Maturity analysis of Cretaceous source rock using 1D basin modeling approach in the Platform area of Middle Indus Basin, Pakistan.

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ABSTRACT

The present paper aimed to conduct multi 1D numerical modeling of Punjab Platform, Middle Indus Basin of Pakistan to evaluate the maturation, hydrocarbon generation, and expulsion history of Cretaceous source rock. The study is based on lab analysis and vitrinite reflectance calculations on core samples and drill cuttings to evaluate the hydrocarbon generation from Cretaceous source rock Chichali/ Sembar Formation in the Middle Indus Basin of Pakistan. Formation tops, Geochemical reports, mud logs, vitrinite reflectance, and borehole temperature (BHT) data was incorporated during calibration of 1D burial and thermal history models for maturity analysis of the Chichali/ Sembar Formation. Burial history of the Middle Indus Basin is characterized by Jurassic rifting induced thermal subsidence, followed by rapid post-Cretaceous tectonic subsidence due to India-Eurasia collision, deposition of thick Molasses post-Oligocene. Lab analysis on drill cuttings samples shows that TOC values of Chichali / Sembar Formation range from 0.4 to 2.2% with an average of 1.4%. The present study shows that the Cretaceous source package could not attain maturity in the north-eastern part of Punjab Platform, marginally mature in western part whereas, the source rock achieved the oil maturity almost 20 my ago in southern parts of study area. The findings of this research show that maturation and expulsion were directly influenced by the India-Eurasia collision, local basement high uplifting, subsequent molasses deposition, and erosion.

1. INTRODUCTION

The Middle Indus Basin is currently the under-explored area which lies in the middle part of Pakistan. Literature related to thermal history evolution, source rock maturation, hydrocarbon generation, and expulsion history of the Middle Indus Basin is not sufficiently available (Kadri, 1995). The study area lies in Punjab Platform which is the eastern part of the Middle Indus Basin (MIB) Pakistan. Punjab platform, adjacent to Suleiman Foredeep, is a westward dipping broad monocline and is least affected by the collision of Indian and Eurasian plates. Sargodha high and Pezu uplift separate the MIB from Upper Indus Basin in the North whereas the Sukkur rift is located in the south (Figure. 01). While, Indian shield is situated in the east and marginal zone of Indian plate in the west of MIB (Kadri, 1995). Exploration activities in the study area began in the middle 1950s, with the drilling of first exploration well i.e. Karampur-1 in 1958 by Shell, which provided evidence for the occurrence of heavy oil in the Infra-Cambrian reservoir. After this number of wells (almost 30) were drilled in Cambrian and Infra-Cambrian reservoirs and only three gas discovery (Panjpir, Nandpur, and Bahu) was made in Mesozoic reservoirs by OGDCL. The overall success ratio is the very low and major reason due to the lack of mature source rocks in the region (Raza et al. 2008; Khalid et al. 2014).

1D basin modeling of the Punjab Platform was carried out for the understanding of the thermal maturity and burial history of the basin. The study aimed to understand source rock maturity evolution, hydrocarbon generation, expulsion, and migration history. Multi 1D burial and thermal history modeling is a very useful tool in hydrocarbon exploration which allows the interpreter to integrate geological and geochemical data for source rock maturity analysis (Handhal et al. 2020; Baniasad et al. 2019; Hlaiem et al, 1997). A well-known quantitative technique known as back stripping was utilized for the reconstruction of the burial history for present study. This technique involves decompaction of sedimentary layers encountered in any drilled well by using porosity vs depth relationships corresponding to each lithology (Perrier and Quiblier, 1974) along with estimates of palaeo-bathymetry (Steckler and Watts, 1982). As the simulation of original depositional thickness of each formation is carried out, back stripping technique allow us to calculate the sedimentation and the subsidence rates within the evolving sedimentary basin (Roberts, 1998).

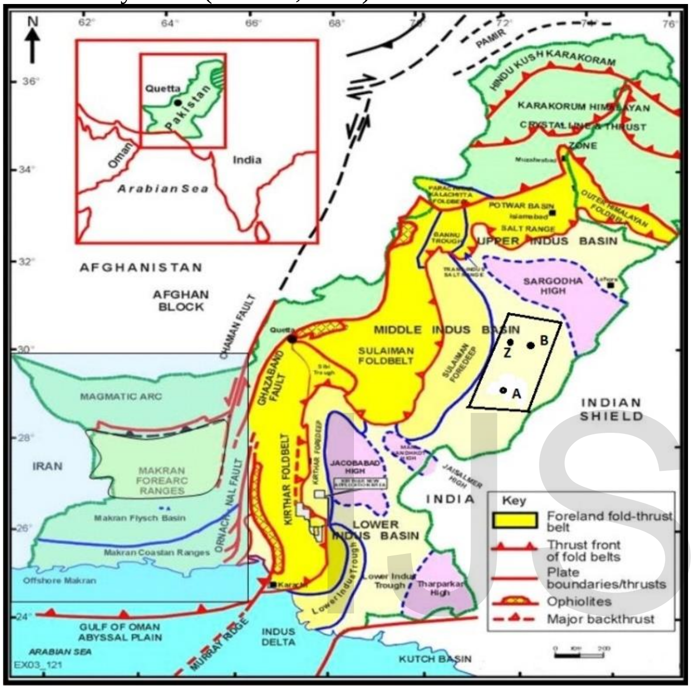

Figure. 1 Location and tectonic map of the study area (After Bank and Warburton 1986)

In this paper, we describe the burial and thermal evolution of the Middle Indus Basin (MIB) using a quantitative approach for one-dimensional (1D) basin modeling. The study is based on the integration of surface data (geological maps, geochemical analysis of outcrop samples) with subsurface data (mud logs, flush cuttings, geochemical data, and well tops data from well reports), to evaluate the maturation of source rocks, generation and expulsion history of hydrocarbons using burial and thermal history models of Middle Indus Basin. The results of this study will enhance the understanding of the timing of hydrocarbon generation and uncertainties and risk involved in exploration activities in the Middle Indus Basin. Three vertical wells A, B, and Z located in Punjab Platform were modeled for burial and thermal history to simulate maturation potential of the Cretaceous source rock (Chichali/ Sembar Formation). The present study will add much value for the interpretation of hydrocarbon generation and expulsion history of the Middle Indus Basin.

