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Petroleum potential of Gurpi Formation and its role within the Cretaceous petroleum system, eastern Persian Gulf

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ABSTRACT

The Gurpi Formation marls and shales in the eastern Persian Gulf display high gamma ray signatures on well logs, suggesting potential source rock behavior. This study assesses the hydrocarbon generation potential of Gurpi across the eastern Persian Gulf and its role in charging the Ilam reservoir. Ten oilfield samples were analyzed using Rock – Eval pyrolysis, GC, GC – MS, Py-GC – MS, stable carbon isotope, elemental analysis, and visual kerogen petrography. One-dimensional basin modeling was applied to reconstruct burial, thermal, and maturation histories. Geochemical data indicate fair petroleum-generation potential in southeastern localities (Sirri A, D, E, Nosrat, Farzam). Kerogen is dominated by Type II/III, deposited in a marine setting. Biomarker and isotopic signatures corroborate marine organic input and limited thermal alteration. Maturity indicators and basin models show Gurpi is largely immature within sampled fields but reaches early to peak oil-window conditions in deeper structural depressions east of these fields. Although most sampled Gurpi intervals remain below effective generation thresholds, localized depocenters have likely generated and expelled hydrocarbons. Downward migration from these kitchens presents a plausible charge mechanism to the Ilam Formation. These results refine the regional petroleum system model and identify target areas where Gurpi sourced charge to Ilam reservoirs is most probable.

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KEYWORDS

Gurpi Formation; Persian Gulf; source rock evaluation; biomarker; 1D modeling

Introduction

The Persian Gulf constitutes a geographical area of paramount significance concerning hydrocarbon reserves, as it represents a crucial locus for global oil production activities. The importance of this region as a source of hydrocarbon resources lies in its geology. The Persian Gulf is situated on a major geological feature known as the Arabian Plate, which holds enormous reserves of oil and gas (Ghazban 2007). The study area is situated in the eastern region of the Persian Gulf within the Iranian domains and is characterized by the presence of numerous oil and gas reserves (Figure 1).

In order to a successful petroleum exploration, understanding of the petroleum system(s) and its elements in the basin is very critical. The accurate assessment of source rocks is a cornerstone of petroleum system analysis. The hydrocarbon generation potential of a source rock is not solely a function of Total Organic Carbon but is critically dependent

