



Organic richness and maturity modeling of cretaceous age Chichali shales for enhanced hydrocarbon exploration in Punjab platform, Pakistan

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Abstract

This study employs comprehensive source rock evaluation using seismic inversion, rock-eval pyrolysis, organic petrography and basin modeling techniques. The kerogen type is determined by using the Van Krevelen diagram, confirming Bahu-01, Nandpur-01 and Zakria-01 wells have kerogen type III, whereas Panjpir-01 well exhibits kerogen type II to III. The TOC was calculated using core data from (34) samples by employing organic geochemistry technique and post stack seismic inversion, applied on 2D seismic data. Bahu-01 well indicates poor source rock potential, with an average TOC value of 0.34%. In contrast, Panjpir-01 and Nandpur-01 wells represent moderate to good organic richness, with average TOC values of 1.25% and 1.36%, respectively. However, Zakria-01 well with a TOC of 0.72%, exhibits fair organic richness. The Maturity estimation from organic petrography and basin modeling reveals that the Bahu-01, Panjpir-01, and Nandpur-01 wells have average vitrinite reflectance (%Ro) values below 0.50, indicating immature source rock. In contrast, the average %Ro value for the Zakria-01 well is 0.63, confirming the source maturity in the early oil window, with peak generation occurring during Eocene age. Finally, the source rock evaluation proves the source is mature in the western part only and future hydrocarbon exploration should be focused in the western area. The integrated source rock evaluation approach is novel in Punjab Platform. The diverse methodologies enhanced our understanding about source rock characteristics for pursuing hydrocarbon resources. An integrated approach will also provide valuable insights for hydrocarbon exploration in numerous other basins worldwide.

Keywords Punjab platform · Organic richness · Thermal maturity · Seismic inversion · Basin modeling

Introduction

The continuous instability of the global energy market, coupled with increased consumption has led to a significant rise in the worldwide demand for oil and gas (Ayorinde et al. 2024). The demand for energy is projected to rise at a rate of 41% between 2012 and 2035 (Sohail et al. 2024). Meeting the gap between production and consumption requires aggressive exploration activities (Latief and Lefen 2019).

For carrying aggressive hydrocarbon exploration for reservoir quality prediction and identification of sweet spots, it is important to understand the economic importance of the petroleum system (Ashraf et al. 2020, 2024). The petroleum system includes the accumulation, conversion and migration of hydrocarbon into a reservoir from source rock over sufficient geologic time. These processes occurred under adequate burial depth and temperature pressure conditions. Now within the petroleum system, source rock evaluation represents a critical step that demands meticulous attention. The assessment of source rock potential includes the elucidation of organic richness, kerogen type, and thermal maturation (Cappuccio et al. 2021; Ehsan et al. 2024).

The complexities regarding the source rock evaluation can be resolved by integrated approach using various methodologies including organic geochemistry, petrography and basin modeling. Xiao et al. (2024) evaluated the organic

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richness by using an organic geochemistry approach. The variation of source rock characteristics is resolved in Punjab Platform which is located in Central Indus sub basin, Pakistan. In study area, limited hydrocarbon has been explored despite of aggressive exploration activities. Thirty exploratory wells have gone dry in the region. Only three fields (Bahu, Panjpir and Nandpur) are producing gas. The petroleum system in this location predominantly comprises of Cretaceous Chichali as potential source rock. Uncertainties related to source rock richness and maturation are main hindrances for substantial hydrocarbon exploration which could add size-able reserves. In the past several authors including (Gakkhar et al. 2011; Nazeer et al. 2018; Shah et al. 2021) evaluated the source rock potential predominantly by using single technique. It restricted them to completely evaluate the source rock potential for enhanced hydrocarbon exploration specially in western part of Punjab Platform, where limited data is available. TOC can be derived from seismic inversion technique (Atarita et al. 2017). To circumvent data limitation in western part of study area, seismic inversion techniques are used for Chichali Shales. For Chichali Shales, total organic carbon (TOC, wt%) content was derived both from lab analysis using core data and from seismic inversion through the application of the stochastic seismic inversion technique on post-stack seismic data. Mahmood et al. (2018) also determined TOC from seismic amplitude response in Lower Indus Sub Basin, Pakistan. Ali et al. (2023a) explained the way to establish relationships between various rock attributes and rock physics models is via controlled experiments by simple cross-plotting.

Besides seismic, well logs are very useful for calculating TOC in potential source rocks. It is possible to detect source rocks with wireline logs, which may also be utilized as an indicator of the potential of the source rocks. By correlating sonic logs with seismic data, it is possible to gain a better understanding of the lithology, structure, and stratigraphy of the subsurface (Ali et al. 2023a). Ullah et al. (2023) examined the distribution of minerals and their thermal properties. The natural radiation emitted from the minerals within the geological formations is quite beneficial in detecting the lithological variations through the Gamma Ray (GR) log (Ali et al. 2024). Also, organic petrography is considered one of the most reliable and precise techniques for assessing source rock maturity (Wilkins et al. 2018). Source rock thermal maturity in term of vitrinite Reflectance (%Ro) can be calculated from core samples (Hakimi et al. 2023). In this study, source rock thermal maturity was calculated from core samples. The maturity and timing of source maturation were also calculated from the 1D basin modelling, it involves the construction of burial history and source rock maturation levels. This method considers several parameters, including hydrogen Index (HI), oxygen index (OI),

temperature maximum (T_{max}), TOC, heat flow (HF), paleo water depth (PWD), surface water interface temperature (SWIT), formation depth and formation thickness to calculate modeled %Ro (Cheng et al. 2024).

The explorationists' primary obstacle in locating substantial resources is the variation in source rock richness and maturation. Mousa et al. (2024) assessed the hydrocarbon potential through seismic and geochemical analysis. Liu et al. (2024) used geochemical methods for the hydrocarbon generation remained unexplored potential. To assess the hydrocarbon potential in Punjab Platform, it is necessary to understand the source rock variation in terms of organic richness, maturity, and timing of hydrocarbon expulsion. To address this challenge comprehensive source rock evaluation of Chichali Shales is adopted by using different techniques such as seismic inversion, rock-eval pyrolysis, organic petrography and basin modeling. It results in source rock uncertainty mitigation which will help the exploration companies to add sizeable reserves in near future.

Geology and stratigraphy of the area

The Punjab Platform is a key geological feature, located in Pakistan's Middle Indus Basin. It is located on the western slope of the Indian Shield, this region exhibits structural stability in the form of a continuous monocline (Khalid et al. 2014). Geographically, it is bordered by the Sargodha high to the north, the Mari high to the south and the Sulaiman Depression to the west (Fig. 1). Its eastern boundary extends to the Bikaner Nagaur Basin in India (Raza et al. 1989). Notably, the Punjab Platform gradually descends westward from the Indian Shield to the Mesozoic to Tertiary core of the Sulaiman Depression (Aadil and Sohail 2011). During the Late Proterozoic era, the Indian Plate which was a part of the Gondwanaland supercontinent underwent significant geological changes (Kemal et al. 1991). Rift-related faulting during this period had a discernible impact on the seismic profiles of the Bikaner Nagaur Basin in India. In contrast, although the Punjab Platform does show normal faults, their displacement is relatively minor. The Precambrian basement in the study area is characterized by non-fossiliferous metavolcanics, metasediments, and granites. The overburden sedimentary sequence has undergone several cycles of sea level regression and transgression, resulting in age-specific unconformities. In the southern part of the study area, these strata were later folded to form anticlines with salt cores (Kadri 1995).

