Fahad Ali Alizai[5]

[1]*Department of Geology, University of Peshawar*
[2]*Department of Earth and Atmospheric Sciences, University of Houston, USA*
[3]*National Center of Excellence in Geology, University of Peshawar*
[4]*Department of Geography, University of Peshawar*
[5]*Department of Geology, Bacha Khan University Charsadda.*
**Corresponding author's email: fa_swati939@yahoo.com*
Submitted: 20/08/2019 Accepted: 30/10/2019 Published online: Nov, 29, 2019

Abstract

In this paper the hydrocarbon source rock potential of the Early Permian strata of the Choa-Khewra Road Section in eastern Salt Range and the Zaluch Nala Section in western Salt Range, Potwar Basin, Pakistan is presented. The six outcrop samples of organic clays from the Tobra and Dandot Formations from eastern Salt range while Warchha and Sardhai Formations from the Zaluch Nala sections were collected for the Total Organic Carbon (TOC) and Rock Eval Pyrolysis analyses. Various geochemical cross plots were constructed using the total organic carbon and pyrolysis values of the analyzed rock samples to know the qualitative assessment of organic matter and presence of any indigenous or migrated hydrocarbons. Our result shows that the Tobra Formation is thermally mature with 0.55 % and 0.83 % TOC hence Type III kerogen with a tendency to generate indigenous hydrocarbons. The Dandot Formation is thermally immature Type III kerogen, with 0.78 % TOC that can generate indigenous hydrocarbons. The Warchha and Sardhai formations both are thermally immature Type III kerogen and a 0.73 %; 1.05 % and 1 % respectively, with an indigenous hydrocarbons generation potential. The XRD results shows that the percentage of clay minerals i.e. ductile minerals are less than the brittle minerals i.e. Quartz etc. Brittleness Index for the Tobra, Dandot and Warchha Formations shows brittle nature and are suitable for hydraulic fracturing while the Sardhai formation shows less brittle material and considered suitable for fracking.

Keywords: Hydrocarbon, Lower Permian, Thermal maturity, Potwar basin.

1. Introduction

The energy crises of Pakistan need proper attention in order to device novel strategies for resolving this issue. Pakistan hosts a very good potential of hydrocarbon, the total prognosed potential is 282 trillion cubic feet (TCF) of natural gas, 27 billion barrels of oil and 185 billion tons of coal. Presently, 47.6% of the total energy requirement is fulfilled by natural gas reserves (Kusskaraa, 2013). This data suggests that hydrocarbon potential of Pakistan have not been fully exploited, sedimentary area of Pakistan is 827,365 km2 out of which only 10-20% area is studied and explored (Jamil et al., 2009) (Fig. 1). Pakistan is generally unexplored, despite the huge sedimentary terrain because onshore Indus Basin been primarily focused for hydrocarbon exploration. The energy supply is on downturn while its demand is rising as 45% reserves of discovered natural gas and 66.5% of oil been already consumed by the country (Jamil et al., 2009). And the fact is that majority of the discovered oil fields are mature in Pakistan due to which production could have considerable amount of downturn.

The main sedimentary basin of Pakistan is "The Indus Basin", which consist of Precambrian to recent sediments (Ahmad et al., 2018). The Salt Range and the Trans-Indus ranges, Indus Basin, Pakistan are considered as significant location for Late Paleozoic sections; nevertheless substantial research have not been carried out and just few studies exists on the stratigraphy and biostratigraphy (e.g. Noetling, 1901; Teichert, 1967; Hussain, 1967; Wardlaw and Pogue, 1995; Mertmann, 1999, Jan et al., 2009, Shah, 2009). In the western Salt Range area of the Indus Basin Permian age Nilawahan Group represents a thick sequence of clastic sediments (Krishnan 1960; Jan and Stephenson 2011; Stephenson et al., 2013; Ahmad et al., 2018). These sediments are poorly known in terms of their source rock potential, although substantial literature is available on their reservoir rock potential. However detail work on the said topic is scare to no existed, so for this purpose, the organic rich intervals in Tobra, Dandot, Warchha and Sardhai formations of the Lower Permian Nilawahan Group have been targeted to evaluate their source rock potential in the Potwar sub-Basin of Pakistan.

2. Geological setting

India-Eurasia collision produced 2500 km extended Himalayan mountain range along the northern boundary of Indian plate (Le Fort, 1975). According to Seeber et al. (1981) Indian plate is continuously subducting beneath the Eurasian plate. The Indian Plate subduction under Eurasia forms the key tectonic fabrication of Pakistan where it comprises of “Main Karakorum Thrust” (MKT), “Main Mantle Thrust” (MMT), “Main Boundary Thrust” (MBT) and the “Salt Range Thrust” (SRT) (Coward et al., 1986) (Fig 2). The Salt Range is active frontal zone of Himalayan orogeny formed as intraplate thrust after collision of Eurasian plate with Indian plate and shift of stress factor to south (Baker et al., 1988; Jaume & Lillie, 1988). The Salt Range makes the southern border of the Potwar Plateau along the northwestern side of the Indo-Pakistan Plate. The Salt Range is primarily divided into two sub divisions; the area to the East of the Indus River called “Main Salt Range” or “Cis-Indus Salt Range” and the area located at its West is called “Trans-Indus Salt range” (Gee, 1981; Yeats et al., 1984). The “Main Salt Range” is further divided into 3 divisions: The Eastern Salt Range (from Jogi Tila to Nilawahan), the Central Salt Range (Nilawahan to Warchha) and the Western Salt Range (from Warchha to Kalabagh) (Yeats et al. 1984). The Eocambrian to recent sediments are exposed in the Salt Range (Gee, 1981; Shah, 2009).The Permian succession of the Salt Range is subdivided into two groups i.e. the Lower Nilanwahan Group represented dominantly by siliciclastic units and the Upper Zaluch Group, represented by the shallow marine dominantly carbonate units (Wardlaw & Pogue 1995; Jan et al. 2009). The Permian Nilawahan Group is comprised of four Formations namely Tobra, Dandot, Warchha and Sardhai formations of the Gondwanan affinity (Wardlaw & Pogue, 1995; Shah, 2009) (Fig. 3).

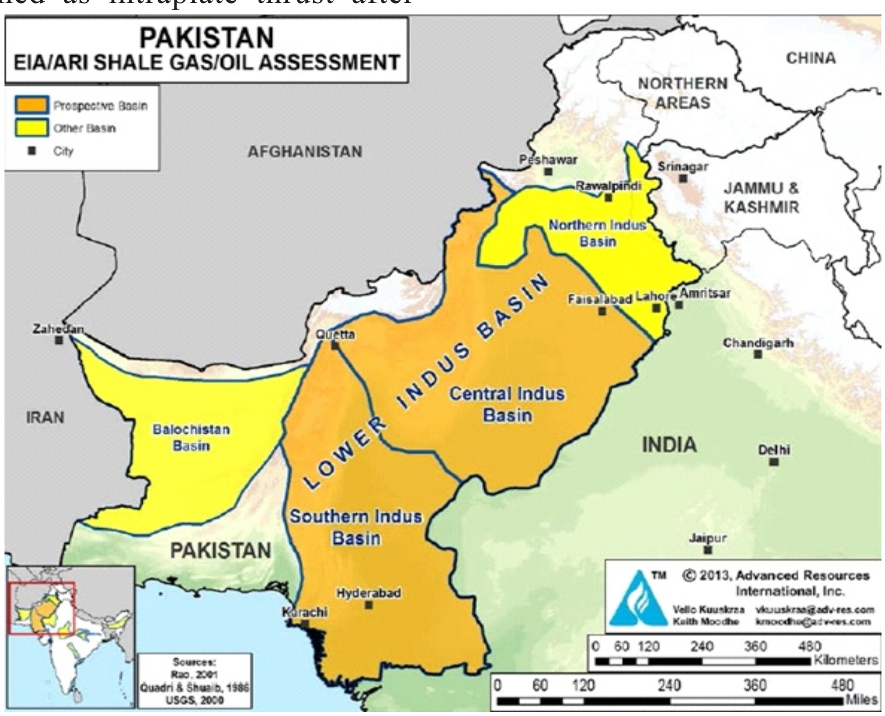

Fig.1 . Map showing Pakistan basins where Lower Indus basin is the best suited for the shale gas exploration (Kusskaraa, 2013).