During the study, different data sets including formation tops, mud logs, geochemical analysis of drill cuttings, and wireline well logs were integrated to evaluate burial and thermal history evolution of Cretaceous Source rock i.e., Chichali/ Sembar Formation. Vitrinite reflectance, Tmax, and corrected BHT along with formation tops and mud logs were used to construct calibrated burial history diagrams using the Petroleum systems module of Petrel software.

2. Geological Setting:

The Indus Basin is situated on the western edge of the Indian plate at India-Pakistan fringe. Indian plate has confronted various scenes of rifting, collision, and orogenesis. Indian plate isolated from Madagascar through rifting in Jurassic-Cretaceous and moved towards the north (Aiticheson et al. 2007). As per few research works (Lee and Lawyer, 1995; Bouilhol et al. 2013), the collision of India – Kohistan/ Ladakh arc began around 50 to 55 Mya, whereas India-arc-Eurasia collision began around ~41Ma. In contrast, Klootwijk et al. 1992 proposed that India-Eurasia may have collided between 65-70 Mya. The Indus Basin, which most probably came into being after the separation of Indian plate from Madagascar, is usually divided into three parts, upper, middle, and southern Indus Basin (Kadri, 1995).

Major extensional activity occurred in the Middle Indus Basin (MIB) during the late Jurassic and Cretaceous. This rift assiciated phase also resulted in the reactivation of the basement involved faults throughout the Indian plate. In MIB, faults are mostly NNE-SSW to NE-SW trending very similar to Pre-Cambrian-Cambrian rifting. This may suggest a dominant basement influence on the Mesozoic extension. The base of Jurassic is unconformable upon the Triassic and collectively referred to as the Wulgai formation. Triassic is entirely missing in some wells (Karmpur-01 and Marrot-01). The overlying Jurassic rocks sequence includes the Shirinab or Datta and Shinawari formations. Middle Jurassic carbonate platforms with uniform deposition settings are extended in the Middle and Lower Indus Basin, designated as Samana Suk / Chiltan Formation. The top of Jurassic may be attributed as Basin wide unconformity.

The early cretaceous marks the separation of Eastern Gondwanaland (India, Antarctica, and Australia) from the western Gondwanaland (Africa and South-America) and consists of Sembar and Goru formations deposited in coastal, and shallow-marine environments. The Sembar formation is correlated with the Chichali Formation of the Northern Punjab Platform and the upper Indus Basin. It is considered the primary source rock in Lower Indus Basin (Iqbal and shah 1980; Kadri 1995) and is composed of shale with a subordinate amount of siltstone and sandstone. The thermal maturity increases towards the west of the platform while less mature to the eastern part of the Indus basin. Total organic carbon (TOC) values in Badin area wells ranges from 0.5 to 3.5 % and average about 1.4% (Wandrew et al. 2004). The Cretaceous source rock is designated as Chichali Formation in the Middle Indus region, as it is considered as the source rock for the reservoirs of Lockhart and Lumshiwal Formation (Kadri, 1995). According to Qureshi et al. (2007), Chichali Formation consisted of shales and glauconitic sandstone deposited in variable environments from shallow marine to anoxic environments.

The Punjab Platform is a large monocline, which dips towards the west forms the eastern part of the Middle Indus Basin (Raza et al. 2008; Hasany et al. 2007). The seismic and well data suggest that different strata pinch out towards east

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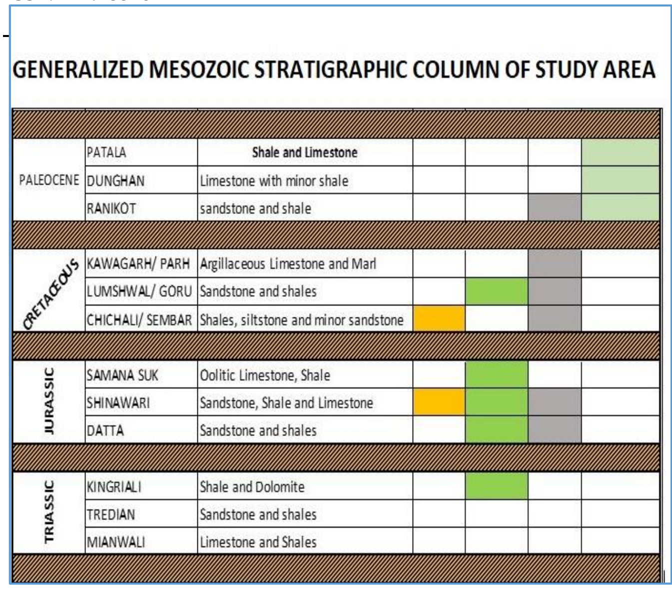


GENERALIZED MESOZOIC STRATIGRAPHIC COLUMN OF STUDY AREA

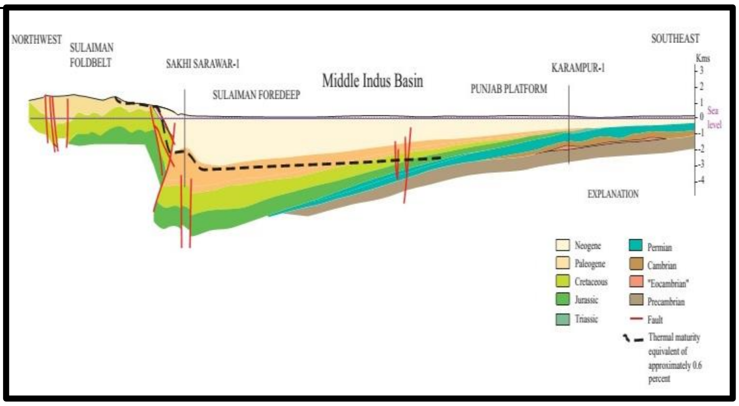
Age	Formation	Lithology
PALEOCENE	PATALA	Shale and Limestone
	DUNGHAN	Limestone with minor shale
	RANIKOT	sandstone and shale
CRETACEOUS	KAWAGARH/ PARH	Argillaceous Limestone and Marl
	LUMSHWAL/ GORU	Sandstone and shales
	CHICHALI/ SEMBAR	Shales, siltstone and minor sandstone
JURASSIC	SAMANA SUK	Oolitic Limestone, Shale
	SHINAWARI	Sandstone, Shale and Limestone
	DATTA	Sandstone and shales
TRIASSIC	KINGRIALI	Shale and Dolomite
	TREDIAN	Sandstone and shales
	MIANWALI	Limestone and Shales