Apart from understanding tectonic evolution, petroleum system elements are equally important for hydrocarbon exploration (Ehsan et al. 2023). A petroleum system is characterized by a genetic connection that connects a source rock

Fig. 1 (a) Tectonic map shows major tectonic elements. Punjab platform is part of Indus basin (Raza et al. 2008) (b) Black color box shows the location of study area which mainly lies in Punjab Platform, Pakistan. Study area is bounded by Sulaiman Foredeep in west, Sargodha high in north and Mari Kandkot high in south

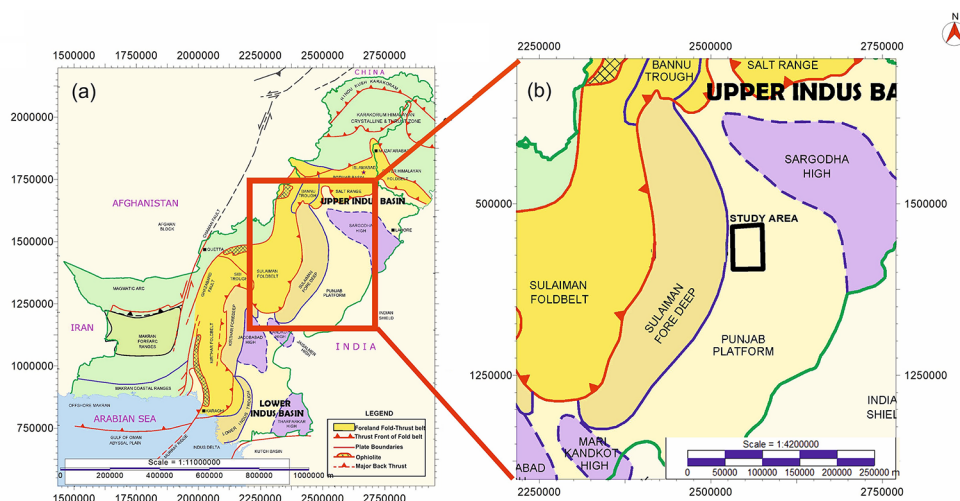


Fig. 2 Represents the petroleum system elements of Punjab Platform. Chichali Shales are the source rock lies in late Cretaceous age. Lumshiwai sandstone acts as main reservoir, with Ranikot Formation providing seal to cretaceous reservoirs (Malkani and Mahmood 2016)

Age	Formaion	DESCRIPTION	SOURCE	RESERVOIR	SEAL
PALEO CENE	Late DUNGHAN	Limestone, Shale			
	Early RANIKOT	Shale			
CRETACEOUS	SUJHANDA	Limestone, Sandstone, Shale			
	Early LUMSHIWAL	Sandstone, Shale & Traces of Limestone			
	CHICALI	Shale			
JURASSIC	Mid SAMANASUK	Limestone, Shale			
	SHINAWARI	Sandstone, Shale			
	Early DATTA	Sandstone, Shale			

to all of the oil and gas that it has produced. Additionally, a petroleum system is comprised of all of the geologic materials and processes that are necessary for the production of petroleum accumulation (Fig. 2). The petroleum system in this area primarily includes Cretaceous and Infra-Cambrian rock formations. Among these, the Chichli formation of late Cretaceous age stands out as a potential source rock. It is composed of glauconitic shale that has dark greenish gray color. Lumshiwai formation of early cretaceous age is a proven reservoir in study area. It consists of cross bedded sandstone and is deposited in a coastal marine environment. Ranikot formation of early Paleocene age act as the seal rock for Lumshiwai reservoir. The Punjab Platform, next to the Bikaner Nagaur Basin in India hosts considerable reserves that remain unexplored (Raza et al. 2008). Notably, this region also boasts of exploring the hydrocarbon in vicinity of Bahu, Panjpir, and Nandpur gas fields (Shah 2023). The possible source rock, Chichali shale is buried deep in the western part of the Punjab Platform.

Data and methods

To assess the source rock potential of Chichali shales, we conducted a detailed study that involved the interpretation of 2D seismic data covering 765 line kilometers across the entire study area (Fig. 3). Acquisition parameter of 2D seismic utilized for this study has source and receiver interval of 50 m. The fold of the 2D seismic data is 100. The quality of the seismic data in the region varied from fair to good. We obtained a total of thirty-four core samples from the Cretaceous shale of the Chichali Formation, these samples were collected from four wells namely Bahu-01, Panjpir-01, Nandpur-01, and Zakria-01. Detailed information on these samples can be found in the appendix (Table 1). We performed analyses for TOC and Rock-Eval on thirty-four core samples of Chichali Shales in G&R lab, Pakistan. Additionally vitrinite reflectance (%Ro) analysis was carried at Hydrocarbon Development Institute of Pakistan lab (Table 2).

This research adopted a comprehensive approach for evaluating the source rock potential of the Chichali Shales

Table 1 Rock-Eval and TOC analysis results from core samples of cretaceous Chichali Shale

Sr.no	Well name	Sample name	(TOC, wt%)	HI (mg/g)	OI (mg/g)
1	Bahu-01	Sample 1	0.41	110	120
2	Bahu-01	Sample 2	0.25	98	100
3	Bahu-01	Sample 3	0.37	114	190
4	Panjpir-01	Sample 1	1.20	83	43
5	Panjpir-01	Sample 2	1.54	124	28
6	Panjpir-01	Sample 3	1.02	125	47
7	Panjpir-01	Sample 4	1.53	75	50
8	Panjpir-01	Sample 5	1.42	101	48
9	Panjpir-01	Sample 6	1.02	302	67
10	Panjpir-01	Sample 7	1.40	138	41
11	Panjpir-01	Sample 8	1.34	128	51
12	Panjpir-01	Sample 9	1.21	163	40
13	Panjpir-01	Sample 10	1.23	160	82
14	Panjpir-01	Sample 11	0.99	119	45
15	Panjpir-01	Sample 12	1.10	103	37
16	Nandpur-01	Sample 1	2.01	11	54
17	Nandpur-01	Sample 2	2.57	38	69
18	Nandpur-01	Sample 3	1.81	6	60
19	Nandpur-01	Sample 4	1.14	6	93
20	Nandpur-01	Sample 5	1.21	8	88
21	Nandpur-01	Sample 6	1.65	6	64
22	Nandpur-01	Sample 7	1.20	47	136
23	Nandpur-01	Sample 8	1.78	3	52
24	Nandpur-01	Sample 9	0.96	2	84
25	Nandpur-01	Sample 10	1.19	2	26
26	Nandpur-01	Sample 11	0.42	4	30
27	Nandpur-01	Sample 12	0.43	6	55
28	Zakria-01	Sample 1	0.99	120	96
29	Zakria-01	Sample 3	1.19	56	290
30	Zakria-01	Sample 3	0.42	48	302
31	Zakria-01	Sample 4	0.36	67	270
32	Zakria-01	Sample 5	0.61	61	250
33	Zakria-01	Sample 6	0.64	130	198
34	Zakria-01	Sample 7	0.82	99	132

Acoustic impedance was calculated from well logs using sonic and density logs. The acoustic impedance is defined as $Z = \rho v$, where ρ is the density of the medium and V is the velocity through the medium. Velocity is computed from the sonic log, while density is determined from the density log. Velocity is calculated from sonic by using $V = 1/DT$, where DT is the sonic log and V indicates velocity. Initially, the relationship between acoustic impedance and TOC was established at the Zakria-01 well.

The calculated acoustic impedance was plotted against TOC (calculated from core samples), leading to the establishment of a linear relationship at the Zakria-01 well (Fig. 5). The equation derived from this cross-plot ($Y = -0.000466368 * X + 1.37812$) was then used to transform seismic impedance data into TOC values through the seismic inversion technique (Fig. 6).