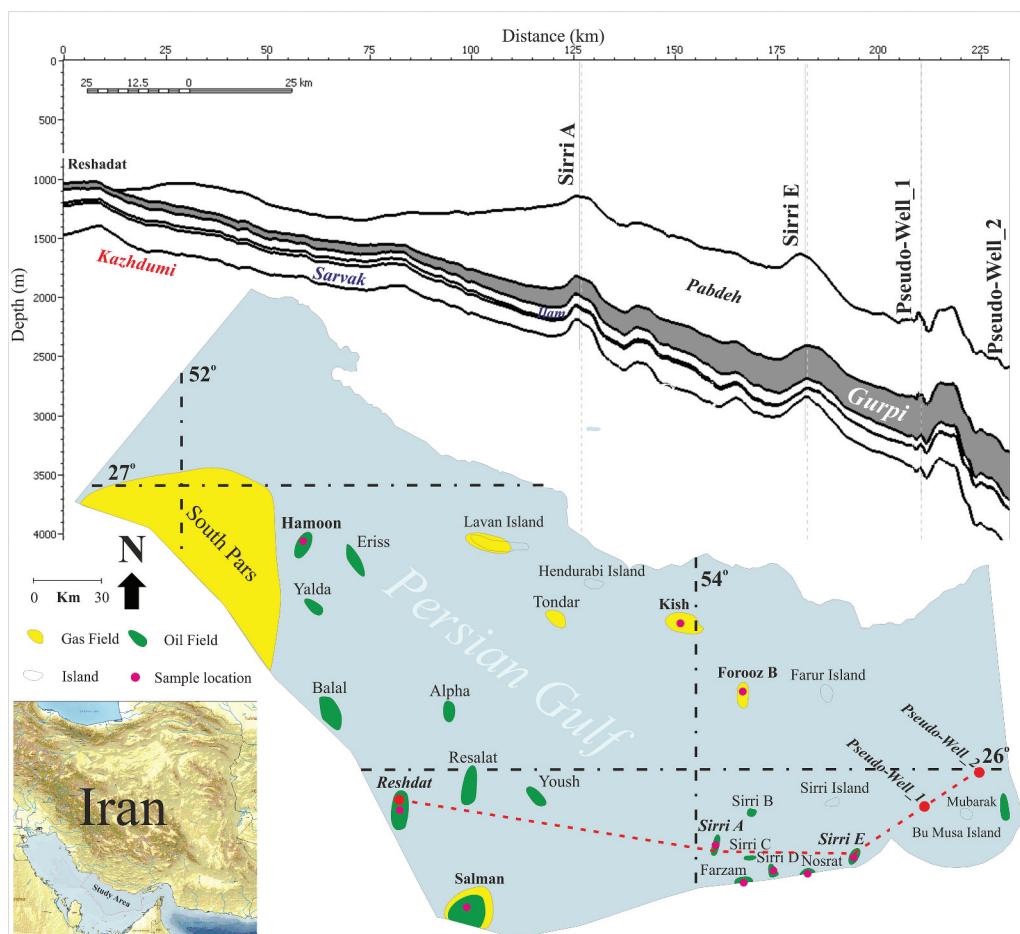


Figure 1. 2D section and study area location map.

on kerogen type, thermal maturity, and the depositional paleo-environment. Various techniques such as Rock-Eval pyrolysis, biomarker geochemistry, stable carbon isotope and organic petrography have been developed and employed over time. Recent global studies indicate a robust source rock evaluation requires integrating optical, geochemical, and thermal history data to characterize quantity, quality, and maturity of organic matters (Hatem et al. 2026; Hakimi et al., 2023; Kumar et al. 2025). These studies emphasize that a multi-proxy approach reduces uncertainty about kerogen type, maturity assessment, and the timing of oil and gas generation. Building on these global insights, the present study applies the integrative framework to the Gurpi Formation.

The Cretaceous Period represents a zenith for the accumulation of organic-rich sediments globally, positioning it as a critical interval for the formation of world-class petroleum systems. Globally recognized units such as Garau and Kazhdumi Geomorphology in the Zagros sedimentary basin have been extensively characterized through geochemical and basin modeling studies, which effectively map their oil kitchens and hydrocarbon migration routes (Sfidari et al. 2016; Shekarifard et al. 2019). By contrast, some intervals in the prolific Persian Gulf Basin – notably the Late Cretaceous Gurpi Formation – have been less

thoroughly investigated using integrated approaches. While recognized regionally as a seal, its role as a potential source rock, particularly in the eastern Persian Gulf, remains ambiguously defined and inadequately incorporated into the regional Cretaceous petroleum system model.

In recent years, a number of scholars have conducted investigations into the petroleum systems located in the eastern region of the Persian Gulf (Hosseiny 2024; Hosseiny, Rabbani, and Moallemi 2017; Rabbani et al. 2014). Three main source rocks have been identified for the region's oil and gas so far. The Silurian Sarchahan Formation is the primary source rock for gases in Kangan and Dalan reservoirs (Rahmani, Naderi, and Hosseiny 2023). Moreover, Middle Surmeh and Middle Sarvak source rocks charge the Upper Surmeh and Upper Sarvak oil reservoirs, respectively (Hosseiny, Rabbani, and Moallemi 2016, 2017). The marl and shales of Gurpi Formation indicate high gamma ray in petrophysic logs. Therefore, it can be a potential source for some gas and oil in the study area. The paper provides the first integrated geochemical and basin-modeling evaluation of the Gurpi Formation across eastern Persian Gulf oilfields, combining Rock-Eval, GC – MS, Py-GC – MS, stable carbon isotopes, petrography, and 1D burial/thermal modeling on the same sample suite to assess Gurpi hydrocarbon generation potential and its possible role in charging the Ilam reservoir. It therefore revises the regional petroleum system model and a probable source/reservoir linkage not previously demonstrated in the region.