(Figure. 03). The central part of middle Indus Basin known as Suleiman Foredeep and generally considered as possible kitchen area is bounded by Punjab Platform in the east and the west by Suleiman Fold and Thrust Belt (Kadri, 1995). Suleiman Fold and Thrust Belt are present in the westernmost part comprising compressional structures (folds and thrusts), which are the result of a collision between the Indian and Eurasian plates (Figure. 01) (Kadri, 1995). From the late cretaceous to middle Paleocene time, oblique convergence of Indian plate with Afghan plates resulted in wrench faulting. Punjab Platform, developed due to such type of tectonics

Figure. 2 Stratigraphic columns of the study area.

processes, has a sedimentary thickness ranging from 500 - 3000 m above the Proterozoic basement (Khalid et al. 2014).

The stratigraphic succession in the northern part of the Punjab platform is correlateable with the stratigraphy of upper Indus basin, whereas the southern part is much related to the Sindh Platform (Arif et al. 2009; Raza et al. 2008). The well data of different hydrocarbon wells drilled in the study area show that the stratigraphy consists of ranging from Infra-Cambrian to recent strata. The stratigraphic succession shows different episodes of non-deposition/ erosion which mark the unconformities, including Cambrian-Permian boundary, Permo-Triassic boundary, Triassic- Jurassic boundary, K-T boundary, and Eocene- Miocene boundary. Infra-Cambrian Salt Range Formation is generally considered as probable source rock as it has attained maturity in the area (Hasany et al. 2007). The depositional styles of the stratigraphic succession of the study area can be divided into different Tectono-stratigraphic episodes, which include pre-rift, syn-rift, post-rift, and post-collision phases. The stratigraphic section developed based on drilled wells and seismic reflection data depicts that marine Paleozoic-Cenozoic rocks comprised of carbonates and clastic rocks dominate with some depositional gaps (Raza et al. 2008). The Pre-Cambrian basement rocks are composed of granites, unfossiliferous metasediments, and metavolcanic. The salt range formation is unconformably overlying the basement. The Jhelum group is conformably underlain by Salt range formation. Jhelum Group includes the Khewra, Kussak, Jutana, and Baghanwala formations. Seismic image and well data reveal that Cambrian and infra-Cambrian strata thinning towards the southwest and



is thickening in the northeast direction (Khalid et al. 2014). The rift associated faults form horst and graben in a north-south direction are visible on seismic data of the Punjab platform (ZAIDI et al. 2012). The top of Lumshiwal Formation can be designated as the K-T boundary in the study area, keeping in view that the Lumshiwal Formation uncomfortably lies below Paleocene Ranikot Formation and overlying Chichali Formation of Cretaceous age. The Lumshiwal Formation is comprised of sand and shale sequences with increasing sand content towards the top (Arif et al. 2009; Kadri, 1995). It is comprised of multiple coarsening upwards cycles of clastic sediments with varying

Figure. 3 Schematic cross-section of middle Indus Basin (After Kadri, 1995).

thicknesses. Figure. 02 represents Mesozoic stratigraphic of northern and southern parts of Punjab Platform.

The major targets for hydrocarbon exploration activities carried out in the study area were focused in Palaeozoic and Mesozoic reservoirs, including Datta, Shinawari, Samana Suk and Lumshiwal Formation. In the Punjab Platform area, hydrocarbon exploration activities are still in progress and three gas fields are discovered in the area i.e. Nandpur, Panjpir, and Bahu gas fields. The clean sandstones of Lumshiwal Formation which have good reservoir quality are producing hydrocarbons in these gas fields of the Punjab Platform. The success ratio in the study area is very low, which makes it a high risk area for hydrocarbon exploration (Khalid et al. 2014).

3.Materials and Methodology:

Geochemical analyses and basin modeling were carried out to evaluate the hydrocarbon generating potential of Cretaceous source rock in the Punjab Platform area of the Middle Indus Basin. To achieve this purpose, well data of 03 exploration wells (well- A, B & Z) were utilized to evaluate the burial and thermal history of the area. Rock eval pyrolysis data, kinetics data, corrected BHT, geothermal gradient, and vitrinite reflectance values of wells A, B, and Z was incorporated to construct the burial and thermal history models for hydrocarbon generation and migration modeling of cretaceous source rock Chichali/ Sembar Formation. To conduct this study, the exploration module of the Petrel Software 2017 version by Schlumberger was used. The basic input data required include stratigraphy, formation thickness, formation tops, absolute ages, lithology, and petroleum system