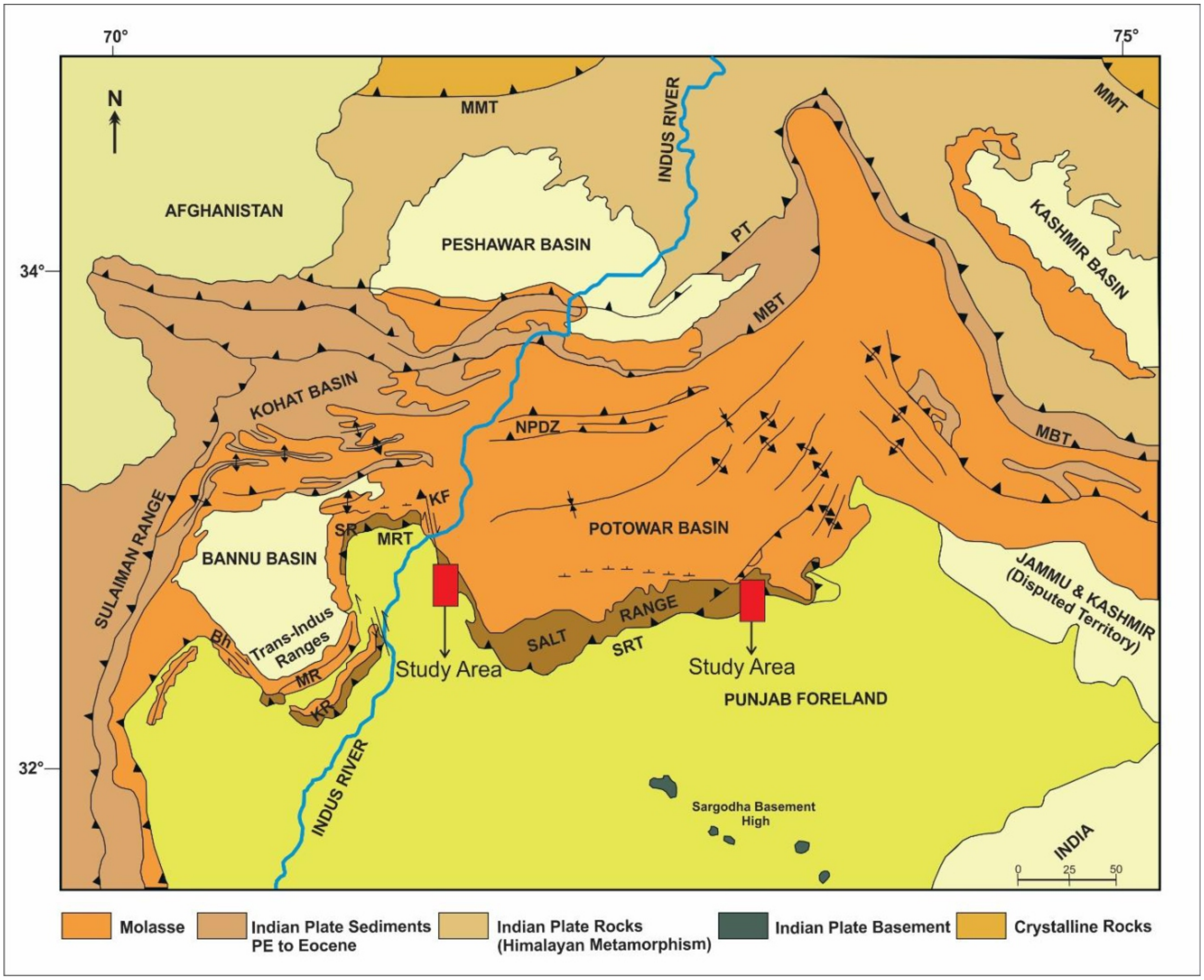

Fig. 2. Tectonic map of Upper Indus Basin, Pakistan showing the study area (after Kazmi and Rana, 1982).

3. Materials and methods

The outcrop samples of the potential source rock intervals within the Nilawahan Group rocks were collected from the Tobra i.e. TB1 and TB2 and Dandot (DND1) formations along the Choa-Khewra Road Section and samples from the Warchha i.e. WR1 and WR2 and Sardhai (SD1) formations were collected from the Zaluch Nala Section. The number of samples represents almost all the organic rich intervals i.e. six collectively in these units.

The organic geochemical analysis were carried out in Geology and Reservoir (G & R) Labs of the Oil and Gas Development Company Limited (OGDCL), Pakistan and Hydrocarbon Development Institute of Pakistan (HDIP) Labs. The Muffle furnace in G & R labs of OGDCL is used for TOC analysis while the Rock Eval 6 pyrolyzer (Turbo version) housed at HDIP labs was used for Rock Eval Pyrolysis. The Mapping of active source rock can easily be obtained from geochemical cross plots (Magoon & Dow, 1994). Different parameters were plotted using geochemical cross plots. These cross plots were prepared from surface Data (Peters & Cassa, 1994). The geochemical cross plots such as Tmax and Production Index were used to calculate maturation level of source rock and types of kerogen (Bacon et al. 2000). Geochemical cross plots including HI vs OI cross plot, Tmax vs HI cross plot, GP vs TOC cross plot, Tmax vs PI cross plot and S1 vs TOC cross plot were used to define the Kerogen type, maturation level of source rock, source rock quality and indigenous or non-indigenous hydrocarbons generation potential respectively (Ahmad et al. 2018). The organic richness of the sample is calculated using TOC analysis (Jarvie, 1991) and measured in weight percentage (wt %). TOC is used to measure the hydrocarbon generation potential of a source rock. As the thermal maturity of the rock increases the value of TOC decreases. The minimum value of TOC for a petroleum source rock is 0.5 wt %, but the rock is considered noncommercial for hydrocarbon production having less than 1.0 wt % by most geochemists (Hunt 1996). The minimum required value for source rock facies for shales is 0.5 wt % of TOC and for carbonates the value of TOC is 0.3 wt % (Tissot and Welte, 1984; Ahmad et al., 2018). Pyrolysis was carried out in a nitrogen inert atmosphere and oxidation oven is used to burn remaining carbon (Behar et al., 2001). According to a programmed temperature pattern the petroleum potential of rock samples by pyrolysis is being estimated. Flame ionization detector (FID) is used to identify the release of HC during pyrolysis. CO and CO2 released during pyrolysis were calculated by infrared detectors. Initially 300 ℃ temperature is required to initiates the process of pyrolysis, which the gradually increase to 650 ℃ with increase of 25 ℃ per minute, trailed by the increase in temperature to 850 ℃ with increase of 20 ℃ per minute. Parameters documented during the pyrolysis analyses are; free/volatile hydrocarbons S1, amount of HC released during pyrolysis, Tmax, Hydrogen index and Oxygen index. S1 and S2 are measured in mg HC/g TOC unit (Johannes et al., 2006). The results were described on the basis of dry weight (Mani et al., 2014). For the determination of the type of kerogen and approximate level of maturation; oxygen index (OI) and hydrogen index (HI) are used (Ghori, 1998). Low HI and high OI characterizes the gas prone kerogen while oil prone kerogen is determined by low OI and high HI (Tissot and Welte, 1978). The MS Excel was used for various cross plots of the TOC and Pyrolysis data. The graphic work was later finalized through the use of Corel Draw X7. Vitrinite reflectance (Ro %) is calculated by using formula after Jarvie (2007). Vitrinite Reflectance = 0.018 Tmax – 7.16.

The X-Ray Diffraction (XRD) analyses was carried out to determine the mineral composition of a rock. The XRD was carried out using X-ray Diffractometer JDX-3532, JEOL, (Japan) at the Centralized Resource Laboratory (CRL), University of Peshawar, Pakistan. The Cu-Kα (Alpha) source (λ=1.54 Å) was used in the 2θ range of 0-800 at 40 kV and 30 mA with 1.030/min to determine the mineralogical composition (Shah et al., 2017). The percentage of the minerals were calculated by using the Match3 Software. The Brittleness Index (BI) can be defined on the basis of constituent minerals of the shale where talking of quartz tends to be more brittle minerals (Jarvie et al., 2001; Jarvie et al., 2007).

$$\boldsymbol{BI}jarvie(2007) = \frac{Qz}{Qz + Ca + Cly}$$

The Qz is the Quartz content, Ca is the carbonate content, and Cly is the clay content present in the rock sample by weight percentage. Quartz is the numerator while amount of quartz mineral, clays and carbonates are in denominator here it produces BI (Jarvie et al., 2007).