Type of kerogen

Rock-Eval pyrolysis is widely recognized as one of the most effective geochemical techniques for source rock evaluation, especially regarding the determination of kerogen type (Espitalié et al. 1977). This technique is extensively used to assess source rock organic matter type, generation potential, and maturity level (El Diasty et al. 2022). In this study, 100 mg of each sample were subjected to Rock-Eval measurements using the Rock-Eval 6 machine. The analysis provided results for S_1 , S_2 , S_3 , and T_{max} values (Peters and Cassa 1994). During pyrolysis, the first peak S_1 was obtained at 300 °C, representing the amount of free hydrocarbons (mg HC/g) present in the rock without cracking the kerogen. The S_2 peak showed the quantity of hydrocarbon generated through the thermal cracking of kerogen during programmed pyrolysis within the temperature range of 300–600 °C. According to (Kibria et al. 2020), the S_2 peak is considered more reliable, as (TOC, wt%) includes dead carbon that cannot generate petroleum. The S_3 peak corresponds to CO_2 yield produced during the thermal cracking of kerogen. Additionally, the temperature at which the maximum amount of hydrocarbon was generated during pyrolysis, known as T_{max} , was recorded. HI was used to normalize the S_2 value to HC/g of (TOC, wt%), while the OI is the amount of oxygen in kerogen and expressed in CO_2/g of (TOC, wt%). Kerogen type was determined by plotting the HI against the OI.

Source rock maturity

Source rock maturity is a critical element of source rock evaluation. In this study, source rock maturity was calculated using a direct approach (organic petrography) by estimating vitrinite reflectance from core samples in the laboratory. Additionally, vitrinite reflectance was calculated using the modeled EASY% Ro algorithm in basin modeling (Sweeney and Burnham 1990). Results obtained from both organic petrography and basin modeling were compared. Rock-Eval data T_{max} was also used for maturity assessment. Maturity estimation from T_{max} in some cases gives suspicious results when S_2 has more than one peak or suffers weak intensity (Snowdon 1995). Organic petrography is a better and more precise maturity evaluation by calculating the vitrinite reflectance, which can deliver more accurate results when the facies effects have an impact on the T_{max} (Sadegh-tabaghi et al. 2021). Vitrinite reflectance is the most widely used factor for source rock maturity determination (Burnaz et al. 2023; Ola et al. 2018). For source rock maturity, vitrinite reflectance was measured from Zeiss Z1M microscope fitted with a Spectrometer. The microscope has both fluorescent and white (halogen) light sources. Microscope was

Table 2 Calculated %Ro from core samples (Chichali Shale) in Bahu-01, Panjpir-01, Nandpur-01 and Zakria-01 wells

Sr.no	Well name	Sample name	Formation name	Depth (m)	%Ro
1	Bahu-01	Sample 1	Chichali	1622	0.44
2	Bahu-01	Sample 2	Chichali	1626	0.35
3	Bahu-01	Sample 3	Chichali	1630	0.30
4	Panjpir-01	Sample 4	Chichali	1682	0.34
5	Panjpir-01	Sample 5	Chichali	1710	0.30
6	Panjpir-01	Sample 6	Chichali	1750	0.45
7	Panjpir-01	Sample 7	Chichali	1780	0.48
8	Panjpir-01	Sample 8	Chichali	1950	0.50
9	Nandpur-01	Sample 9	Chichali	1680	0.30
10	Nandpur-01	Sample 10	Chichali	1690	0.32
11	Nandpur-01	Sample 11	Chichali	1695	0.37
12	Nandpur-01	Sample 12	Chichali	1780	0.39
13	Nandpur-01	Sample 13	Chichali	1782	0.42
14	Nandpur-01	Sample 14	Chichali	1790	0.41
15	Zakria-01	Sample 15	Chichali	1863	0.59
16	Zakria-01	Sample 16	Chichali	2142	0.55
17	Zakria-01	Sample 17	Chichali	2148	0.76
18	Zakria-01	Sample 18	Chichali	2156	0.51
32	Zakria-01	Sample 19	Chichali	2413	0.78

Fig. 4 Flow chart showing a comprehensive approach for Chichali Shales source rock evaluation. Source rock is evaluated in terms of organic richness, maturity and timing of maturation. Post-stack seismic inversion and organic geochemistry were used for the calculation of TOC. Source rock maturity was calculated from petrography and basin modeling techniques

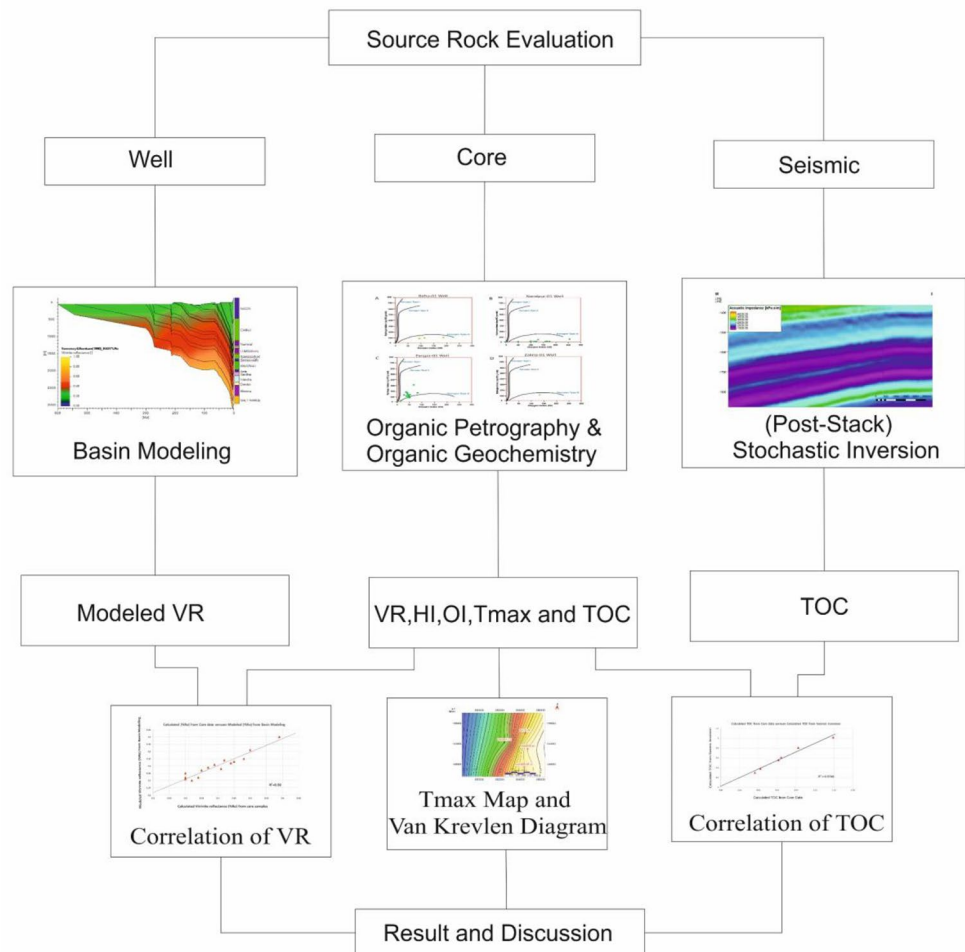


Fig. 5 Graph showing the linear relationship between P-impedance plotted against TOC. It shows the linear relationship of P-impedance with TOC. Also equation was derived from this cross-plot ($Y = -0.000466368 * X + 1.37812$) which was used to transform seismic impedance data into TOC.