	Period	Facies	Code	Color	Lithology group	Lithology	Petroleum system elen	Kinetics group	Kinetics	TOC [%]	HI [unitless]
	ALLUVIUM	ALLUVIUM	0		PUNJAB PLATFORI	ALLUVIUM	Overburden Rock				
2	SIWALIKS	SIWALIKS	1		PUNJAB PLATFORI	NAGRI	Overburden Rock				
3	KIRTHAR	KIRTHAR	2		PUNJAB PLATFORI	SAKESAR	Overburden Rock				
4	DRAZINDA	DRAZINDA	3		PUNJAB PLATFORI	DRAZINDA	Overburden Rock				
5	PIRKOH	PIRKOH	4		PUNJAB PLATFORI	PIRKOH	Overburden Rock				
6	SRIKI	HRL	5		PUNJAB PLATFORI	HRL	Overburden Rock				
7	HRL	SIRKI	6		PUNJAB PLATFORI	DRAZINDA	Overburden Rock				
8	GHAZIJ	GHAZIJ	7		PUNJAB PLATFORI	GHAZIJ	Overburden Rock				
9	GHAZIJ SHALE	GHAZIJ SHALE	8		PUNJAB PLATFORI	GHAZIJ	Overburden Rock				
10	SUL	SUL	9		PUNJAB PLATFORI	SAKESAR	Overburden Rock				
11	SML	SML	10		PUNJAB PLATFORI	SAKESAR	Overburden Rock				
12	DUNGHAN	DUNGHAN	11		PUNJAB PLATFORI	DUNGHAN	Overburden Rock				
13	RANIKOT	RANIKOT	12		PUNJAB PLATFORI	RANIKOT	Seal Rock				
14	PAB SANDSTONE	PAB SANDSTONE	13		PUNJAB PLATFORI	PAB SANDSTONE	Reservoir Rock				
15	KAWAGARH	KAWAGARH	14		PUNJAB PLATFORI	KAWAGARH	Seal Rock				
16	LUMSHIWAL	LUMSHIWAL	15		PUNJAB PLATFORI	LUMSHIWAL	Reservoir Rock				
17	CHICHALI	CHICHALI	16		PUNJAB PLATFORI	CHICHALI	Source Rock	Kerogen-oil-gas	Behar_et_al(1997)_1	1.50	200.00
18	SAMANA SUK	SAMANA SUK	17		PUNJAB PLATFORI	SAMANA SUK	Reservoir Rock				
19	SHINAWARI	SHINAWARI	18		PUNJAB PLATFORI	SHINAWARI	Reservoir Rock				
20	DATTA	DATTA	19		PUNJAB PLATFORI	DATTA	Reservoir Rock				
21	KINGRIALI	KINGRIALI	20		PUNJAB PLATFORI	KINGRIALI	Reservoir Rock				
22	TREDIAN	TREDIAN	21		PUNJAB PLATFORI	TREDIAN	Overburden Rock				
23	MIANWALI	MIANWALI	22		PUNJAB PLATFORI	MIANWALI	Overburden Rock				
24	CHHIDRU	CHHIDRU	23		PUNJAB PLATFORI	CHHIDRU	Overburden Rock				
25	WARGAL	WARGAL	24		PUNJAB PLATFORI	WARGAL	Overburden Rock				
26	AMB	AMB	25		PUNJAB PLATFORI	AMB	Overburden Rock				
27	SARDHAI	SARDHAI	26		PUNJAB PLATFORI	SARDHAI	Source Rock	Kerogen-oil-gas	Behar_et_al(1997)_1	1.00	100.00
28	WARCHHA	WARCHHA	27		PUNJAB PLATFORI	WARCHHA	Overburden Rock				
29	DANDOT	DANDOT	28		PUNJAB PLATFORI	DANDOT	Overburden Rock				
30	TOBRA	TOBRA	29		PUNJAB PLATFORI	TOBRA	Overburden Rock				
31	BAGHANWALA	BAGHANWALA	30		PUNJAB PLATFORI	BAGHANWALA	Overburden Rock				
32	JUTANA	JUTANA	31		PUNJAB PLATFORI	JUTANA	Overburden Rock				
33	KUSSAK	KUSSAK	32		PUNJAB PLATFORI	KUSSAK	Overburden Rock				
34	KHEWRA	KHEWRA	33		PUNJAB PLATFORI	KHEWRA	Reservoir Rock				
35	SALT RANGE	SALT RANGE	34		PUNJAB PLATFORI	SALT RANGE	Source Rock	Kerogen-oil-gas	Behar_et_al(1997)_1	2.00	200.00

information. Wireline data is very important in the evaluation of source rock maturation because it provides information on lithology, generation, compaction, erosional amount, and borehole temperature BHT and mud weight.

Table 1 depicts the heat capacity, thermal conductivity, initial porosity, compressibility and average bulk density of the layers. While Figure-4 shows a facies table with facies, kinetics, TOC and petroleum system elements assigned to all wells.

Paleo-bathymetry inputs were carried out by using depositional environments of each lithological horizon, which

Figure. 4 Facies Table and PSE assigned to the studied wells

show that water depths were generally low during the

Mesozoic (about 50 to 200 m), and were very low during the Late Paleogene (0 to about 50 m). Surface water Interface temperatures (SWIT) were used after Wygrala (Wygrala, 1989). The average thermal conductivity of the rocks was incorporated by using percentage lithologies.

Heat flow is a very essential parameter as a boundary condition in hydrocarbon maturity modeling and there are many methods available to calculate this parameter (Gallagher and Sambridge, 1992; Lachenbruch, 1970). Heat flow is calculated by the formula known as heat flow equation as given below:

$$Q = \lambda \frac{\Delta T}{\Delta Z} \quad (3)$$

Whereas, λ is a thermal conductivity of rock and $\frac{\Delta T}{\Delta Z}$ is the geothermal gradient.