4. Results

4.1. Source rock quality and organic richness

The results of total organic carbon analysis of collected samples (Table 1) from the Permian rocks exposed in Choa-Khewra Road and Zaluch Nala sections is presented. The Tobra Formation sample TB1 have 0.55 wt % of TOC and sample TB2 have 0.83 wt % of TOC (Table 1) that correspond to a fair source rock. The Dandot Formation sample DND1 has TOC value of 0.78 wt % (Table 1) that shows a fair source rock potential (Bacon et al., 2000; Ahmad, 2018). The sample WR1 having 0.55 wt % TOC and sample WR2 has 1.05 wt % of TOC (Table 1) of the Warchha Formation are reflected to having a fair source rock potential (Bacon et al., 2000). Similarly SD 1 sample of the Sardhai formation having 1 wt % of TOC (Table 1) is having a fair source rock potential.
Table 1. Results of TOC and pyrolysis analyses with vitrinite reflectance of the examined Permian Tobra Fm, Dandot Fm, Warchha Fm and Sardhai Fm of the Upper Indus Basin, Pakistan.

4.2. Thermal maturity and type of kerogen

The samples TB1 and TB2 of the Permian Tobra Formation consist of Type III kerogen evident from HI vs OI cross plot (Fig. 4), whileTmax vs HI cross plot suggests these to be mature source rock (Fig. 5). The sample DND1 of the Dandot formation as mentioned in Table1 has Type III kerogen (Fig. 4) while Tmax vs HI cross plot corresponds to an immature source rock (Fig. 5). The Warchha Formation samples WR1 and WR2 as mentioned in Table 1 represents Type III kerogen as illustrated by the HI and OI cross plot (Fig. 4) and Tmax vs HI cross plot suggests it to be an Immature source rock (Fig. 5). The Sardhai formation (sample SD1) of Lower Permian age represents a Type III kerogen determined from HI vs OI cross plot (Fig. 4) and Tmax vs HI cross plot shows an immature source rock (Fig 5).

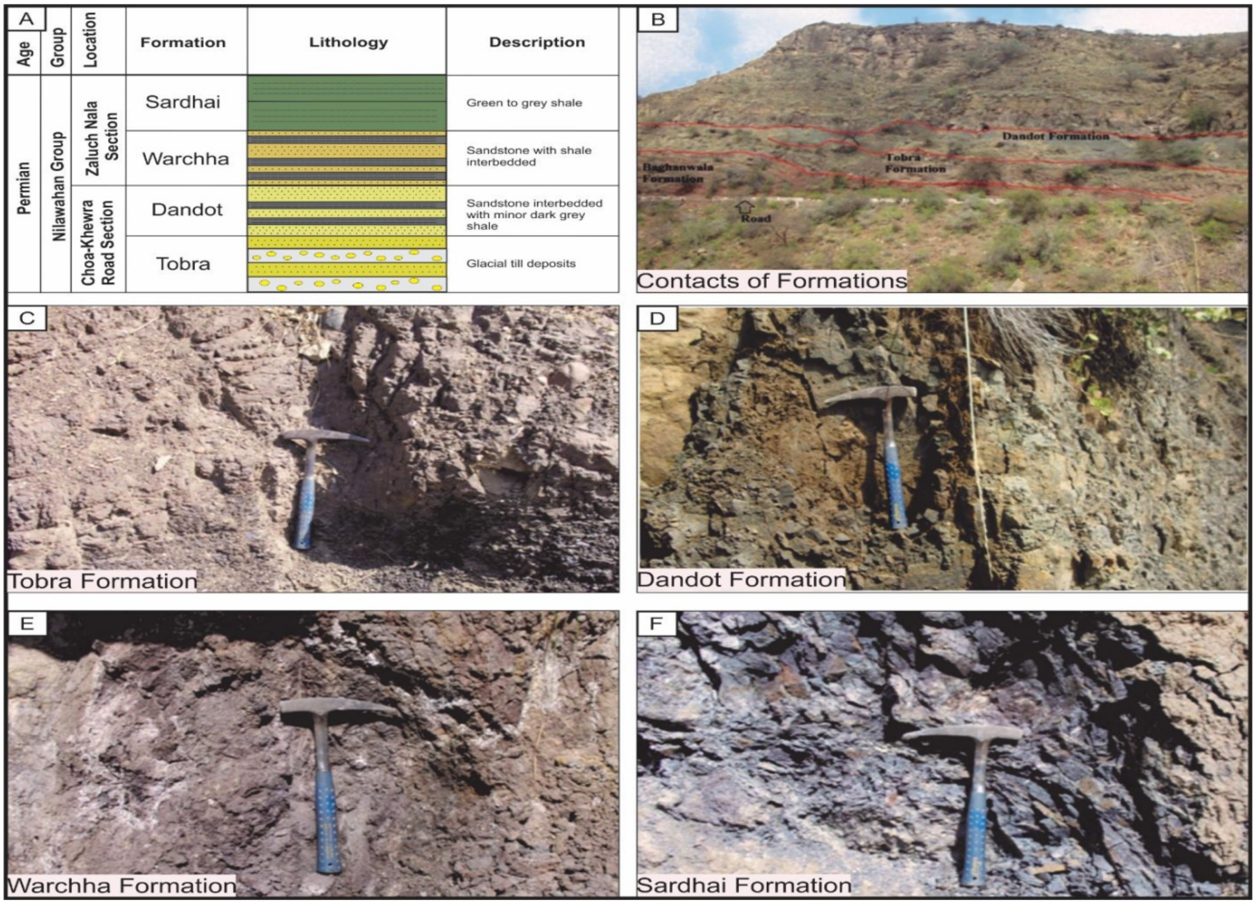

Fig. 3. Show the sub figures of A). Generalized stratigraphic column of Nilawahan Group; B). Contact between Tobra and Dandot formation at Choa-Khewra Road Section; C). Field photograph of Tobra formation; D). Field photograph of Dandot formation; E). Field photograph of Warchha formation; and F). Field photograph of Sardhai formation of Permian Nilawahan Group.

Table 1. Results of TOC and pyrolysis analyses with vitrinite reflectance of the examined Permian Tobra Fm, Dandot Fm, Warchha Fm and Sardhai Fm of the Upper Indus Basin, Pakistan.

Sample Location		Age	Formation	Samples	TOC wt%	S1 [mg/g]	S2 [mg/g]	S3 [mg/g]	GP (S1+S2 [mg/g]	T max (℃)	HI (S2/TOC)	OI (S3/TOC)	PI	Ro %
Stratigraphic Sections	Choa-Khewra Road section	Permian	Tobra	TB 1	0.55	0	0.05	0.17	0.05	430	9	31	0	0.562
				TB 2	0.83	0	0	0.16	0	439	0	19	0	0.742
			Dandot	DND 1	0.78	0	0	0.11	0	441	0	14	0	0.778
	Zaluch Nala section		Warchha	WR 1	0.73	0.02	0.02	0.18	0.04	428	3	25	0.5	0.526
				WR 2	1.05	0.01	0	0.13	0.01	427	0	12	1	0.526
			Sardhai	SD 1	1	0.02	0.01	0.5	0.03	429	1	50	0.7	0.562

Key to the Abbreviations used:

TOC: Total Organic Carbon. **S1:** Free hydrocarbon, mg HC/g rock. **S2:** Residual HC potential, mg HC/g rock. **S3:** Yield of CO2, mg CO2/g rock. **GP:** Generation Potential (S1+S2). **Tmax:** Temperature at maximum of S2 peak. **HI:** Hydrogen Index ¼ S2 X 100/TOC, mg HC/g TOC. **OI:** Oxygen index ¼ S3 X 100/TOC, mg CO2/g TOC. **PI:** Production Index (S1/ (S1+S2)). Ro % (Vitrinite Reflectance) = 0.018 Tmax – 7.16.