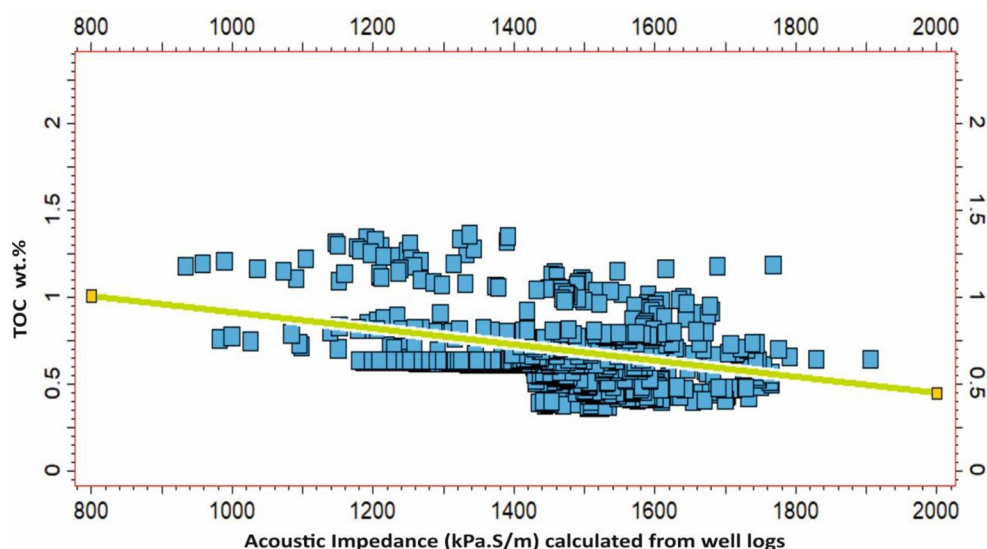
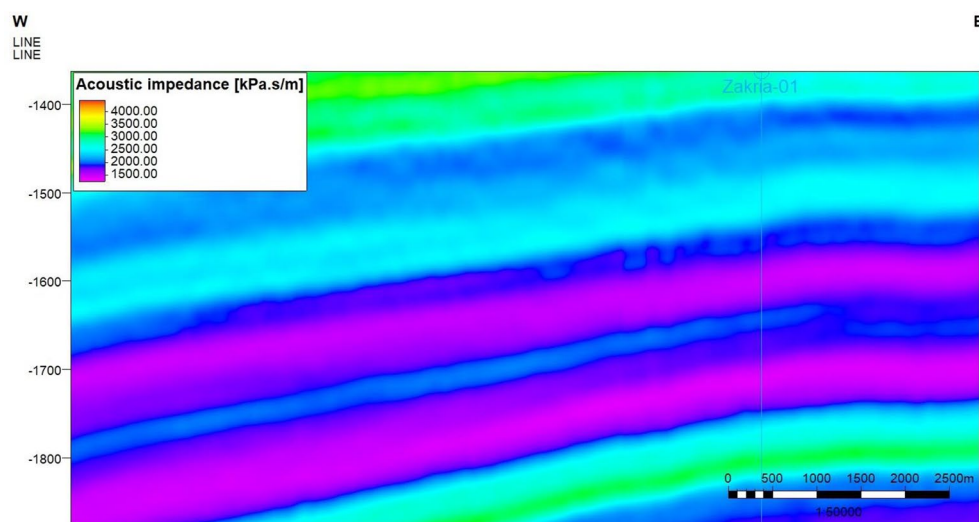


Fig. 6 P-impedance 2D seismic section passing through Zakria-01 well generated by using seismic inversion technique. P-impedance values are decreasing toward the west



attached with a high-resolution C-mount camera. Spectra Vision Spectra Vision software program was used for measuring vitrinite reflectance. Immersion oil used was made by Carl Zeiss (518 C, DIN 58 884, ISO 8036/1 Ne = 1.518 at 230 C). Random vitrinite reflectance ($R_m\%$) measurements were made using monochromatic non-polarized light and a 50X ocular oil immersion objective, calibrated against three sets of reference standards: saphir ($R_m\%$) = 0.589%, yttrium-aluminum-garnet ($R_m\%$) = 0.907% and gadolinium-gallium-garnet ($R_m\%$) = 1.711%. The measured vitrinite reflectance from Zeiss Z1M was plotted versus depth to see the maturity of Cretaceous rock.

Determining the timing of maturity and understanding the burial history of source rocks is equally vital in source rock evaluation (Dembicki & Harry, 2017). The 1D basin modeling technique serves as a robust tool for constructing the burial history and assessing the levels of source rock maturation (Abdelwahhab et al., 2020). In a study by (Yasin

et al. 2021), the burial history and maturity of source rocks were evaluated using the 1D basin modeling approach. Elatrash et al. (2021) calculated source rock maturation using vitrinite reflectance values from the EASY% Ro algorithm. In our study, we employed the 1D basin modeling technique to develop the burial history and maturation profiles of source rocks. This was achieved by considering factors such as formation age, depth, lithology, TOC and boundary conditions. We conducted 1D basin modeling at four well locations, namely Bahu-01, Panjpir-01, Nandpur-01, and Zakri-01. Paleo-bathymetry inputs were adopted using the deposition environment of each formation. SWIT was used for each well. The model also incorporated kinetics, rock-eval data, bottom hole temperature, lithology of formations, thickness, erosion, and paleo-bathymetric data to construct the maturity model within the Petrel software. Kinematics (heat flow) is main factor that impacts the reconstruction of history of sedimentary basin to predict the process of

Fig. 7 Average TOC map of Cretaceous Chichali Shale showing the TOC distribution in study area

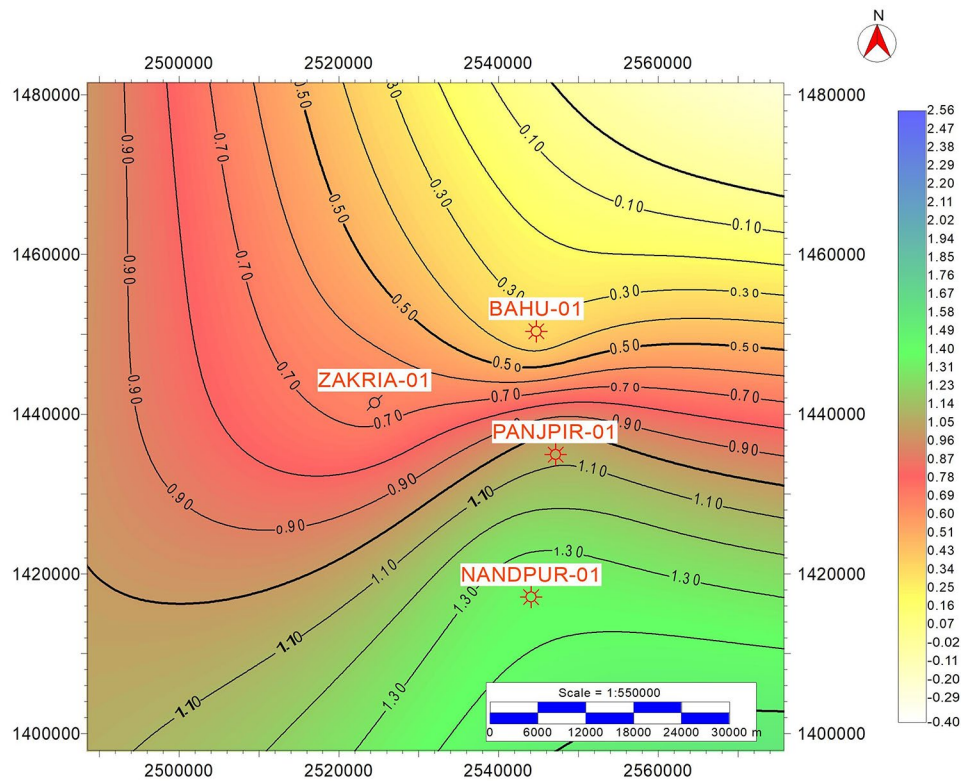
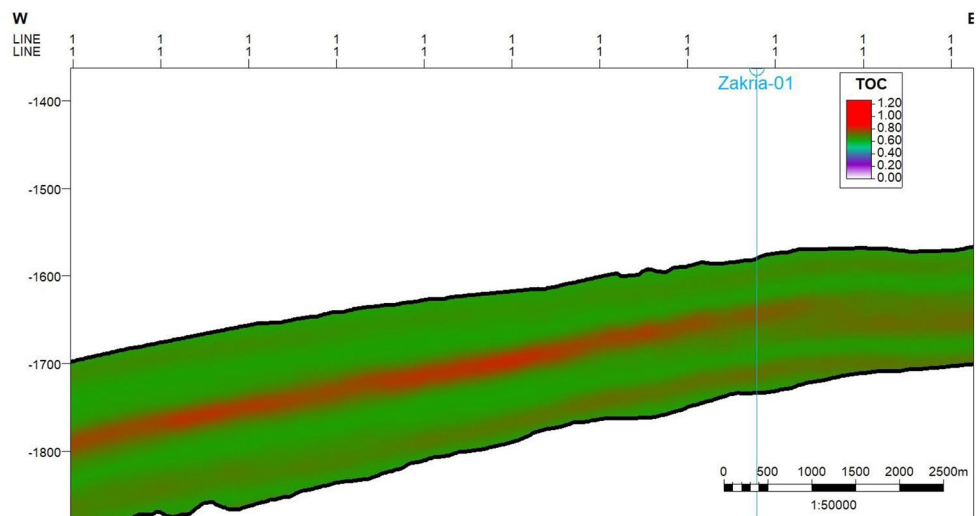