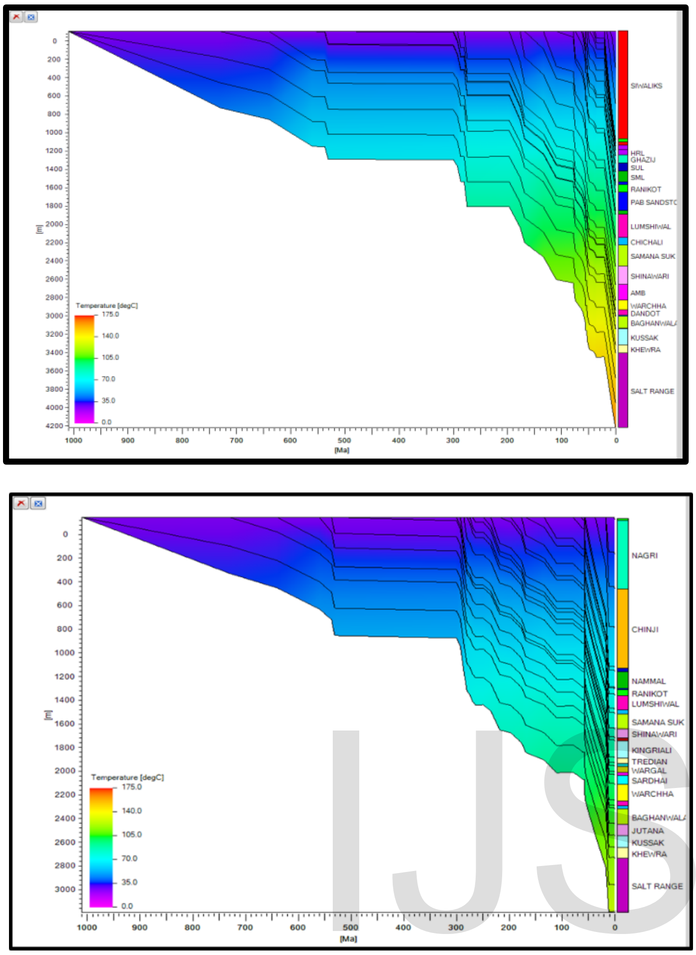
For the present study, heat flow calculated by using the above equation by incorporating geothermal gradient after corrected borehole temperature and conductivity data, heat flow ranged from 55 to 60 MW/m2, which is in correspondence with maturity data.

The thermal and burial models can be integrated with geochemical data of the Cretaceous source-rock interval, to simulate hydrocarbon generation and expulsion over time. The kinetic parameters and the geochemical characteristics of the organic matter were utilized using the model of Behar et al.1997 to simulate hydrocarbon generation from the source rock.

4.Results and Discussions

Multi 1D Basin modeling was performed using geological field data, well logs, well tops, and geochemical data to calculate burial and thermal history and to incorporate both burial and thermal models with kinetics data to calculate petroleum expulsion timings for Middle Indus Basin. Burial history curves for three exploratory wells well - A, well - B, and well - Z were constructed by using well data. The net compaction is the result of the overburden of overlying strata and sedimentation rate (Hlaiem, 1997; Handhal 2020). In the Middle Indus Basin, compaction is highly affected by Neogene molasses deposition, which caused molasses deposition in Miocene and post-Miocene.

By interpreting the aforementioned subsidence curves, four stages (A, B, and C) of subsidence can be distinguished between the Cambrian and the present at wells A, B, and Z (Fig. 5). Numerical simulations of the wells (Fig. 5) indicate that subsidence from Cambrian to Early Permian (Phase A) was characterized by deposition of Salt Range formation and clastics along with some carbonates of Cambrian strata. After Cambrian, there is unconformity where Ordovician to Carboniferous strata is missing. Then B-stage starts with the deposition of glacial deposits of Tobra Formation showing the end of an ice age and this phase continued till cretaceous time. This phase is characterized by relatively low burial rates (6-11 meters per million years (m/MM yr) in Well - A). This phase of subsidence is related to Tethyan rifting associated with the breakup of Gondwana as recognized by previous studies (Biju-Duval et al., 1977;

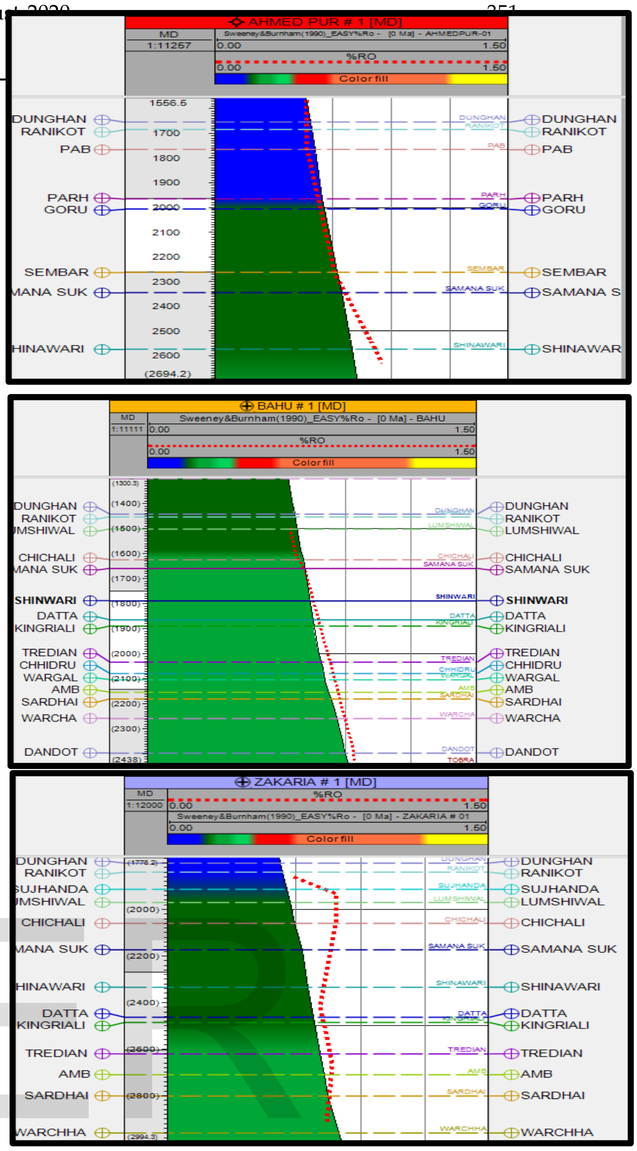


Burrus et al., 1987; Dercourt et al., 1992). However, the impact of rifting in the Middle Indus Basin is very less depicted by seismic data. By early Paleocene (63 Ma), subsidence curves show an inflection, after which their gradient increases as the subsidence rate averages 100 m/MM yr. This period (Phase B) represents a principal phase of the Indian-Eurasian collision, which started to occur at this time (Kazmi and Jan 1997). Phase C represents a sudden increase in burial depths as characterized by high sedimentation rates of molasses (around 250 m/MM yr) during Himalayan orogeny (Figure. 5).