2. Geological setting

The Gurpi Formation is extended almost everywhere in the south and southwestern Iran except to Qatar-Gavbandi Arch (Ghazban 2007) (Figure 2). The type section with 350 m thickness is located in Tange-e-Pabdeh north of the Masjed-Soleyman (James and Wynd 1965) (Figure 2(A)). In the Late Cretaceous period, the pelagic and hemipelagic deposits from Gurpi Formation settled at the shallow-marine limestones of Ilam Formation with a minor disconformity along the northeast edge of the African – Arabian plate, situated at an equatorial paleo-latitude (Al Rawahi and Jones 2019; Gowhari et al. 2020). The upper boundary features a disconformity in relation to the Pabdeh Formation which is the marker of the Cretaceous/Paleogene boundary. It has a considerable thickness in the study area and thickens toward the east. The thickness in Sirri fields reaches 236 m (Ghazban 2007). Moreover, the depth of Gurpi increases from the western part to the eastern part of the study area (Figure 1). This Formation made up of pelagic marl, argillaceous limestone and hemipelagic shale throughout the study area (Bordenave and Hegre 2010). Gowhari et al. (2020) reported shale, argillaceous limestone, and thin to medium limestone for lithology of Gurpi and recognized two species of nine genera of benthic foraminifera and 22 species of 12 genera of planktonic foraminifera in coastal Fars, northern study area. Toward the south Persian Gulf, the facies change to carbonate secessions of Simsim and marls/shales of Fiqa Formation in the United Arab Emirates and Oman (Ghazban 2007) (Figure 2). According to Micro-paleontological analysis from northern Oman, the Fiqa was deposited in a neritic environment (Packer 2002). The Fiqa deep marine environment was interrupted by several sea level fall (Al Rawahi and Jones 2019). The Lower Fiqa in the northern UAE was deposited in a deep marine setting and contain hemipelagic fine terrigenous clastics, shales, and interbeds of marls (Alsharhan 1995).

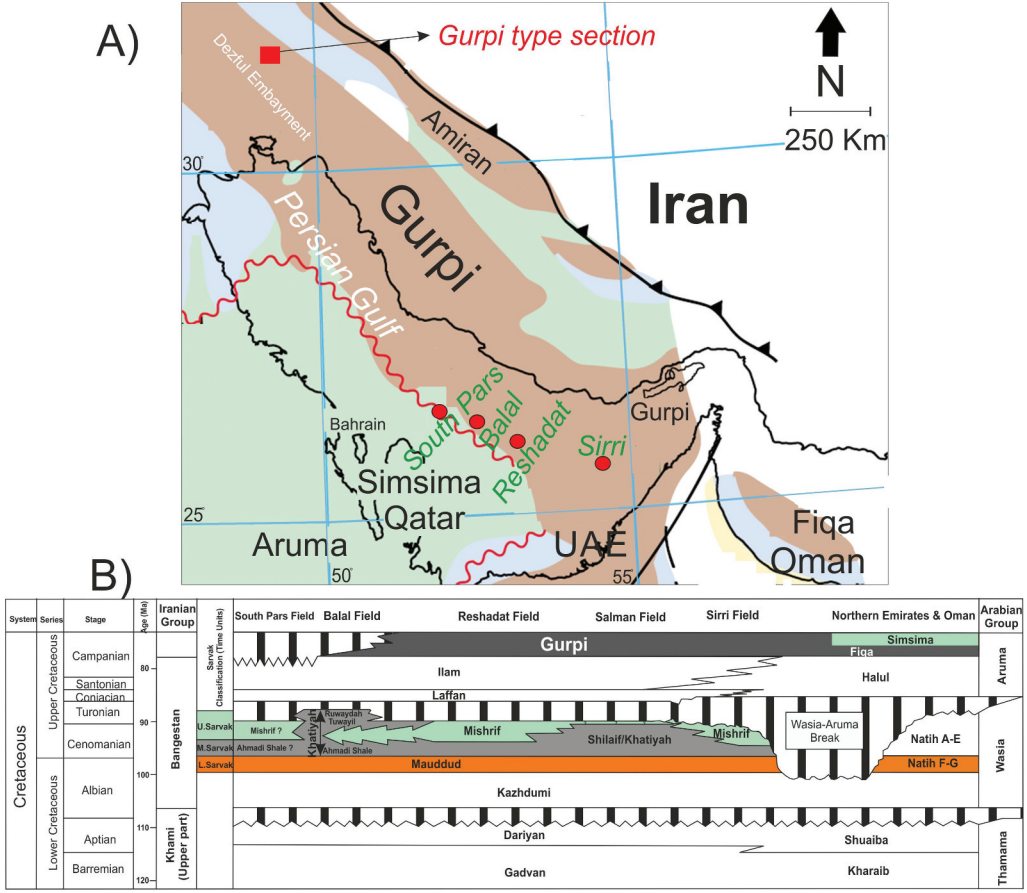


Figure 2. (A) The expansion of the Gurpi Formation in southern and southwestern Iran (modified from Ziegler, 2001). (B) Lithostratigraphy and correlation of the Cretaceous deposits in the study area.