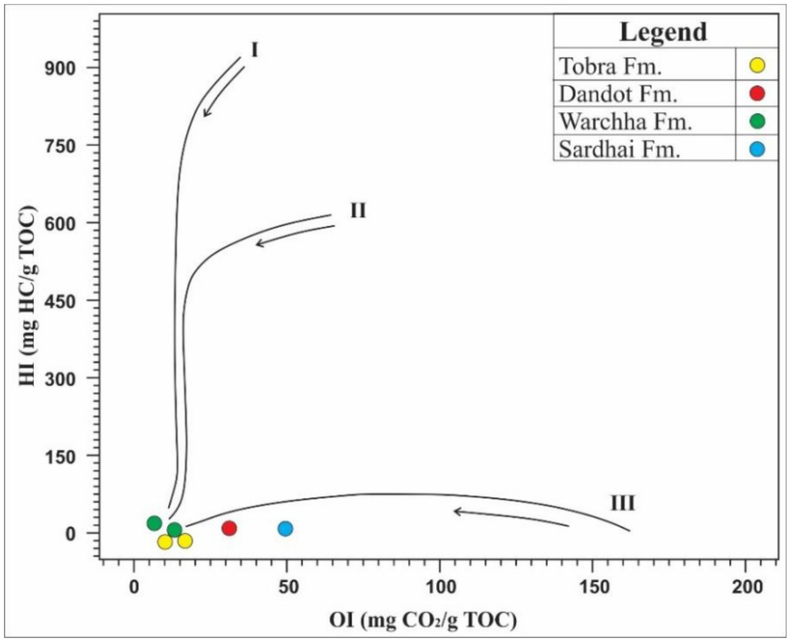

Fig. 4. Shows of HI versus OI cross plot to determine Type of Kerogen of Permian Tobra, Dandot, Warchha and Sardhai formations samples from the study area (after Van-Krevelen, 1961; Tissot and Welet, 1984).

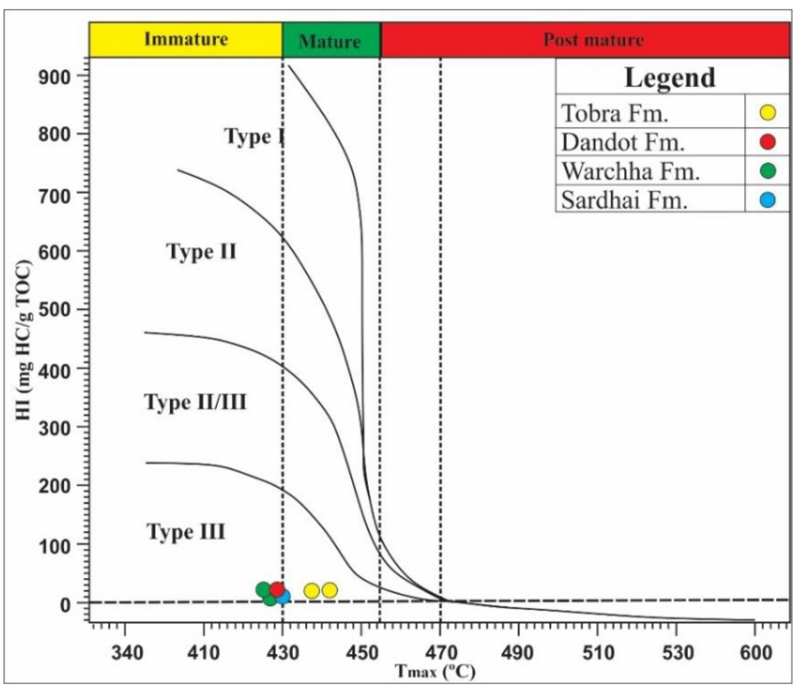

Fig. 5. Shows Tmax versus HI cross plot to cross check type of kerogen and maturity of Permian Tobra, Dandot, Warchha and Sardhai Formations samples from study area (after Hunt, 1996).

4.3. Source rock generation potential (GP)

The total organic carbon content and generation potential values are used to construct a cross plot for the determination of hydrocarbons generation potential and source rock quality in the Nilawahan group rocks. The hydrocarbon generation potential and source rock quality in the Tobra, Dandot, Warchha and Sardhai formations, displays a poor quality of source rock as determined from GP vs TOC cross plot (Fig 6).

4.4. Hydrocarbon migration and expulsion history

The PI and Tmax cross plot adopted after Tabatabaei (2017) is used to identify the thermal maturity of rock. The Permian Tobra formation is mature source rock with PI of 0. Dandot formation, Warchha formation, Sardhai formation is indicating an immature source rock with PI of 0, 0.5 & 1 and 0.7 respectively (Fig 7). The Tobra Formation lies in the Oil Window, Dandot Formation, Warchha and Sardhai Formation lies in the Immature -stained zone (Fig 7). The S1 vs TOC wt % cross plot for the studied samples collected from outcrop of Tobra formation, Dandot formation, Warchha and Sardhai formations illustrate source of the hydrocarbons as an Indigenous source (Fig. 8).

4.5. Measurement of vitrinite reflectance (% Ro)

The Vitrinite is the first component of coal and sedimentary kerogens (Dow, 1977). It is a maceral type which organic components of coal (Dow, 1977). It has shiny appearance like glass (vitreous). The vitreous material is resultant of material from cell wall or plants tissue from which coal was formed (Bjorlykke, 2010). Mature organic matter tends to give elevated reflectance of light. Thermal maturity of the kerogen can be calculated from Rock-Eval Pyrolysis, Therefore change of thermal maturity to reflectance of light will produce acceptable results (Dembicki, 2009).

Key to use vitrinite is its sensitivity to temperature variation which correspond to the hydrocarbon generation i.e. 60 to 120o C. Therefore to evaluate the hydrocarbon source rock maturity, vitrinite reflectance is the best indicator. Generally the oil generation onset has 0.5-0.6% reflectance and oil generation termination with 0.85-1.1% reflectance. (Dow, 1977; Selley, 1985; Mukhopadhyay, 1994; Hunt, 1996; Linley, 2014). According to the calculated Vitrinite reflectance results (Table. 1), the Permian Tobra, Dandot, Warchha and Sardhai Formation Ro values lies between 0.5-0.7 % and hence in oil window.

4.6. Brittleness index

The Brittleness Index (BI) depends on the percentage of brittle and ductile minerals, it mostly depends on quartz mineral which is a brittle mineral in nature. The clay minerals are ductile in nature while quartz, calcite dolomite are minerals that are brittle in nature. If the percentage of brittle minerals are more than the ductile minerals in a strata that strata is suitable for fracking and vice versa. Characteristic of shale reservoir is highly dependent on brittleness index. Barnett shale is the most productive reservoir, the wells are in the areas of 45% quartz and 27% clay content in the formation.

The Tobra Formation (Fig. 9) has the highest quantity of Quartz (57.2%) and least constituent as Gypsum (2.1%) (Table 2), Dandot Formation (Fig. 10) has 89.2% of Quartz 1.9% of Dolomite (Table 2) while the Warchha Formation (Fig 11) has 74% Quartz and 25.9% clay minerals and Sardhai formation (Fig 12) shows that the highest quantity of Quartz (45.7%) and the lowest quantity of clay minerals (3.8%) (Table 2). The Tobra, Dandot, Warchha and Sardhai formations has BI values of 0.89, 0.89, 0.74 and 0.46 respectively which shows that Tobra, Dandot and Warchha formations are Brittle in nature and suitable for fracking while Sardhai formation shows less brittle in nature and somehow suitable for hydraulic fracturing.

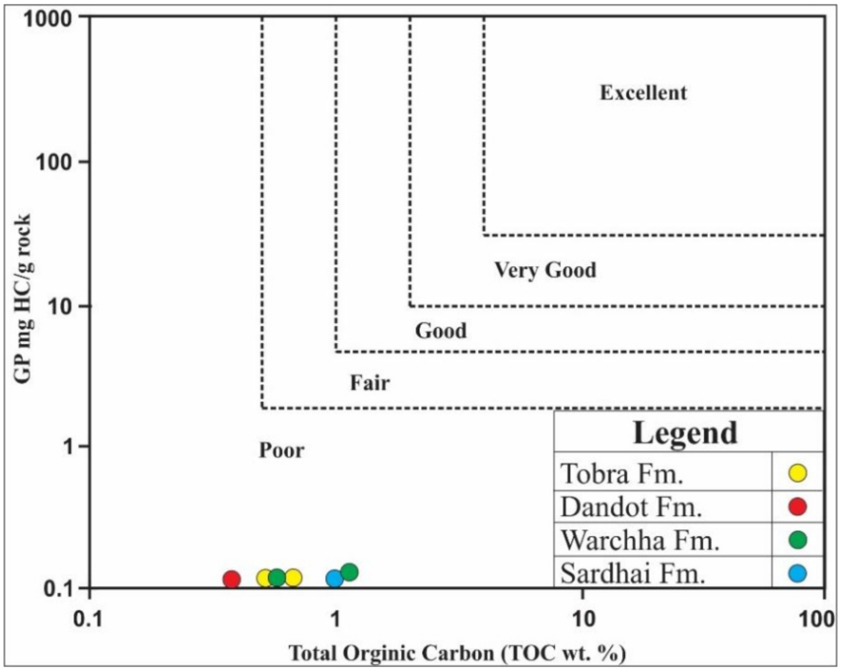

Fig. 6. Variations in TOC content & GP to find out source rock quality of Permian Tobra, Dandot, Warchha and Sardhai formations samples from study area (after Ghori, 2002; Mohamed et al., 2015).