Figure. 5 Burial history of Well A, B & Z

1D models were simulated and calibrated by using the actual vitrinite reflectance (%Ro) data from the laboratory analysis on selected core and drill cutting samples (Figure. 05). Multiple heat flows were simulated for input parameters to

delineate the best fit paleo heat, flow model. Based on our simulations for wells A, B, and Z, an average heat flow of 55 to 60 ± 2 mW/m2 yielded the best fit matches for actual %Ro values and corrected borehole temperature data. Possible errors in the heat flow calculations may arise from errors in



thermal conductivity, formation depths, bottom hole, and surface temperature data (Chapman et al., 1984).

In the Middle Indus Basin, the shales of the Cretaceous source rock (Chichali Formation) constitute the most promising source-rock intervals. These shales are sufficiently mature and are associated with several gases and oil shows which have been encountered in various parts of the Middle Indus Basin (Kadri, 1995).

The organic facies based source rock kinetic models (Behar et al. 1997) shows that the Early Cretaceous source rocks entered

Figure. 6 Calibration of Maturity data (%Ro of the lab and modeled % Ro).

the "oil window" (Ro = 0.7%) at about 13 Ma

(Table-02). Significant expulsion of hydrocarbons is predicted to have started in 10 MA (Figures. 7 & 8). This delay is probably due to either erosion of molasses overburden as a result of basement uplift along with Sargodha High or differences in burial between the margin and the center of the basin.

Comparative analysis of wells proves that Cretaceous source rock achieved maturity after the deposition of molasse sequence and thus directly associated with Himalayan orogeny.

Using these geothermal parameters and a numerical modeling procedure, we have attempted to study the burial history of organic matter and the timing of oil expulsion in the study area. These results are of particular relevance to petroleum exploration because hydrocarbon expulsion continued until the Quaternary.Hydrocarbon generation, expulsion and migration analysis by using 1D basin models even after calibration by present-day temperatures obtained from well logs and DST charts along with vitrinite reflectance data is a challenging job and is always subject to error. This is probably due to errors in erosion calculations and parameters used for modeling including thermal conductivity of different rock lithologies, as the 1D model assumes vertical heat flow only ignoring lateral heat flow. Despite these limitations, the 1D model still provides valuable information regarding hydrocarbon generation, expulsion, and migration history. In the present study, various scenarios were tested using different boundary conditions and amount of erosion before finalizing the most acceptable scenario, which was close to the calibration data.

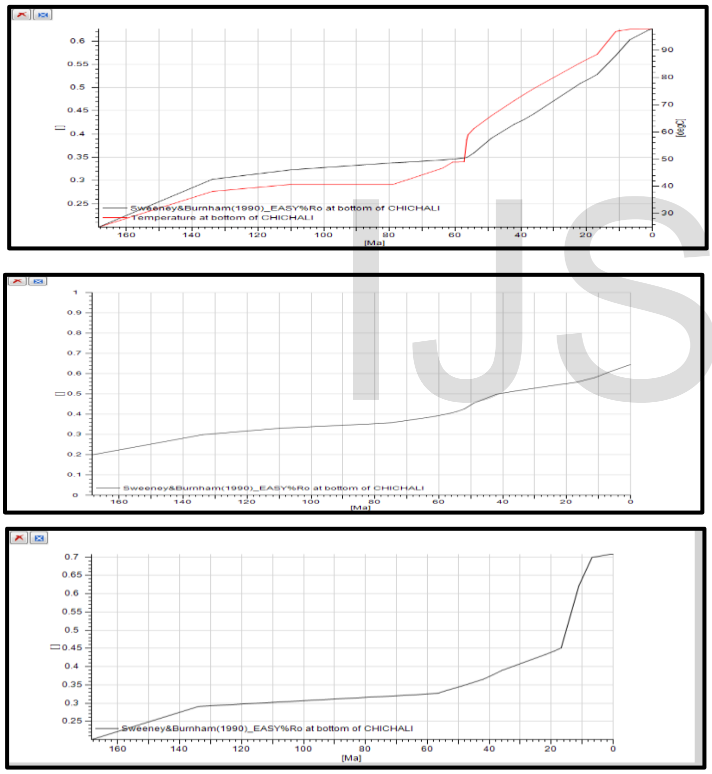


Figure. 7 Time versus Maturity evolution of well – A, B & Z

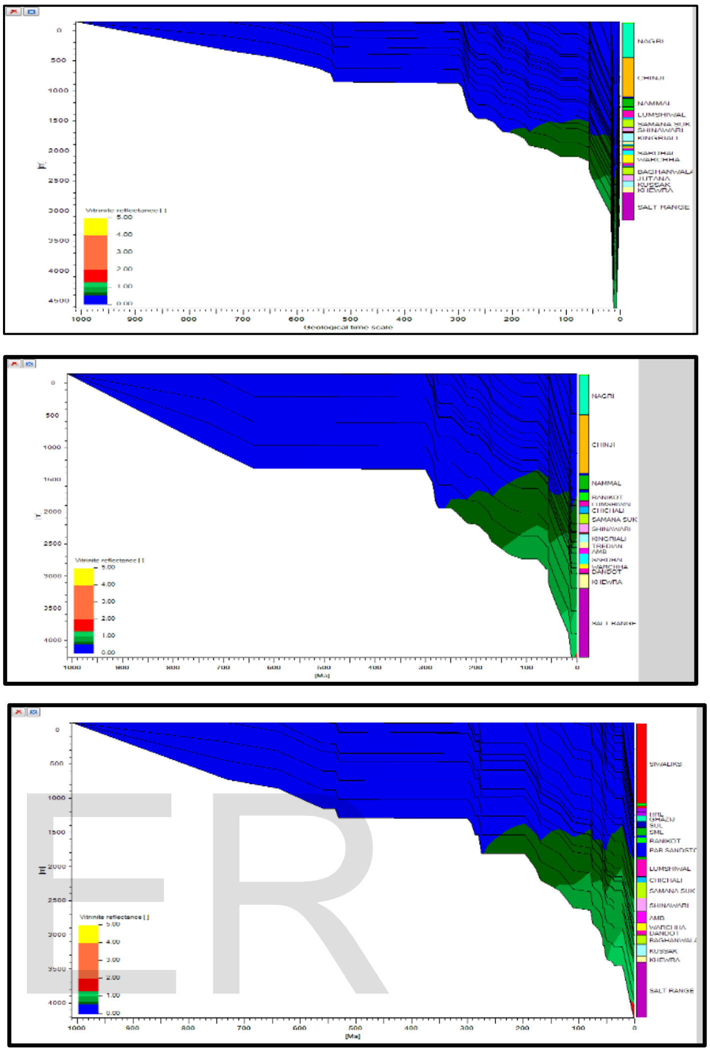


Figure. 8 Burial history overlaid with maturity data of studied wells.