According to existence of pelagic fauna in Gurpi Formation, it could be estimated that a paleo water depth of 200 m for this formation during its deposition. Lithologically speaking, the Gurpi Formation is the seal rock for Ilam/Sarvak reservoir and a potential source rock for Ilam reservoir. Some research report the fair petroleum potential for Gurpi in the southwestern Iran. Hosseiny, Karmalachab, and Barati Boldaji (2020) reported poor to fair petroleum potential for Gurpi Formation in the south-west of Iran and the north-west of Persian Gulf. The organic matter of Gurpi Formation in most samples has types III and II/III kerogen with low levels of maturity. Due to source rock assessment results, the Gurpi Formation cannot be an effective source rock in the southwest Iran and the northwest Persian Gulf. However, it can act as a secondary source rock in some areas such as Aghajari, Mansourabad, and Binak fields in Dezful Embaymnet (Hosseiny, Karmalachab, and Barati Boldaji 2020).

3. Materials and methods

The Gurpi geochemical study was conducted to assess its hydrocarbon generation potential and to understand the participation in charging the Ilam reservoir in the east Persian Gulf. In total, 111 cuttings were gathered from 10 oilfields within the research area (Figure 1). Sampling was guided by well gamma ray log and confirmed by macroscopic and petrographic inspection. Intervals exhibiting elevated gamma ray counts, interpreted as clay/marl rich horizons, were flagged for sampling. Only intervals confirmed as marl or shale were retained for geochemical analyses. The results of the geochemical analyses are summarized in three tables: Rock-Eval pyrolysis and vitrinite reflectance data are shown in Table 1; elemental composition, visual kerogen data, and Py – GC – MS results appear in Table 2; and biomarker ratios along with stable carbon isotope data are presented in Table 3.

The pyrolysis is usually the first and best tool for evaluating petroleum potential. The powdered samples were analyzed by Rock-Eval 6. It measured geochemical parameters, including S_1 , S_2 , S_3 , TOC, Hydrogen Index, Oxygen Index, and T_{max} . Rock Eval results were subjected to standard quality control protocols prior to interpretation. Samples exhibiting anomalously high PI values (>0.5) or high S_1 /TOC ratios (>1.5) were flagged as potentially contaminated sample (Hosseiny and Barati Boldaji 2020). T_{max} values outside the 420–520°C range were manually checked and removed if they coincided with low S_2 (>0.5 mg HC/g rock) or strong disagreement with independent maturity parameters (%Ro or biomarker ratios).

Using the Soxhlet technique, bitumen was extracted from 13 representative samples with a solvent mixture of 93% dichloromethane and 7% methanol. The asphaltene of bitumens were precipitated by hexane, then saturated, aromatic, and resin were separated by a silica-alumina column chromatography. Gas chromatography and gas chromatography – mass spectrometry evaluated various geochemical parameters. The GC system used a 25 m $\times$ 25 μ m capillary column (CP-Sil 5 CB) with helium gas flowing at 5 ml/min. For GC-MS, an Agilent 7890A gas chromatograph was linked to a 5975C mass selective detector (MSD).

Py-GC-MS was performed on six samples using a Pye Unicam Curie point pyrolyzer combined with a gas chromatograph (Hewlett/Packard 5890 series II) coupled to an MS-Engine quadrupole mass spectrometer. Pyrolysis was carried out at a Curie point temperature of 220°C for 4 s. The GC oven was programmed from 40°C (held isothermally for 2 min) to 235°C at 20°C min⁻¹, followed by a ramp to 265°C at 1°C min⁻¹, with a final hold of 5 min. Helium served as the carrier gas at 1.8 mL min⁻¹. The GC MS transfer line was maintained at 250°C, the ion source at 200°C, and the quadrupole analyzer at 100°C.

Stable carbon isotope measurement was performed on kerogens and fractions of crude oils using a Finnigan Delta Plus mass spectrometer calibrated against the PDB standard. In order to identify macerals and quality of organic matters, the visual kerogen analysis was used. For this purpose, seven rock samples were crushed to approximately 1 mm. Then, carbonate and silicate minerals were eliminated by hydrochloric and hydrofluoric acid, respectively. The isolated kerogen description was done using a microscope of Leitz-MPV-SP operating at a wavelength of 546 nm.