Fig. 8 Section showing the TOC variation of Chichali Formation, TOC is further increasing toward the west as a result of deep marine setting. TOC values were derived at Zakria-01 well from P-impedance by using linear equation $Y = -0.000466368 * X + 1.37812$ with $R^2 = 0.95$



hydrocarbon maturity, timing, migration and trapping. For heat flow, Mckenzie method was adopted. Inputs for the rift phase, post rift phase, depth of crust and mantle were incorporated. To validate the source rock maturity results, we compared modeled (%Ro) values generated using the modeled EASY% Ro algorithm (Sweeney and Burnham 1990) with (%Ro) values obtained through organic petrography in the laboratory.

Results and discussion

The average TOC values were calculated from core samples. Calculated TOC values at Bahu-01, Panjpir-01, Nandpur-01 and Zakria-01 wells are 0.34%, 1.25%, 1.36%, and 0.72% respectively. Based on these values, an average TOC map was generated for the Cretaceous source rock (Fig. 7). Bahu-01, with its TOC of 0.34%, exhibits a poor source rock potential. In contrast, Panjpir-01 and Nandpur-01, with TOC values of 1.25% and 1.36%, respectively, signify

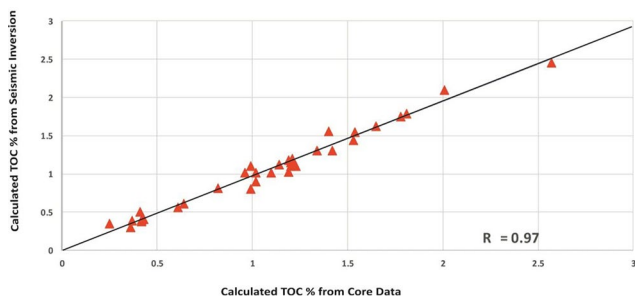


Fig. 9 The coefficient of determination was calculated by plotting calculated TOC from core samples versus calculated TOC from seismic inversion. It is showing an excellent correlation coefficient of ($R=0.97$)

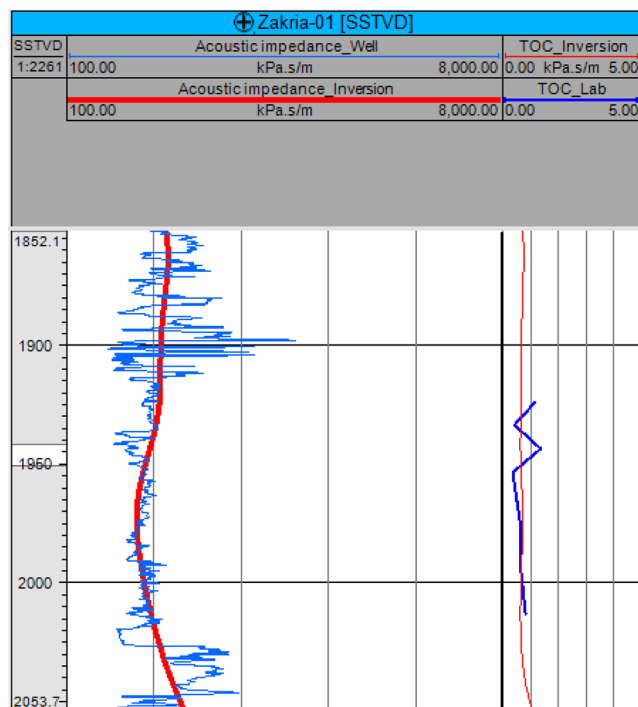


Fig. 10 Shows the comparison of calculated acoustic impedance from seismic (red curves) versus well (blue curves). Also calculated TOC from seismic inversion is compared with TOC, calculated from core. Acoustic impedance and TOC calculated from core and seismic data represent same trend. At Zakria-01 well, the calculated TOC from seismic inversion is 0.78, aligning closely with the TOC of 0.72 obtained through lab analysis from core samples

moderate to good organic richness. Zakria-01 well, with a TOC of 0.72%, demonstrates fair organic richness.

Also, the average TOC was calculated from seismic inversion at the Zakria-01 well location. TOC at Zakria-01 well is 0.77%, closely matching the actual average TOC of 0.72% obtained from lab analysis. The main purpose of calculating the TOC from seismic inversion was to calculate the TOC in the western part of the study area where no wells have been drilled. Calculating TOC from the seismic inversion approach is novel in the study area. The seismic inversion

reveals that TOC is increasing from east to west and has an excellent TOC of 1.50% in most western parts (Fig. 8). The TOC variation in the area is also supported by the tectonic setting and stratigraphy of the source rock, which indicates that sediments deposited from proximal sedimentary settings in the east to distal sedimentary settings in the west. The comparison between TOC values derived from core samples and those calculated from seismic inversion shows a strong correlation ($R=0.9774$) for assessing the organic richness of the Chichali Shales in the Punjab Platform area (Fig. 9).

The TOC results obtained from core and seismic are compared and this highlights the effectiveness of the seismic inversion technique for TOC estimation, particularly in situations where core data is unavailable. Calculated acoustic impedance from seismic inversion (red curves) plotted versus core data from well (blue curves) (Fig. 10). Also calculated TOC from seismic inversion is compared with TOC calculated from the core. Acoustic impedance and TOC calculated from core and seismic data represent the same trend. At Zakria-01 well, the calculated TOC from seismic inversion is 0.78%, aligning closely with the TOC of 0.72% obtained through lab analysis from core samples. The main goal achieved from seismic inversion is to evaluate the organic richness of source rock, especially in the western portion of Punjab Platform, where no wells were drilled and source rock potential was never addressed before.