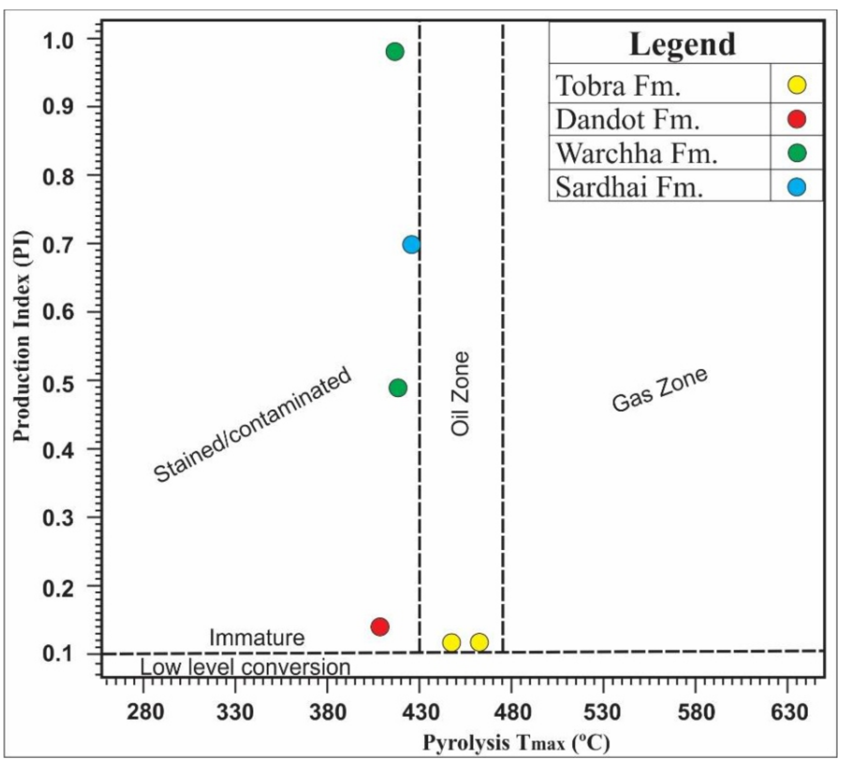

Fig. 7. Variations in Tmax and Production Index for maturity and oil & gas generation of Permian Tobra, Dandot, Warchha and Sardhai formations samples from study area (after Tabatabaei, 2017).

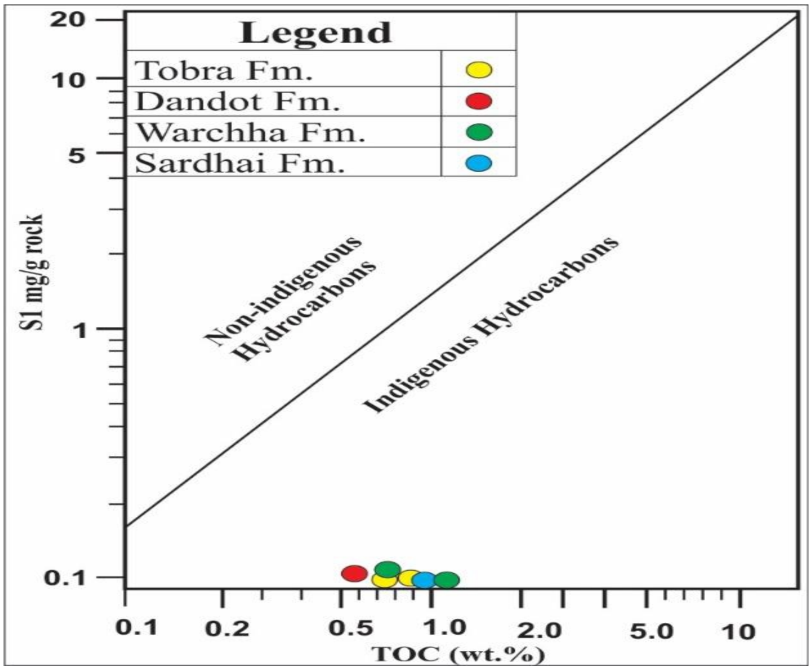

Fig. 8. S1 versus TOC% for indigenous and non-indigenous Hydrocarbons in Permian Tobra, Dandot, Warchha and Sardhai formations samples from study area (after Hunt 1996).

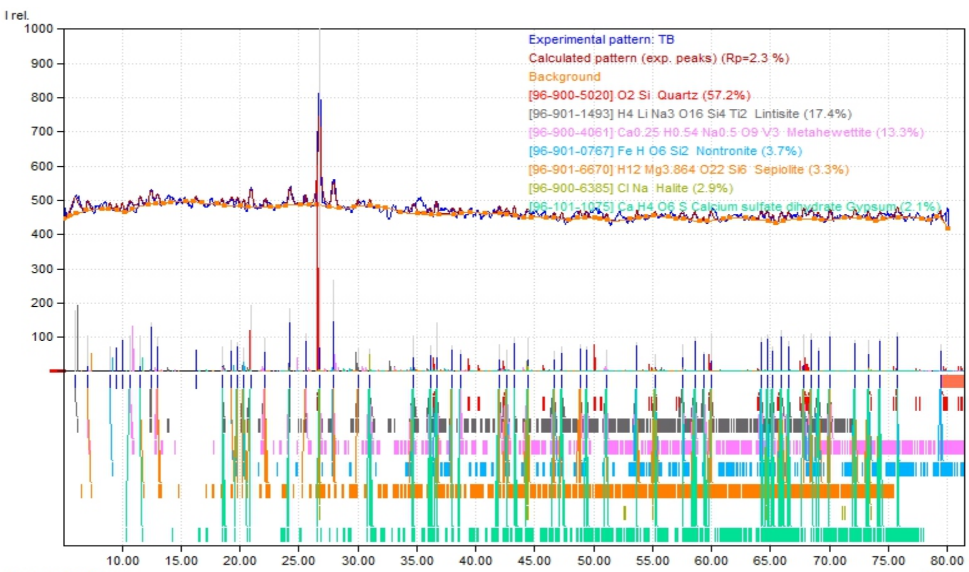

Fig. 9. Shows X-Ray diffraction results of Tobra Formation from study area.

Table 2. The Composite Table shows the mineralogical distribution (% age of Quartz, Calcite, Dolomite, Gypsum and Clay Minerals) and Brittleness Index (BI) of Permian Tobra, Dandot, Warchha and Sardhai formations.

Formation	Quartz	Calcite	Dolomite	Gypsum	Other Minerals	Total Clay Minerals %	Qz+Ca+Cly	BI
Tobra	57.2			2.1	33.6	7	64.2	0.89
Dandot	89.2		1.9			8.9	100	0.89
Warchha	74					25.9	99.9	0.74
Sardhai	45.6	32.5				21.9	100	0.46

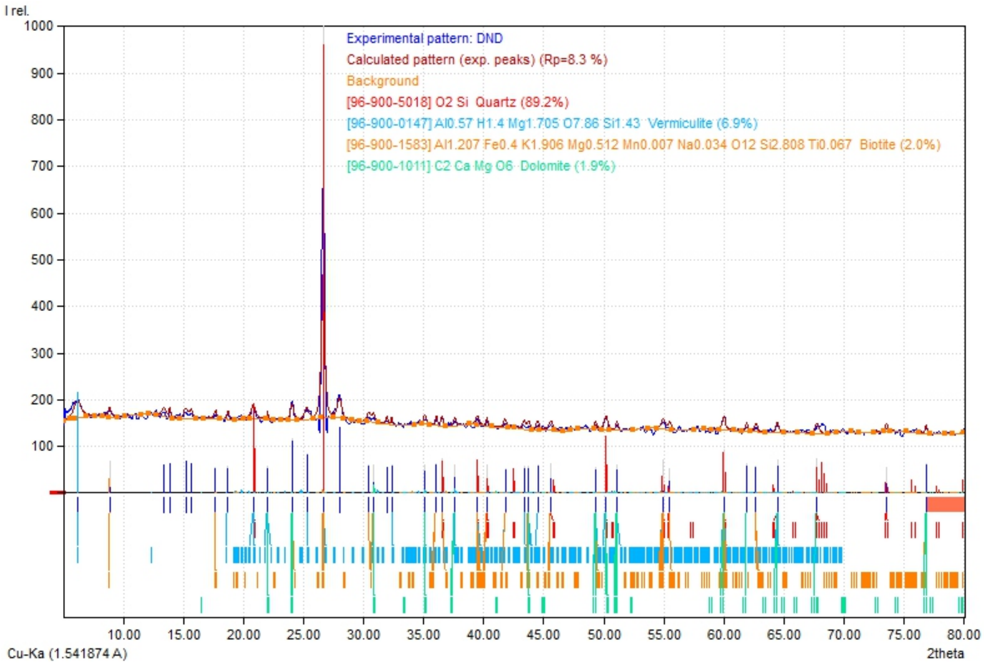

Fig. 10. Shows X-Ray diffraction results of Dandot Formation from study area.