The predominant elemental constituents in kerogen include carbon (C), hydrogen (H), nitrogen (N), oxygen (O), and sulfur (S). Six kerogen samples were analyzed for elemental

Table 1. Rock-Eval pyrolysis and vitrinite reflectance results of Gurpi Formation.

Field	Depth (m)	TOC (%)	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	T _{max} (°C)	HI (mg/gTOC)	OI (mg/gTOC)	PI (S1/S1+S2)	%Ro
Reshadat	1102	0.08	0.07	0.14	0.24	424	175	300	0.50	
	1040	0.10	0.06	0.08	0.22	366	80	220	0.43	
Salman	1465	0.28	0.33	0.35	1.18	349	125	421	0.94	
	1438	0.46	0.46	0.46	1.82	411	100	396	1	
	1351	0.28	0.52	0.3	1.88	342	107	671	1.7	
	1323	0.43	2.25	0.15	1.78	337	35	414	15	
	1159	0.21	0.2	0.23	0.45	430	110	214	0.87	
Kish	1467	0.44	0.42	1.42	1.17	433	323	266	0.29	
	1442	0.33	0.32	1.24	1.09	433	376	330	0.26	
	1426	0.84	0.11	0.96	0.66	426	114	79	0.11	
	1412	0.39	0.32	1.02	1.07	427	262	274	0.31	
	1403	0.53	0.57	1.23	1.1	435	232	208	0.46	0.44
	1398	0.25	0.5	0.15	0.58	429	60	232	3.3	
	1396	0.93	0.16	1.27	0.72	429	137	77	0.12	
	1393	0.47	0.54	2.21	0.88	430	470	187	0.24	
	1387	0.39	0.49	0.58	1.16	428	149	297	0.84	
	1381	0.66	0.43	3.73	2	435	565	303	0.11	
Sirri A	2703	0.61	0.16	0.94	1.65	430	154	270	0.17	0.58
	2696	0.8	0.12	0.7	1.5	426	87	187	0.17	
	2689	0.55	0.07	0.35	1.64	425	64	298	0.2	0.54
	2675	0.43	0.09	0.37	1.74	426	86	405	0.24	
	2660	1.83	0.77	6.92	3.67	424	378	201	0.11	0.53
	2650	1.81	0.54	3.55	8.21	403	196	454	0.15	
	2640	0.68	0.35	1.43	3.51	413	210	516	0.24	0.49
	2625	0.5	0.12	1.38	2.13	432	276	426	0.08	0.52
	2605	0.62	0.12	1.97	2.16	433	318	348	0.06	0.53
	2595	0.47	0.11	1.33	1.94	433	283	413	0.08	
	2585	0.63	0.1	1.06	1.85	430	168	294	0.09	0.51
	2575	0.5	0.09	1.06	2	432	212	400	0.08	0.52
	2565	0.51	0.1	0.96	1.86	434	188	365	0.10	0.55
	2555	0.5	0.24	1.22	1.93	433	244	386	0.20	
	2535	0.77	0.24	2.43	2.1	431	316	273	0.10	0.52
	2525	0.7	0.2	1.98	1.98	432	283	283	0.10	0.53
	2515	0.69	0.2	1.88	1.98	431	272	287	0.11	0.54
	2503	0.54	0.15	1.56	1.96	434	289	363	0.10	
	2495	0.81	0.18	1.74	2.58	432	215	319	0.10	0.53
	2475	0.98	0.36	2.25	2.86	431	230	292	0.16	0.51
	2440	1.17	0.5	3.32	3.81	430	284	326	0.15	0.51
	2413	0.8	0.26	2.8	1.75	430	350	219	0.09	0.51
	2405	0.84	0.22	2.71	1.82	432	323	217	0.08	0.49
	2395	0.9	0.14	3	1.77	431	333	197	0.05	0.48
	2385	0.99	0.17	3.13	1.79	431	316	181	0.05	0.48
	1980	0.82	0.21	1.31	1.24	432	160	151	0.16	
	1942	0.62	0.21	0.58	2.47	434	94	398	0.36	
	1911	0.14	0.18	0.2	7.47	518	143	5335	0.90	
	1891	1.62	0.41	3.46	2.04	430	214	126	0.12	
Sirri E	1870	0.18	0.2	0.21	3.11	431	117	1727	0.95	
	3230	0.74	0.12	1.46	1.76	432	197	238	0.08	0.62
	3220	0.68	0.12	1.46	1.5	432	215	221	0.08	
	3210	0.75	0.12	1.48	1.78	431	197	237	0.08	0.61
	3200	0.76	0.11	1.14	1.65	430	150	217	0.10	0.61
	3190	0.71	0.15	1.19	2.04	430	168	287	0.13	
	3175	0.68	0.16	1.35	2.46	431	199	362	0.12	0.61
	3165	0.67	0.13	1.58	1.59	433	236	237	0.08	
	3155	0.83	0.26	2.34	1.71	435	282	206	0.11	0.6
	3145	0.48	0.15	1.39	1.47	434	290	306	0.11	0.59
	3135	0.38	0.12	1	1.58	432	263	416	0.12	
	3115	0.44	0.12	1.33	1.53	433	302	348	0.09	0.57
	3105	0.35	0.14	1.27	1.48	435	363	423	0.11	
	3085	0.6	0.16	1.76	1.87	433	293	312	0.09	0.56
	3045	0.55	0.17	1.46	1.5	435	265	273	0.12	0.55
	2875	0.35	0.13	0.68	1.79	430	194	511	0.19	
	2865	0.4	0.11	0.86	1.25	433	215	312	0.13	0.49