For the determination of kerogen type, rock-eval data, Hydrogen and Oxygen Index were utilized. Rock-Eval data HI versus OI are plotted at the Bahu-01, Panjpir-01, Nandpur-01, and Zakria-01 wells. Based on these Van Krevelen diagram (Modified) graphs all the samples taken from Bahu-01, Nandpur-01, and Zakria-01 well falls in Kerogen type-III. Samples from Panjpir-01 well falls in kerogen type-II-III (Fig. 11). Based on these results, it is concluded that Panjpir-01 well dominates kerogen type type-III and has gas generation potential. In exploration phase, this better understanding about kerogen type and hydrocarbon generation potential will help to add more resources in Punjab Platform.

In addition to source rock richness, source rock maturity plays an equally vital role in source rock evaluation. Peter and Cassa (1994) applied Rock-Eval analysis to determine thermal maturity based on T_{max} parameters. This approach relies on the thermal decomposition of organic matter in an inert atmosphere, yielding a T_{max} value at which the maximum hydrocarbon generation occurs (Chen et al. 2023). Rock-Eval pyrolysis data T_{max} is used for this study for estimating essential geochemical parameters in source rock geochemical assessment. T_{max} values less than 435 °C indicates the immaturity of source rock whereas T_{max} range from 435 to 470 °C represents the maturity of source rock.

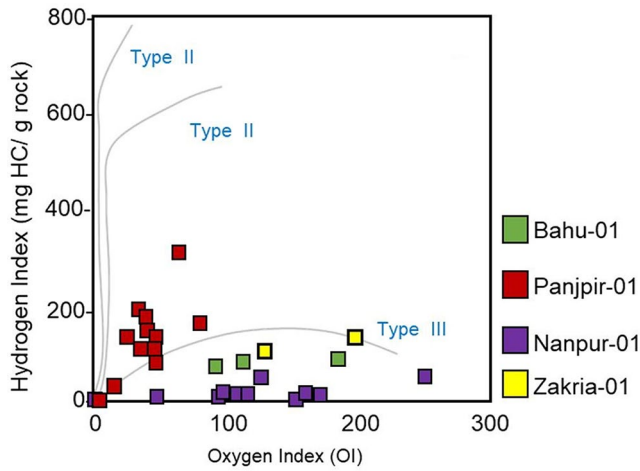


Fig. 11 Source rock Kerogen Type is identified using Van Krevelen diagram (Modified). Rock-Eval data HI is plotted against OI. HI is in mg HC/g rock and OI is in mg/g. Bahu-01, Nandpur-01 and Zakria-01 wells falls has kerogen type III, whereas samples from the Panjpir-01 well falls within kerogen types II to III

Over maturity of source rock attains at greater than 470 °C. Rock-Eval pyrolysis data was utilize to generate an average T_{max} map.

Average T_{max} values below 435 °C at Bahu-01, Panjpir-01, and Nandpur-01 indicate immaturity, while a T_{max} value exceeding 435 °C at Zakri-01 confirms maturity of source rock. It clearly divides the western source mature zone from eastern immature zone (Fig. 12). The source

Fig. 12 Rock-Eval pyrolysis data T_{max} is also utilized for source rock maturity. Average T_{max} map of Cretaceous Chichali Shale is generated. Dotted green line separates source rock immature eastern zone from mature western zone. Source rock in Bahu-01, Panjpir-01 and Nanpur-01 wells falls in immature zone. However, it is mature in Zakria-01 well

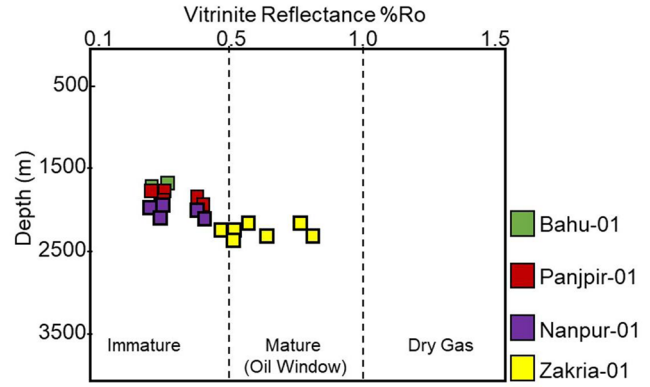
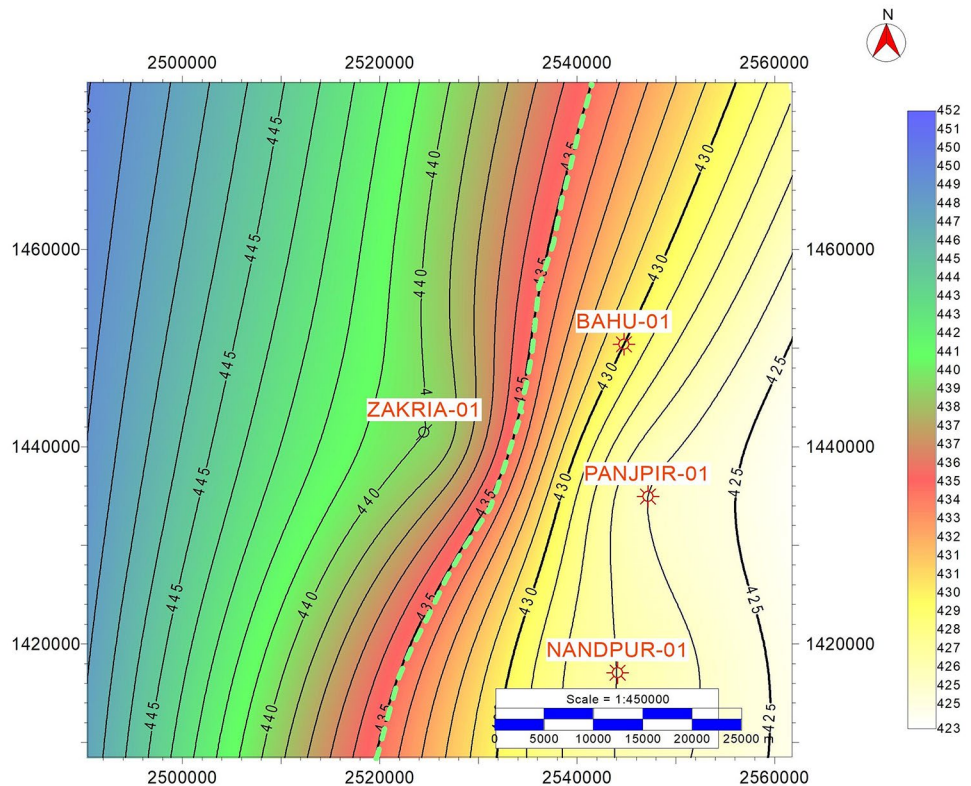
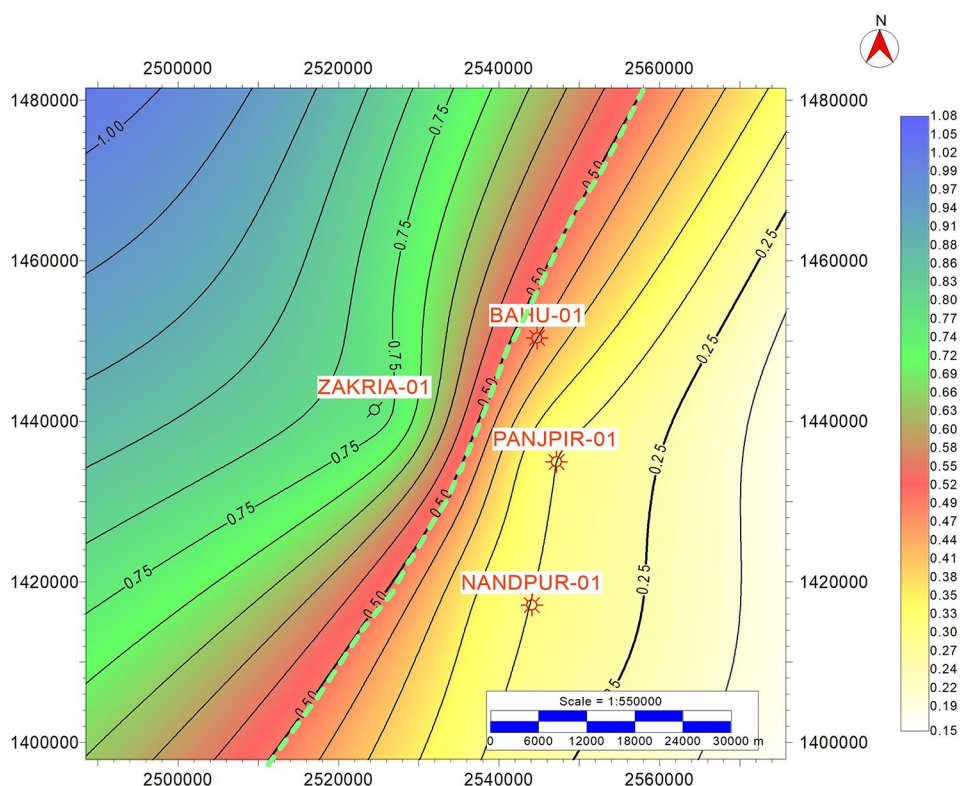