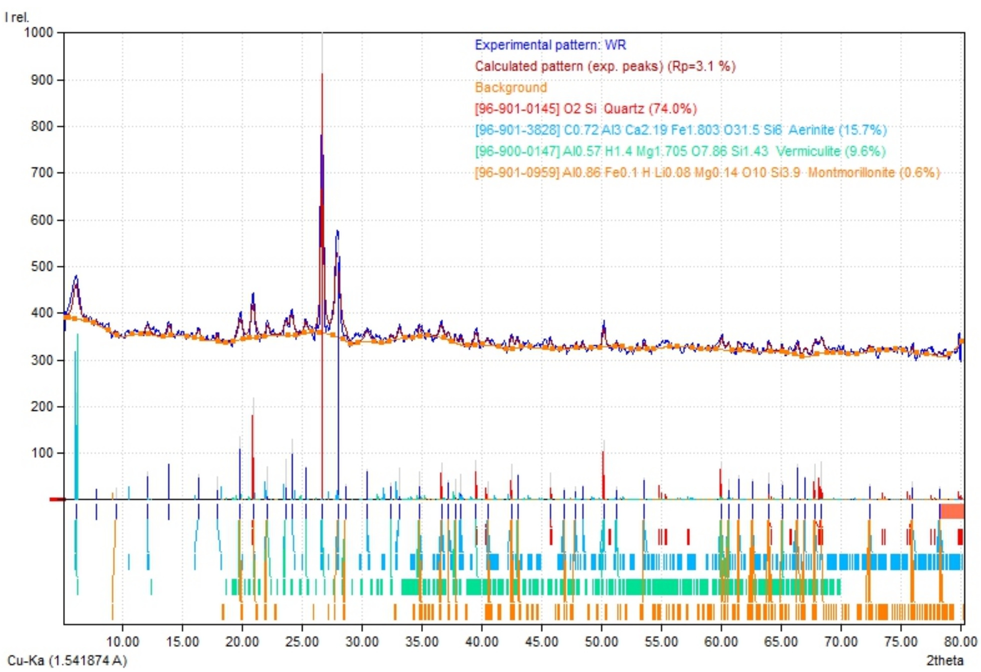

Fig. 11. Shows X-Ray diffraction results of Warchha Formation from study area.

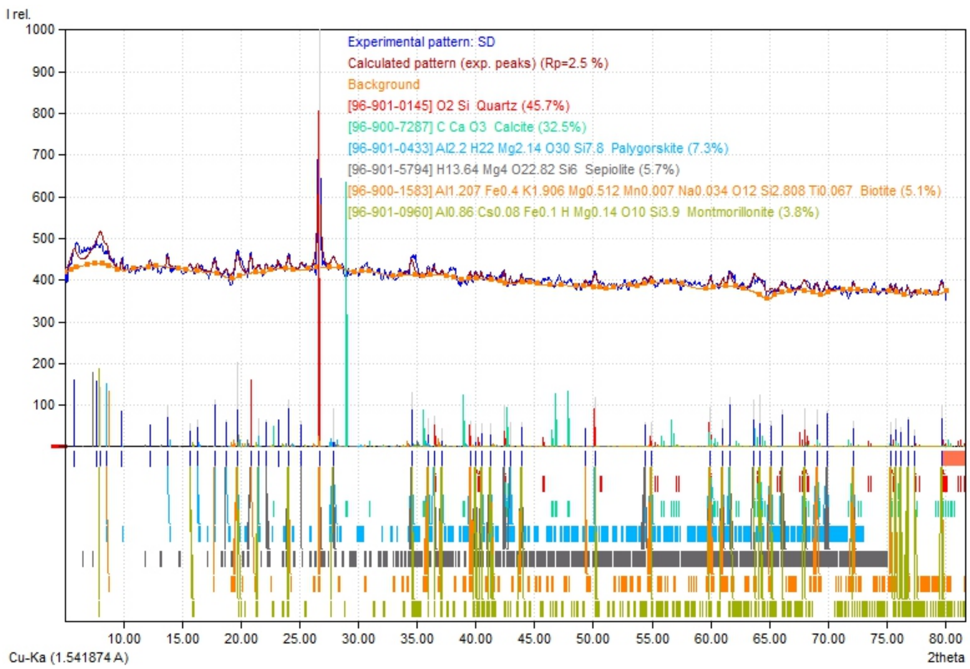

Fig. 12. Shows X-Ray diffraction results of Sardhai Formation from study area.

5. Discussion

The potential source rock has the tendency to generate sufficient quantity of hydrocarbon which later can migrate to a reservoir rock (Law, 1999). As source rock is the primary element of a petroleum play therefore the determination of Kerogen type, its thermal maturity are of key importance in evaluating the hydrocarbon potential of an area (Peters and Cassa, 1994; Rodriguez and Philp, 2010). The brownish, greenish-grey to grey color of the considered organic rich samples of shale from Tobra, Dandot, Warchha and Sardhai formations indicates moderate content of organic matter (Potter et al., 1980; Pettijohn, 1984; Varma et al., 2014). The minimum value of TOC for a petroleum source rock is 0.5 wt %, however most organic geochemists do not consider the rocks with less than 1.0 wt % organic carbon as potential source rock (Hunt, 1996). The least valve of TOC for petroleum source rock facies for shales is 0.5 wt % and 0.3 wt % for carbonates (Tissot and Welte, 1984; Ahmad et al., 2018). The laboratory calculated values of TOC varies from 0.55-0.83 wt% for Tobra Formation; 0.78 wt% for Dandot Formation, 0.73-1.05 wt% for Warchha Formation and 1 wt% for Sardhai Formation. The highest TOC content is observed in the samples of Warchha Formation. The difference in the TOC content in the sedimentary sequence is caused by deposition environment of sediments, decomposition of organic matter, and temperature increase with increase in burial depth (Schlesinger, 1977; Potter et al., 1980; Hunt, 1996; Stein, 2007; Wang, 2013). The best environment for preservation of organic matter in the sedimentary sequence is low energy anoxic environment (Demaison and Moore 1980). The low TOC content of the analyzed samples from all the stratigraphic units can be attributed to the depositional environment as these units are mostly deposited in terrestrial to shallow marine environments (Shah, et al., 2010; Ghazi, et al., 2012; Jan, et al., 2016; Jan, et al., 2017).

The amount of temperature at which the maximum amount of hydrocarbons are released from the disintegration of kerogen is Tmax. For Type III kerogen the boundary between immature and mature kerogen is 430 ℃ and the limit between over-mature and mature kerogen is 460 ℃ (Espitaliè, 1986). The samples from Tobra Formation have Tmax values of 430 and 439 ℃ and those of the Dandot Formation has Tmax value of 441℃ which shows that the kerogen in these formations is thermally mature. The samples from Warchha and Sardhai formations have Tmax values of 428, 427 ℃ and 429 ℃ respectively, which shows that immature kerogen is present in these formations. Diverse type of hydrocarbons can be produced from different type of kerogens. Kerogen has variety of compositions which is dependable on the composition of organic matter and can be divided into 3 main types. The Type I Kerogen contains high lipid content and it is a representative of oil bearing shales (Eble et al., 2015). The Type II kerogen is a composite mixture of marine organisms, algae and plant remains, this type of kerogen is the common source of oil generation (Bjorlykke, 2010). The Type III Kerogen which is also known as humic kerogen is mainly the derivative of organic remains of land plants i.e. tannins, cellulose and lignin (Bjorlykke, 2010). The initial H/C ratio in Type III Kerogen is low and initial Oxygen-Carbon (O/C) ratio is high of this type, it can generate abundant carbon dioxide, water and methane during maturation and is the common source of gas generation. The direct relationship between hydrocarbon generation potential and pyrolysis data is specified in several studies (Bordenave, 1993; Hunt, 1996). The HI and OI values are measured by mg HC/g TOC unit. Peters and Cassa (1994) defines the threshold values of HI for source rock: rock sample having Type III kerogen and the HI values less than 200 is expected to generate gas. A rock sample would generate gas as a main product and oil in less amount having HI values greater than 200, whereas samples can generate oil with HI values greater than 300 (Bordenave, 1993; Hunt, 1996).