(Continued)

Table 1. (Continued).

Field	Depth (m)	TOC (%)	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	T _{max} (°C)	HI (mg/gTOC)	OI (mg/gTOC)	PI (S1/S1+S2)	%Ro
Nosrat	2965	1.39	1.24	4	2.92	431	288	210	0.31	0.50
	2951	0.82	0.44	1.49	1.74	431	182	212	0.30	
	2942	0.96	0.91	2.53	2.37	429	264	246	0.36	0.49
	2934	0.83	1.04	1.28	1.62	430	154	195	0.81	
	2927	1.05	0.81	2.71	2.37	431	258	225	0.30	0.51
	2916	0.77	0.82	1.56	1.46	439	203	190	0.53	
	2909	1.04	0.8	2.04	2.41	427	197	232	0.39	0.50
	2896	0.87	0.905	2	1.83	428	230	210	0.45	
	2884	1.12	0.99	2.47	2.89	429	221	258	0.40	0.49
	2877	1.09	1.275	2.71	2.12	430	249	194	0.47	0.53
	2848	1.18	1.76	3.47	3.32	432	294	281	0.50	0.51
	2838	0.79	0.9	1.48	2.01	439	187	254	0.61	
	2831	0.85	0.62	2.41	2.74	432	284	322	0.26	0.52
	2825	0.88	1.05	1.86	2.17	432	211	247	0.56	
	2819	0.83	0.83	2.41	2.94	432	290	354	0.34	0.50
	2812	0.8	0.745	1.74	1.65	435	217	206	0.43	
	2805	0.76	0.76	1.62	1.66	440	213	218	0.47	
	2793	0.77	0.49	2.35	2.5	432	305	325	0.21	0.48
	2782	1.06	1.08	2.71	2.02	433	256	191	0.40	
	2768	0.89	0.93	2.97	3.01	433	334	338	0.31	0.47
	2756	1.09	1.455	2.93	2.41	432	269	221	0.50	
	2749	0.9	0.69	2.72	2.37	432	302	263	0.25	0.46
	2738	1.01	1.06	3.22	3.26	428	319	323	0.33	
	2701	0.87	0.965	2.03	1.95	430	233	224	0.48	
	2689	0.79	0.69	2.53	2.79	431	320	353	0.27	0.41
	2677	0.8	0.8	2.28	3.06	430	285	382	0.35	
	2649	1.23	1.05	3.9	2.84	432	317	231	0.27	0.44
	2631	1.05	1.255	2.26	2.16	432	215	206	0.56	0.46
	2622	0.85	0.7	1.98	3.02	432	233	355	0.35	0.41
	2613	0.8	1.135	1.4	2.04	433	175	255	0.81	
	2599	0.62	0.38	1.5	2.15	434	242	347	0.25	0.45
	2581	0.6	0.75	0.79	1.23	434	132	205	0.95	0.47
	2567	0.5	0.39	1.09	1.71	435	218	342	0.36	0.53
	2558	0.38	0.64	0.47	1.05	434	124	276	1.36	
	2547	0.38	0.18	0.68	1.21	433	179	318	0.26	
Sirri D	2348	0.88	0.23	1.07	1.32	435	122	150	0.21	0.55
	2345	0.9	0.31	1.14	1.43	433	127	159	0.27	
	2340	0.78	0.18	0.75	1.29	430	96	165	0.24	
Farzam	2335	0.96	0.29	1.31	1.53	433	136	159	0.22	0.53
	2337	1.11	0.34	1.49	2.45	431	134	221	0.23	
	2229	1.27	0.24	2.7	1.74	434	213	137	0.09	0.51
	2221	1.03	0.17	1.86	1.77	432	181	172	0.09	
Farur	2215	1.09	0.48	1.54	1.87	436	141	172	0.31	0.5
	2199	2.57	0.31	7.21	1.89	431	281	74	0.04	0.5
	1760	0.62	0.67	1.46	1.23	433	235	198	0.46	
Hamoon	1687	0.35	2.33	0.19	1.12	413	541	320	12.2	0.37
	1013	0.65	0.55	1.18	0.67	423	182	103	0.47	
	1005	0.55	0.6	1.2	0.65	425	218	118	0.33	