Fig. 13 Calculated Vitrinite reflectance (%Ro) from core samples plotted against depth. Source rock samples in Bahu-01 Panjpir-01 and Nanpur-01 wells falls in immature window. Immature source rock represents no hydrocarbon generation potential in these wells. Samples from Zakria-01 well lies in source mature window representing early oil generation potential

generation potential based on T_{max} values indicates the early to mature source potential. Also %Ro values calculated through organic petrography are analyzed. The %Ro values calculated from core samples are plotted against depth to reveal the maturity of the Cretaceous source rock (Fig. 13). Source rock samples having %Ro values less than 0.5 lies in immature zone, with no hydrocarbon generation potential. The onset of oil generation is correlated with %Ro of 0.5 and termination of oil generation at %Ro of 1.1. The gas generation ranges lie between %Ro values of 1.1–1.5.

Fig. 14 Average Vitrinite Reflectance map of Cretaceous Chichali Shale. Dotted green line separates source rock immature eastern zone from mature western zone. Bahu-01, Panjpir-01 and Nandpur-01 wells lies in source rock immature zone while Zakria-01 well falls in source mature zone



This %Ro plotted versus depth graph shows that the vitrinite reflectance values at Bahu-01, Panjpir-01, and Nandpur-01 are all less than 0.5%, signifying immature source rock. Immature source rock represents no hydrocarbon generation potential in these wells. In contrast, Zakria-01 well displayed an average %Ro of 0.63%, revealing that the Cretaceous source rock is within the oil window (Fig. 13). This corresponds to the geological basin setting. Bahu-01, Panjpir-01 and Nandpur-01 lie in eastern proximal margin of Punjab platform, source rock is not buried deep in term of depth to attain maturity. However, Zakria-01 well is situated toward the western, basin side of Punjab Platform. The source rock has attained maturity due to the adequate overburden and deep burial in terms of depth.

An average vitrinite reflectance map is generated to assess the maturity of the source rock based on Vitrinite results obtained through organic petrography (Fig. 14). The onset of oil generation is correlated with %Ro of 0.5 and the termination of oil generation at %Ro of 1.1. The gas generation ranges between %Ro of 1.1–1.5. The average vitrinite reflectance values in Bahu-01, Panjpir-01, and Nandpur-01 wells are all below 0.5%, confirming the immaturity of the source rock in these wells. In contrast, Zakria-01 well showed an average vitrinite reflectance value of 0.63, indicating source rock maturity. Based on maturity results a clear boundary was marked to separate mature western portion of Punjab Platform from the immature area in eastern side (Fig. 14). The source rock maturity

and its timing of expulsion were calculated from 1D basin modelling approach. The results of Multi 1D basin modeling provide insights into the paleo-water depth and temperature conditions in different geological intervals. Surface water interference temperature remains close to 28 °C. In the Mesozoic interval, the paleo water depth ranged from 0 to 200 m, while in the Late Paleogene, it varied from 0 to 50 m (Fig. 15).

The simulated paleo heat flows were adjusted to match the actual vitrinite reflectance values with the modeled values. An average heat flow ranging from 50 mW/m² to 60 mW/m² provided the best match for actual %Ro. The 1D basin modeling results for Bahu-01, Panjpir-01 and Nandpur-01 well indicate immature source rock having vitrinite reflectance for the Cretaceous source rock is 0.33%, 0.38% and 0.4% respectively (Fig. 16). Zakria-01 well represents the value 0.55% of %Ro obtained from basin modeling, suggesting that the source rock maturity lies in the early maturity stage (Fig. 16d).

Furthermore, the Vitrinite reflectance calculated from the direct lab based approach (petrography) and the indirect method (Basin Modeling) are compared and it showed a strong correlation coefficient value of $R=0.92$ (Fig. 17). This compressive source rock evaluation approach for Chichali source rock Maturity is novel in the study area and the best match between results derived from diverse methodologies reflects that an integrated approach can be adopted in other basins of the world for enhanced hydrocarbon exploration.

Fig. 15 (a) Shows the heat flow (mW/m^2) curve plotted against age. It is showing high heat flow values from 250 (Ma) to 65(Ma) due to rifting phase (b) Showing the paleo water depth (m) curve plotted against age (Ma). Water depth decreases after 65 (Ma) due to the uplifting phase (c) Surface water interface temperature in $^{\circ}C$, plotted against age in (Ma), SWIT remains close to $28^{\circ}C$