The studied samples of the Tobra, Dandot, Warchha and Sardhai formations have Type III kerogen, and can produce gas. While the HI values for these formations ranges from 0-9 S2/TOC which is very low and indicates the generation of gas from the organic rich horizons of these formations. The organic rich intervals in Tobra formation is capable of generating oil owing to mature Type III kerogen.

The generation potential (GP) of a rock is represented by the amount of volatile hydrocarbons (S1) and hydrocarbons generated during pyrolysis (S2). A rock have less or no oil generation and gas generation when the value of GP is less than 2 mg HC/g. Moderate to fair potential of a rock indicates the GP values ranges between 2 to 6 mg HC/g. and hydrocarbon produces above 6 mg HC/g indicates good to excellent potential of a rock (Tissot and Welte, 1985; Dyman et al., 1996). The generation potential of the Tobra, Dandot, Warchha and Sardhai formations ranges from 0-0.05 which is less than 2 which shows that these formations can generate less amount of oil and have some potential for gas generation.

The Type I and II kerogen have production index (PI) values > 0.1 while the PI values ranges from 0.1-0.2 for Type III kerogen. The PI values of Tobra, Dandot, Warchha and Sardhai formation suggests that samples analyzed from these formations have Type III kerogen. The PI and Tmax cross plot proposed that the Tobra formation lies in thermally mature oil zone, while the Dandot, Warchha and Sardhai formations lies in thermally immature contaminated zone. The S1 and TOC cross plot indicated that the samples analyzed from The Tobra, Dandot, Warchha and Sardhai formations have indigenous hydrocarbons.

6. Conclusion

The organic rich intervals in Tobra Formation exposed along Choa-Khewra Road Section consist of mature Type III kerogen and is able to generate indigenous hydrocarbons i.e. gas and condensates. The organic rich intervals in Dandot Formation exposed along Choa-Khewra Road and Warchha, and Sardhai formations exposed in the Zaluch Nala Section are immature, and contains Type III kerogen, capable of generating indigenous hydrocarbons. The vitrinite reflectance values of the analyzed samples from studied formations lies in the oil generation zone. The Tobra, Dandot, Warchha and Sardhai formations has BI values of 0.89, 0.89, 0.74 and 0.46 respectively which shows that Tobra, Dandot and Warchha formations are Brittle in nature and suitable for fracking while the Sardhai formation shows is not suitable for hydraulic fracturing.

Acknowledgement

I greatly acknowledge Higher Education Commission (HEC) Pakistan Indigenous Ph.D.

Fellowship Program and International Research Support Initiative Program (IRSIP) for providing support to my PhD research.

Authors' Contribution

The manuscript contains the data from the Ph.D. research work of Faizan Ahmad. Faizan Ahmad is involved in the field data collection, write up of the manuscript and preparation of illustrations and figures. Sajjad Ahmad, is supervisor. Suleman Khan is Co-Supervisor and Qi Fu is foreign Supervisor. Sajjad Ahmad and Suleman Khan, proposed the main concept and involved in write up. Qi Fu, did provision of relevant literature and review the manuscript. Irfan Ullah Jan, did technical review and proof read of the manuscript before submission. Rafiq Ali Khan, did collection of field data. Shehla Gul, was involved in preparation of figures. Fahad Ali Alizai, did collection of field data.

References

Ahmad, S., Ullah, M., Ullah, S., Khan, S., Khan, Y., Jan, I. U., Rehman, K., Mohibullah, M., Attaulllah, Jan, S., 2018. Stratigraphic and Paleoclimatic Reconstruction of the Upper Carboniferous-Lower Permian strata from the Southern Gondwanaland remnants in Pakistan, Stratigraphy, 15 (2), 69–90.

Bacon, C. N., Calver, C. R., Boreham, C. J., Lenman, D. E., Morrison, K. C., Revill, A. T., Volkman, J. K., 2000. The petroleum potential of onshore tasmania:a review. Geological Survey Bulletin, 71 (1), 93.

Baker, D. M., Lillie, R. J., Yeats, R. S., Johnson, G. D., Yousuf, M., Zamin, A. S. H., 1988. Development of the Himalayan frontal thrust zone-Salt Range, Pakistan. Geology, 16, 3-7.

Behar, F., Beaumont, V., Penteado, H. L., De, B., 2001. Rock-Eval 6 technology: performances and developments. Oil & Gas Science and Technology, French Institute of Petroleum, 56 (2), 111-134.

Bjorlykke, K., Avseth, P., 2010. Petroleum geoscience: From sedimentary environments to rock physics. Berlin, Springer.

Bordenave, M. L., 1993. Applied Petroleum Geochemistry. Editions Technip, Paris.

Coward, M. P., Windley, B. F., Broughton, R., Luff, I. W., Petreson, M., Pudsey, C. J., Rex, D. Asif, K. M., 1986. Collision tectonics in the NW Himalayas, Special Publication, the Geological Society London, 19, 203-219.

Demaison, G. J., Moore, G., 1980. Anoxic environments and oil source bed genesis, American Association of Petroleum Geologists Bulletin, 64 (8), 1179–1209.

Dembicki, J., 2009. Three common source rock evaluation errors made by geologists during prospect or play appraisals. American Association of Petroleum Geologists Bulletin, 93 (3), 341-356.

Dow, W. G., 1977. Kerogen studies and geological interpretations. Journal of geochemical Exploration, 7, 79-99

Dyman, T. S., Palacas, J. G., Tysdal, R. G., 1996. Source rock potential of middle cretaceous rocks in southwestern Montana. American Association of Petroleum Geologist Bulletin, 80, 1177-1184.

Eble, C., John, H., David, H., Michele, C., John R., 2015. Source rock geochemistry. In Patchen, D. G., Carter, K. M., (Eds.), A geologic play book for Utica Shale Appalachian basin exploration, Final report of the Utica Shale Appalachian basin exploration consortium, 102-141.

Espitaliè, J., 1986. Use of Tmax as a maturation index for different types of organic matter, comparison with vitrinite reflectance; Thermal modelling in sedimentary basins, Burrus, Journal Editions Technip, Paris, 475–96.

Gee, E. R., 1981. Pakistan Geological Salt Range Series (6 sheets, Scale 1:50000) Directorate of the overseas survey, United Kingdom, For the Government of Pakistan and Geological survey of Pakistan.

Ghazi, S., Mountney, N. P., Butt, A. A., Sharif, S., 2012. Stratigraphic and palaeoenvironmental framework of the Early Permian sequence in the Salt Range, Pakistan. Journal of Earth system science, 121 (5), 1239-1255.

Ghori, K. A. R., 1998. Petroleum Source-Rock Potential and Thermal history of the Officer Basin, Western Australia, Western Australia Geological Survey, 52.

Ghori, K. A. R., 2002. Modeling the hydrocarbon generative history of the Officer Basin, Western Australia. Petroleum Exploration Society of Australia Journal, (29), 29–42.

Hunt, J. M., 1996. Petroleum Geochemistry and Geology, Second edition, W. H. Freeman and Company, New York, 734.

Hussain, B. R., 1967. Saiduwali Member, a new name for the lower part for the Permian Amb Formation, West Pakistan. University Studies (Karachi), Science and Technology, 4 (3) 88-95.

Jamil, A., Waheed, A., Sheikh, R. A., 2009. Pakistan's major petroleum plays-An Overview of Dwindling Reserves. Search and Discovery, Article, (10399), 1-2.

Jan, I. U., Stephenson, M. H., 2011. Palynology and correlation of the Upper Pennsylvanian Tobra Formation from Zaluch Nala, Salt Range, Pakistan. Palynology, 35 (2), 212–225.

Jan, I. U., Stephenson, M. H., Khan, F. R., 2009. Palynostratigraphic correlation of the Sardhai Formation (Permian) of Pakistan. Review of Palaeobotany and Palynology, 158, 72-82.