The study shows that there is much uncertainty involved regarding source rock organic richness and kinetics which can describe the hydrocarbon generation and expulsion. This uncertainty can be resolved by acquiring new high-resolution geochemical data including vitrinite reflectance data. Proper 2D and 3D basin modeling can also improve the results.

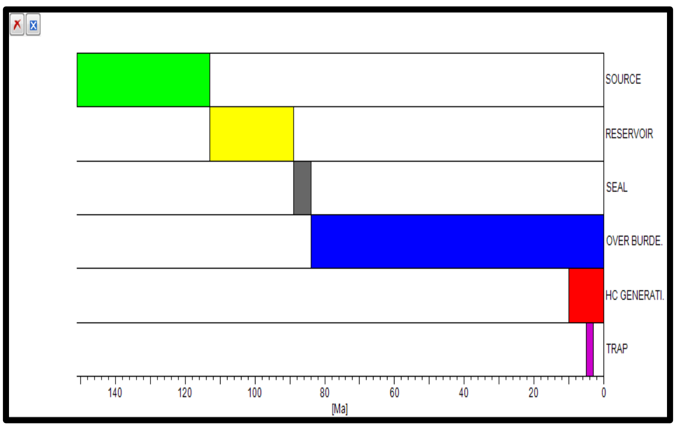


Figure. 9 Petroleum system elements chart of studied wells.

5. CONCLUSIONS

In the basin modeling, burial and thermal history modeling are conducted based on some assumptions e.g. heat flow is steady or transient. In the present study, we have used a steady-state method for evaluation of paleo heat flow, which is based on current flow calculated by using BHT data and geothermal gradient maps. Thermal conductivities of different lithologies were used as default values provided by the software based on litho-types keeping in view the published literature. The present geothermal gradient in the area ranges from 2.4oC/100m to 2.6oC/100m, while the Present heat flow is approximately 55 + 2 mW/m2.

Following findings are attributed to this work:

- Burial history shows that the area faced steady subsidence to the Paleocene until the collision of the Indian Plate with Eurasian in the Late Paleocene-Early Eocene. Then, in the Early Miocene, subsidence triggered due to the rapid deposition of molasses deposit in the Foreland Basin.
- High sedimentation rates in the Paleogene and the Neogene depicts rapid deposition of Molasses sediments in the Middle Indus Basin, which may have contributed to source rock maturity in the region.
- The calculated heat flow based on present heat flow is approximately 55 to 60 +2 mW/M2. This heat flow has been calibrated by using maturity and thermal data i.e. vitrinite reflectance and corrected borehole temperatures.
- The Chichali Formation falls in the early oil maturity window in well A and B while in well –Z, it lies in the late oil generative window.
- The present study shows that the Chichali Formation of Cretaceous age entered into oil window in 13 ma, which well corresponds to suitable overburden provision by high sedimentation rate induced by tectonic activities.
- It is recommended that more maturity data must be acquired to calibrate basin models. Further, 2D and 3D models along with incorporating thrust models should be constructed to evaluate the hydrocarbon generation, expulsion, and migration history.
- It is suggested to acquire biomarkers data for source rock to oil correlation for a better understanding of the petroleum generation history of the basin and mitigating risk and uncertainty.

6. REFERENCES

[1] Aitchison, J. C., Ali, J. R., & Davis, A. M. (2007). When and where did India and Asia collide? Journal of Geophysical Research, 112(B5), 1–19. https://doi.org/10.1029/2006jb004706

[2] Baniasad, A., Sachse, V., Littke, R., & Soleimany, B. (2019). Burial, Temperature And Maturation History Of Cretaceous Source Rocks In The NW Persian Gulf, Offshore SW Iran: 3D Basin Modelling. Journal of Petroleum Geology, 42(2), 125–144. https://doi.org/10.1111/jpg.12727

[3] Behar, F., Vandenbroucke, M., Tang, Y., Marquis, F., & Espitalie, J. (1997). Thermal cracking of kerogen in open and closed systems: determination of kinetic parameters and stoichiometric coefficients for oil and gas generation. Organic Geochemistry, 26(5–6), 321–339. https://doi.org/10.1016/s0146-6380(97)00014-4

[4] Bessis, F., 1986, some remarks on subsidence study of sedimentary basins: application to the Gulf of Lions margin (Western Mediterranean): Marine and Petroleum Geology, v. 3, no. 1, pp. 37–63.

[5] Biju-Duval, B., Dercourt, J., and Le Pichon, X., 1977, From the Tethys Ocean to Mediterranean Seas: a plate tectonic model of the Western Alpine system. International Symposium on Structural History of the Mediterranean Basins, Split (Yugoslavia): Editions *Technip*, 143–164 pp.

[6] Bouilhol, P., Jagoutz, O., Hanchar, J. M., & Dudas, F. O. (2013). Dating the India–Eurasia collision through arc magmatic records. Earth and Planetary Science Letters, 366, 163–175. https://doi.org/10.1016/j.epsl.2013.01.023

[7] Burus, J., Bessis, F., and Doligez, B., 1987, Heat flow, subsidence and crustal structure of the Gulf of Lions, NW Mediterranean: a quantitative discussion of the classic passive margin model. In: Beaumont, C. and Tankard, A., (Eds.): Sedimentary basins and basin forming mechanisms: Canadian Society of Petroleum Geologist Memoir, v. 12, 1–16.