composition through Carlo Erba EA 1108 instrument. The kerogen was isolated by the Vinci Technologies Kerogenatron apparatus.

The vitrinite reflectance (Ro) is a common and powerful tool to examine thermal maturity of organic matters (Ghosh et al. 2022). The measurement was carried out on 55 samples by Zeiss Axioplan II microscope (546 nm wavelength) in random mode under oil immersion (ASTM-D7708-14, 2014). The photometer was calibrated by sapphire glass

Table 2. Elemental composition, visual kerogen analysis and Py – GC – MS data of Gurpi Formation.

Field	Depth (m)	Elemental Analysis		Maceral analysis			Py – GC – MS of kerogen		
		H/C	O/C	Lipt (%)	Vit (%)	Inert (%)	n-nonene (%)	2,3-dm-thiophene (%)	o-xylene (%)
Sirri A	2693	–	–	–	–	–	28.3	11	60.7
	2390	1.04	0.11	40	50	10	41.8	28.8	29.5
Nosrat	2933	0.89	0.09	35	55	10	46.3	17.1	36.6
	2893	–	–	30	60	10	–	–	–
Farzam	2856	1.03	0.09	30	60	10	47.4	21.3	31.3
	2283	1.02	0.16	–	–	–	46	22.6	31.4
	2199	1.11	0.14	40	50	10	38.8	30.8	30.4
Kish	1402	0.84	0.13	35	55	10	–	–	–
	1388	0.89	0.09	30	60	10	–	–	–

standard (0.55%Ro) for every 50 analyses. At least 20 random vitrinite measurements per sample were recorded, reporting mean %Ro.

Petrographic analysis was conducted on seven representative rock samples to characterize kerogen composition and maceral distribution. Macerals are microscopic constituents of organic matter, originating from the remains of terrestrial, lacustrine, and marine vegetation. Maceral identification was performed on a reflected light petrographic microscope equipped with UV fluorescence based on physico-optical properties.

Basin modeling is widely used in geology and petroleum exploration. This method reconstructs the thermal and geological development of a sedimentary basin using the geochemical, geophysical, and geological information. In this paper, one-dimensional modeling (PetroMod software, Schlumberger) was performed to evaluate the thermal and maturation history of Gurpi in the two drilled wells and two pseudo-wells (Figure 1).

4. Results

4.1. Hydrocarbon source rock potential

Rock-Eval pyrolysis results are listed in Table 1. The Total Organic Carbon values of more than 95 range from 0.06 to 2.57 weight percent, with a mean value of 0.76 weight percent. The highest TOC contents belong to the southeastern region of the study area, specifically within the Sirri district. The petroleum potential yield, defined as the sum of S1 (free hydrocarbon) and S2 (generated hydrocarbon during pyrolysis) peaks, is valuable for evaluating the hydrocarbon generation potential of a source rock (Ghosh et al. 2022). The values lower than 6 mg HC/g rock indicate poor to fair generation potential (Tissot and Welte 1984). The cross plot of petroleum potential against TOC indicates that almost all samples have poor to fair petroleum generation potential (Figure 3A). The samples from Sirri A, D, E, Nosrat and Farzam in the south-eastern study area are fair while the others are poor.