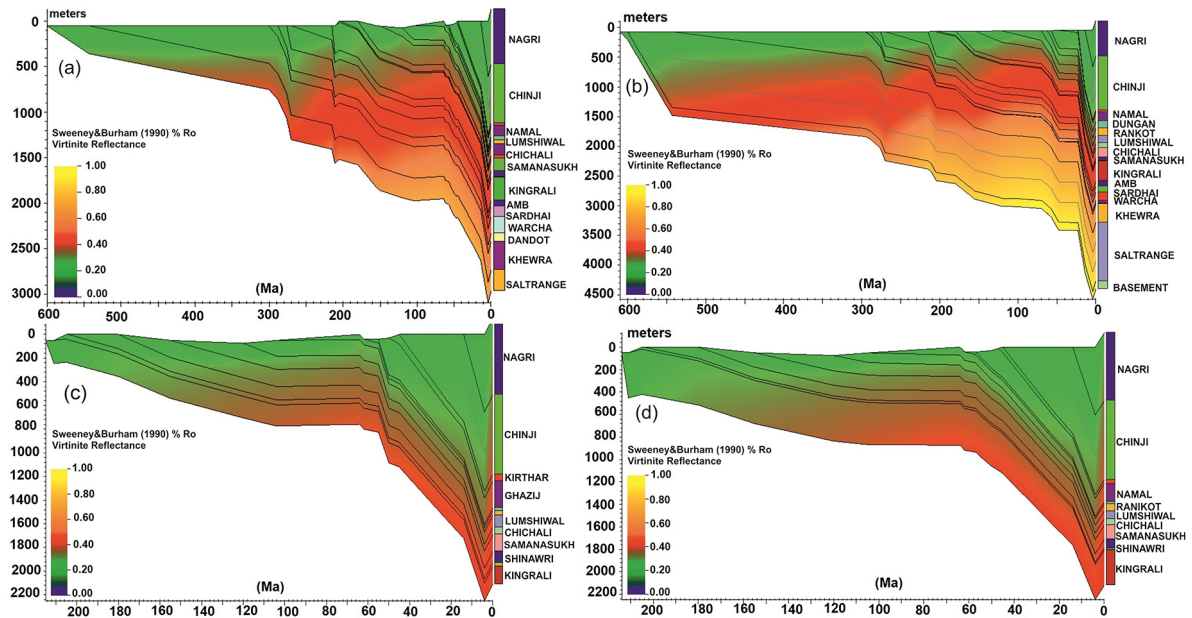
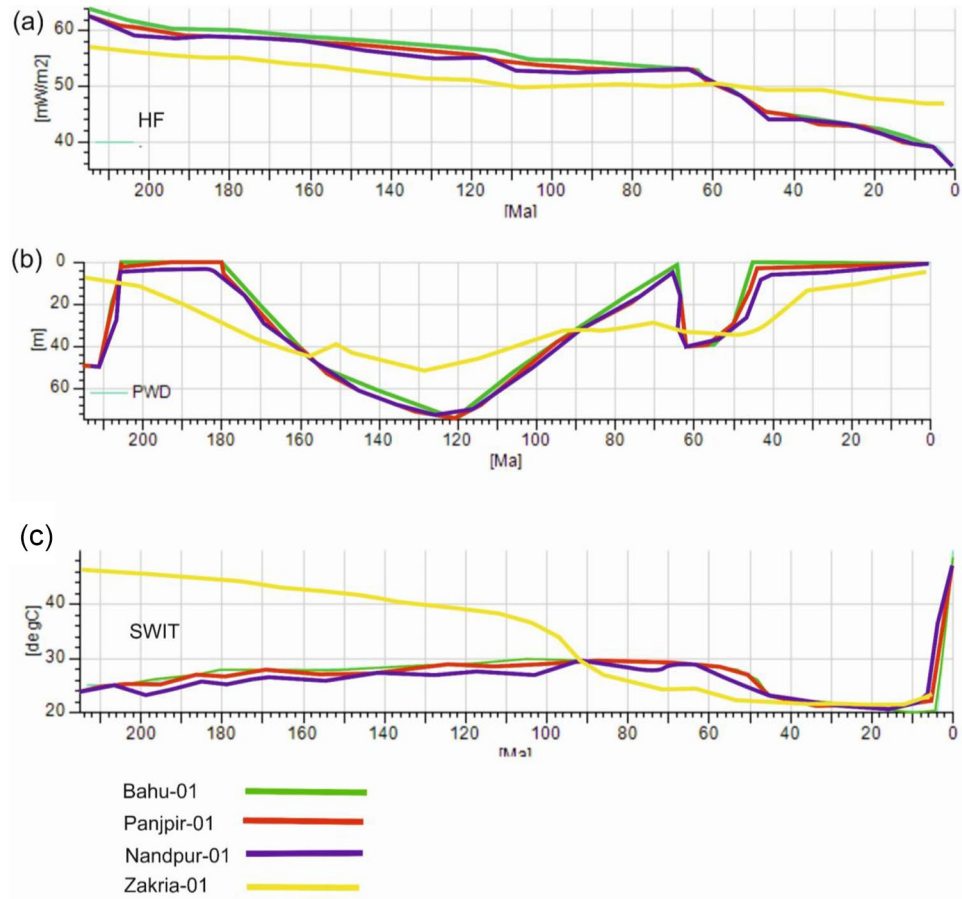


Fig. 16 ID basin Modeling carried at (a) Bahu-01, (b) Panjpir and (c) Nandpur-01 wells. Source rock is immature at (a, b & c) wells because of modeled % Ro less than 0.5 (d) Source rock is mature at Zakria-01

well because of modeled % Ro greater than 0.5% and having oil generation potential and maturity attained at Eocene time

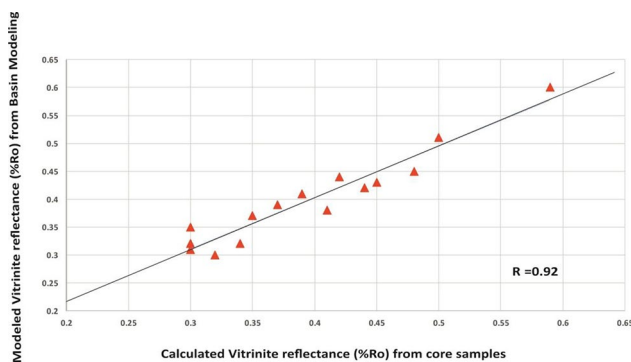


Fig. 17 The coefficient of determination was calculated by plotting vitrinite reflectance calculated from organic petrography in the lab from core samples versus modeled %Ro from basin modeling. It is showing excellent correlation coefficient of ($R=0.92$)

Conclusions

This research addresses the complexities regarding the source rock evaluation by using integrated approach. It includes seismic inversion, organic geochemistry, petrography and basin modeling techniques for conclusive source rock evaluation. Also the results from various techniques are also compared. The primary research findings are outlined below.

- Bahu-01 well indicates poor source rock potential with an average TOC of 0.34%. In contrast, the Panjpir-01 and Nandpur-01 wells displays moderate to good organic richness, with average TOC of 1.25% and 1.36%, respectively. The Zakria-01 well exhibits fair organic richness, with an average TOC value of 0.78%.
- The organic richness results obtained from both direct lab based geochemistry and indirect seismic inversion methods are compared and it displays an excellent correlation coefficient of $R=0.97$.
- Kerogen type concludes that the Bahu-01, Nandpur-01, and Zakria-01 wells has kerogen Type-III, while Panjpir-01 has a kerogen Type-II-III.
- Average T_{max} in eastern side of study area lies below 435 °C at Bahu-01, Panjpir-01, and Nandpur-01 confirms immaturity of source rock, while in western side T_{max} value exceeds 435 °C at Zakria-01 confirms the maturity of source rock.
- Based on 1D basin modeling results, modeled %Ro for the Chichali Shales at Bahu-01, Nandpur-01 and Panjpir-01 indicates immaturity of source rock with values of 0.33%, 0.40% and 0.38%, respectively. At Zakria-01, the %Ro value of 0.55% suggests early oil window with peak hydrocarbon expulsion occurred in Eocene age.

- The comparison of %Ro values from petrography and 1D basin modeling approaches yields a good correlation coefficient of $R=0.92$.
- It confirmed furthermore that in-situ Cretaceous age Chichali Shales are immature in eastern area of Punjab platform where three gas fields namely Bahu, Panjpir and Nandpur are found. However, source is mature in the western portion of study area and it serves as source rock kitchen area for producing fields.
- Single technique restricted explorationists to completely evaluate the source rock potential for enhanced hydrocarbon exploration.
- Integrated source rock evaluation using seismic inversion, rock-eval pyrolysis, organic petrography and basin modeling techniques is novel and it has enhanced our understanding of the variation of source rock characteristics.
- Mitigation of hydrocarbon exploration risks associated with source rock richness, maturity and timing will aid the exploration companies for adding sizeable hydrocarbon resources.

Abbreviations

DT	Sonic log
GR	Gamma ray log
HF	Heat flow
HI	Hydrogen Index
OI	Oxygen Index
PWD	Paleo water depth
Rm%	Random vitrinite reflectance
%Ro	Vitrinite reflectance
S_1	Free hydrocarbon
S_2	Generatable potential
S_3	CO ₂ yield during thermal breakdown
SWIT	Surface water interface temperature
T_{max}	Temperature maximum
TOC	Total organic carbon
V	Velocity through the medium
Z	Acoustic impedance

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Declarations

Competing interests The authors wish to declare that they have no known competing interests that could be perceived as relevant to the content of this article.

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