Jan., U. I., Iqbal, S., Davies, S. J., Zalasiewicz, J. A., Stephenson, M. H., Wagreich, M., Haneef, M., Hanif, M., Ahmad, S., 2017. A Periglacial Palaeoenvironment in the Upper Carboniferous-Lower Permian Tobra Formation of the Salt Range, Pakistan. Acta Geologica Sinica, 91(3), 1063-1078.

Jan., U. I., Shah, A., Stephenson, M. H., Iqbal, S., Hanif, M., Wagreich, M., Hussain, H. S., 2016. The sedimentology of the Lower Permian Dandot formation: A component of the Gondwana deglaciation sequence of the Salt Range, Pakistan. Rivista Italiana di Paleontologia e Stratigrafia, 122 (1), 75-90.

Jarvie, D. M., 1991. Total organic carbon (TOC) analysis. Merrill RK Source and migration processes and evaluation techniques. American Association of Petroleum Geologist Bulletin, Treatise of Petroleum Geology, Handbook of Petroleum Geology, 113–118.

Jarvie, D. M., Brenda, L. C., Floyd, H., John, T. B., 2001. Oil and Shale Gas from the Barnett Shale, Ft. Worth Basin, Texas; National Convention, Denver, CO, American Association of Petroleum Geologist Bulletin, 13, 85.

Jarvie, D. M., Hill, R. J., Ruble, T. E., 2007. Pollastro, R. M. Unconventional Shale Gas Systems. The Mississippian Barnett Shale of North-Central Texas as one Model for Thermogenic Shale-Gas Assessment, American Association of Petroleum Geologist Bulletin, 91 (4), 475-499.

Jaume, S. C., Lillie, R. J., 1988. Mechanics of the Salt Range-Potwar Plateau, Pakistan: a fold-and thrust belt underlain by evaporates, Tectonics, 7, 57-71.

Johannes, J., Kruusement, K., Palu, V., Veski, R., Bojesen, J. A., 2006. Evaluation of oil potential of Estonian Shales and Biomass samples Using Rock-Eval Analyzer, Oil Shale, 23 (2), 110-118.

Kazmi, A. H., Rana, R. A., 1982. Tectonic map of Pakistan at a scale of 1:2,000,000. Geological Survey of Pakistan, 1 sheet.

Krishnan, M. S., 1960. Geology of India and Burma. Madras: Higgnbothams (Private) Ltd, 604.

Kusskaraa, V. A., 2013. Technically Recoverable Shale Gas and Shale Oil Resources: An Assessment of 137 Shale Formations in 41 Countries outside the United States.

Law, C., 1999. Evaluating source rocks. In: Foster, N., Beaumont, E, A., (Eds.), Treatise of the handbook of petroleum geology. American Association of Petroleum Geologists, Tulsa, Oklahoma, 6 (1), 6-41.

Le Fort, P., 1975. Himalaya: the collided range; Present knowledge of the continental arc. American Journal of Science, 275A, 1-44.

Linley, K. A., 2014. User Guide for the Vitrinite Reflectance dataset. British Geological Survey open report, OR/14/055. 13.

Magoon, L. B, Dow, W. G., 1994. The petroleum system-from source to trap, American Association of Petroleum Geologists, Memoir 60.

Mani, D., Dayal, A. M., Patil, D. J., Hafiz, M., Hakoo, N., Bhat, G. M., 2014. Gas potential of proterozoic and phanerozoic shales from NW Himalaya, India: inferences from pyrolysis. International Journal of Coal Geology, 128-129, 81-95.

Mertmann, D., 1999. Das marine Perm in der Salt Range und Trans Indus Ranges, Pakistan. Berliner Geowissenschaftliche Abhandlungen, A204, 1-94.

Mohamed, M. N., Fatma, S. R., Mahmoud, M. H., Nira, M. L., 2015. Evaluation of organic matters, hydrocarbon potential and thermal maturity of source rocks based on geochemical and statistical methods: Case study of source rocks in Ras Gharib oilfield, central Gulf of Suez. Egypt. Egypt Journal of Petroleum, 24, 203–211.

Mukhopadhyay, P. K., Dow, W. G., 1994. Vitrinite reflectance as a maturity parameter. Vitrinite reflectance as a maturity parameter, 570, 1-24.

Noetling, F., 1901. Beitrage zur Geologie der Salt Range, insbesondere der permichem und triasuchen Ablagerungen. Ucucs Jahrb. Mineral. Bcilagc-Band, 14, 369-471.

Peters, K. E., Cassa, M. R., 1994. Applied source rock geochemistry, American Association of Petroleum Geologist Memoir.

Pettijohn, F. J., 1984. Sedimentary Rocks, 3rd edition, Harper and Raw Publisher, USA.

Potter, P. E., Mayand, J., Pryor, W. A., 1980. Sedimentology of shale; Springer Verlag, New York, Heidelberg, Berlin.

Rodriguez, N. D., Philp, R.P., 2010. Geochemical characterization of gases from the Mississippian Barnett Shale, Fort Worth Basin, Texas. American Association of Petroleum Geologist Bulletin, 94 (11), 1641-1656.

Schlesinger, W. H., 1977. Carbon balance in terrestrial detritus, The Annual Review of Ecology, Evolution, and Systematics, 8, 51–81.

Seeber, L., Armbruster, J. G., Quittmeyer, R. C., 1981. Seismicity and continental subduction in the Himalayan arc. Zagros Hindu Kush Himalaya Geodynamic Evolution, 215-242.

Selley, R. C., 1985. Elements of Petroleum Geology. W. H. Freeman and Company, New York. 449.

Shah, A., Haneef, M., Hanif M., Jan, U. I., 2010. Lithofacies and palaeoenvironmental analysis of Carboniferous-Permian Nilawahan Group, Salt Range Pakistan. Pakistan Journal of Hydrocarbon Research, 20, 49-52.

Shah, J., Jan, M. R., Zeeshan, M., Imran, M., 2017. Kinetic equilibrium and thermodynamic studies for sorption of 2, 4-dichlorophenol onto surfactant modified fuller's earth, Applied Clay Science, 143, 227-233.

Shah, S. M. I., 2009. Stratigraphy of Pakistan. Government of Pakistan Ministry of Petroleum and Natural Resources, Geological Society of Pakistan, 22, 20-188.

Stein, 2007. Upper Cretaceous/lower Tertiary black shales near the North Pole: Organic-carbon origin and source rock potential. Marine Petroleum Geology, 24, 67–73.

Stephenson, M. H., Jan, I. U., Al-Mashaikie, S. Z. A. K., 2013. Palynology and correlation of Pennsylvanian glacigene rocks in Oman, Yemen and Pakistan. Gondwana Research, 24, 203–211.

Tabatabaei, H., 2017. Potential Evaluation and Basin Modeling of the Pabdeh Formation in Zagros Basin: A Case Study, Open Journal of Geology, 7, 505-516.

Teichert, C., 1967. Nature of Permian glacial record. Salt Range and KhisorRange, West Pakistan. Ncucs Johrb, Geol. Palacont., Abh., 129 (2), 167-184.

Tissot, B. P., Welte, D. H., 1978. Petroleum Formation and Occurrence: A New Approach to Oil and Gas Exploration. Berlin, Heidelberg, New York: Springer-Verlag. ISBN 3 540 08698 6.

Tissot, B. P., Welte, D. H., 1984. Petroleum Formation and occurrence: A new approach to oil and gas exploration; 2nd ed.: Springer Verlag, Berlin, 150-169.

Tissot, B. P., Welte, D. H., 1985. Petroleum Formation and Occurrence. Eos, Transactions American Geophysical Union Second, Springer-Verlag, Berlin, 66.

Van-Krevelen, D. W., 1961. Coal typology–chemistry–physics-constitution, 1st ed. Elsevier, The Netherlands.

Varma, A. K., Hazra, B., Srivastava, A., 2014. Estimation of total organic carbon in shales through color manifestations, Journal of Natural Gas Science and Engineering, 18, 53–57.

Wang, G., 2013. Organic-rich Marcellus shale lithofacies modeling and distribution pattern analysis in the Appalachian Basin; American Association of Petroleum

Geologist Bulletin, 97 (12), 2173–2205.
Wardlaw, B. R., Pogue, K. R., 1995. The Permian of Pakistan. In the Permian of Northern Pangea, Springer, Berlin, Heidelberg. 215-224.
Yeats, R.S., Lawrence, R.D., 1984. Tectonics of the Himalayan thrust belt in northern Pakistan. In: Haq, B. U., Milliman, J. D., (Eds.), Marine Geology and oceanography of Arabian sea and coastal Pakistan. Van Nostrand Reinhold Co., New York, 177-200.