[8] Chapman, D. S., Keho, T. H., Bauer, M. S., & Picard, M. D. (1984). Heat flow in the Uinta Basin determined from bottom hole temperature (BHT) data. GEOPHYSICS, 49(4), 453–466. https://doi.org/10.1190/1.1441680

[9] Dercourt J., Bassoulet J.P., Baud A., Butterlin J., Camoin G., Cavalie C., Cacca, F., Enay R., Fourcade E., Guiraud R., Lorenz C., Marcoux J., Masse J.P., Orgaz, F., and Philip, J., 1992, Paleoenvironmental atlas of the Tethys from Permian to Recent: 28th International Geological Congress, Kyoto, Japan: Proceedings, I-3-24, v. 1, pp. 116.

[10] Gallagher, K., & Sambridge, M. (1992). The resolution of past heat flow in sedimentary basins from non-linear inversion of geochemical data: the smoothest model approach, with synthetic examples. Geophysical Journal International, 109(1), 78–95. https://doi.org/10.1111/j.1365-246x.1992.tb00080.x

[11] Gansser, A. (1981). The geodynamic history of the Himalaya. Zagros, Hindu Kush, Himalaya: Geodynamic Evolution, 111–121. https://doi.org/10.1029/gd003p0111

[12] Handhal AM. Al-Shawhan MF. Chafeet HA. 2020. Interpretation of Hydrocarbon Generation, Migration And Thermal History Of Mesopotamian Basin Southern Iraq Based 1d Petromod Software. Iraqi Geological Journal. Vol.53, No.1B, 2020.

[13] Hasany, .S.T.; Aftab, M.; Siddiqui, S.A.: Refound Exploration Opportunities in Infracambrian and Cambrian Sediments of Punjab Platform, Pakistan,

PAPG Annual Technical Conference 2007, Islamabad, Pakistan, March 27-28, (2007)

[14] Hlaiem, A., Biju-Duval, B., Vially, R., Laatar, E., & M'Rabet, A. (1997). Burial And Thermal History Modelling of The Gafsa-Metlaoui Intracontinental Basin (Southern Tunisia): Implications For Petroleum Exploration. Journal of Petroleum Geology, 20(4), 403–426. https://doi.org/10.1111/j.1747-5457.1997.tb00924.x

[15] Iqbal, M.W.A. Shah, S.M.I. 1980. A guide to the stratigraphy of Pakistan. Geological Survey of Pakistan records. Quetta. V3. P.34.

[16] Kadri I.B., 1995, Petroleum Geology of Pakistan, Karachi: Pakistan Petroleum Limited., 273-274.

[17] Kazmi, A.H., and Jan, M.Q., 1997, Geology and tectonics of Pakistan: Graphics Publishers, 352–355 pp.

[18] Khan, M.A., Ahmed, R., Raza, H.A., and Kemal, A., 1986, Geology of petroleum in Middle Indus-Potwar depression, Pakistan: AAPG Bulletin, v. 70, pp. 396–414.

[19] Khalid, P.; Naeem, M.; Afzal, MH; Zia, Uddin; Yasin.: Petroleum Play Analysis, Structural And Stratigraphic Interpretation Of Cretaceous Sequence, Punjab Platform, Central Indus Basin, Pakistan, Sci. Int (Lahore), 26(4):2163-2171 (2014).

[20] Klootwijk, C. T., Gee, J. S., Peirce, J. W., Smith, G. M., & McFadden, P. L. (1992). An early India-Asia contact: Paleomagnetic constraints from Ninetyeast Ridge, ODP Leg 121. Geology, 20(5), 395.

[21] Lachenbruch, A. H. (1970). Crustal temperature and heat production: Implications of the linear heat-flow relation. Journal of Geophysical Research, 75(17), 3291–3300. https://doi.org/10.1029/jb075i017p03291

[22] Lee, T.-Y., & Lawver, L. A. (1995). Cenozoic plate reconstruction of Southeast Asia. Tectonophysics, 251(1–4), 85–138. https://doi.org/10.1016/0040-1951(95)00023-2

[23] Qureshi, M.K.A, Ghazi, S., Butt, A.A, Ahmad, N., and Masood, K.R., 2007, Micro-facies Analysis and the environmental pattern of the Chichali Formation, Kala Chitta Range, Pakistan: Geological Bulletin of Punjab University, v. 42, pp. 53-59.

[24] Raza, H.A.; Ahmed, W.; Ali, S.M.; Mujtaba, M.; Alam, S.; Shafeeq, M.; Iqbal, M.; Noor, I.; Riaz, N.: Hydrocarbon Prospects of Punjab Platform Pakistan, With Special Reference To Bikaner-Nagaur Basin of India. Pakistan Journal of Hydrocarbon Research 18, 1–33 (2008)

[25] Raza, S.M. 2001, Stratigraphic chart of Pakistan: Geological Survey of Pakistan, 89–95 pp.

[26] Roberts, A. M., Kusznir, N. J., Yielding, G., & Styles, P. (1998). 2D flexural back stripping of extensional basins; the need for a sideways glance. Petroleum Geoscience, 4(4), 327–338. https://doi.org/10.1144/petgeo.4.4.327

[27] Steckler, M. S., & Watts, A. B. (1978). Subsidence of the Atlantic-type continental margin off New York. Earth and Planetary Science Letters, 41(1), 1–13. https://doi.org/10.1016/0012-821x(78)90036-5

[28] Stecklerl, M. S., & Watts, A. B. (1982). Subsidence history and tectonic evolution of Atlantic-type continental margins. Dynamics of Passive Margins, 184–196. https://doi.org/10.1029/gd006p0184

[29] Wygrala, B. (1989, June 26). Integrated Study of an Oil field in the Southern Po Basin, Northern Italy. Retrieved from http://juser.fz-juelich.de/record/153416

[30] Zaidi S.N.A., Brohi I. A. Ramzan K, Ahmed N., Mehmood F. Brohi A.U. 2012. Evaluation of Infra-Cambrian Plays in Punjab Platform. Sindh Univ. Res. Jour. (Sci. Ser.) Vol.44 (4) 549-554 (2012).