4.2. Organic matters type

The organic matter type has important impacts on both quantity and quality of generated hydrocarbon within a source rock (Tissot and Welte 1984). Kerogens are commonly classified into Type I, II, III, and IV based on its hydrogen maceral contents. Type

Table 3. Saturate biomarker ratios and stable carbon isotope data of rock extracts from Gurpi Formation.

Field	Depth (m)	P ₁₇ / n-C ₁₇	Ph/ n-C ₁₈	n-C ₂₇ / n-C ₁₇	CPI	P _{aqu}	C ₂₉ aaa 20S/(S +R)	C ₂₉ aββ/ (aaa +aββ)	% C27aaa 20 R	% C28aaa 20 R	% C29aaa 20 R	C ₁₉ / C ₂₃ t	C ₂₂ / C ₂₁ t	C ₂₄ / C ₂₃ t	C ₂₆ / C ₂₅ t	C ₂₉ H/ C ₃₀ H	C ₃₁ R/ C ₃₀ H	Mor/ C ₃₀ H	C ₃₅ S/ C ₃₄ SH	GamIndex	δ ¹³ Csat	δ ¹³ C _{Caro}
Sirri A	2693	1.87	0.92	2.11	1.15	0.69	0.39	0.42	48.8	20.3	30.9	0.25	0.26	0.45	0.35	0.88	0.43	0.18	1.06	0.07	-27.6	-27.2
	2655	0.37	0.43	2.78	1.06	0.74	0.17	0.25	34.9	30.2	34.9	0.05	0.29	0.53	0.45	0.82	0.42	0.16	1.23	0.24	-28.1	-27.8
	2445	0.50	0.54	5.60	0.91	0.75	0.15	0.30	34.8	31.7	33.5	0.09	0.34	0.51	0.36	0.76	0.47	0.25	0.86	0.05	-28.2	-27.9
	2390	0.61	0.59	1.80	1.13	0.79	0.10	0.25	35.2	32.0	32.8	0.08	0.41	0.49	0.36	0.64	0.58	0.34	0.31	0.14	-27.9	-28.1
Sirri E	3210	0.69	0.68	0.63	1.00	0.85	0.18	0.27	36.3	26.7	37.0	0.03	0.39	0.57	0.67	0.72	0.46	0.31	1.13	0.15	-27.6	-27.5
Nosrat	2933	0.46	0.58	0.27	0.67	0.83	0.20	0.30	36.9	27.5	35.6	0.17	0.49	0.48	0.33	0.80	0.36	0.24	0.69	0.14	-27.4	-27.2
	2900	0.58	0.67	2.83	0.92	0.80	0.27	0.35	37.0	28.6	34.4	0.04	0.47	0.50	0.37	0.90	0.37	0.16	1.02	0.13	-27.7	-27.4
	2856	0.57	0.63	0.42	1.02	0.86	0.17	0.28	37.2	27.9	34.8	0.21	0.50	0.44	0.39	0.81	0.35	0.21	0.70	0.14	-27.1	-27
	2811	0.52	0.46	0.30	1.13	0.81	0.16	0.31	38.8	29.7	31.6	0.16	0.44	0.46	0.92	0.79	0.42	0.17	0.84	0.14	-27.5	-27.3
Farzam	2767	0.65	0.06	0.41	1.04	0.86	0.15	0.26	37.0	29.4	33.6	0.29	0.43	0.44	0.30	0.67	0.38	0.25	0.76	0.13	-27.6	-27
	2661	0.55	0.55	0.20	1.05	0.84	0.13	0.25	36.1	29.3	34.5	0.28	0.52	0.45	0.41	0.71	0.39	0.24	0.54	0.14	-27.2	-27.1
	2199	0.52	0.62	42.2	1.01	0.45	0.08	0.24	35.4	34.3	30.3	0.02	0.35	0.46	0.34	0.47	0.58	0.35	1.07	0.16	-28.7	-28.8
	2283	0.22	0.49	63.3	1.02	0.55	0.13	0.23	31.7	35.5	32.8	0.02	0.36	0.56	0.49	0.58	0.53	0.37	0.79	0.13	-28.1	-27.5

CPI = [(n-C23+n-C25+n-C27+n-C29+n-C31)+(n-C25+n-C27+n-C29+n-C31+n-C33)]/2x[(n-C24+n-C26+n-C28+n-C30+n-C32)] [El-Nemr et al. 2016]; Paq = (n-C23+n-C25)/(n-C23+n-C25+n-C27+n-C31) (Ficken et al. 2000).

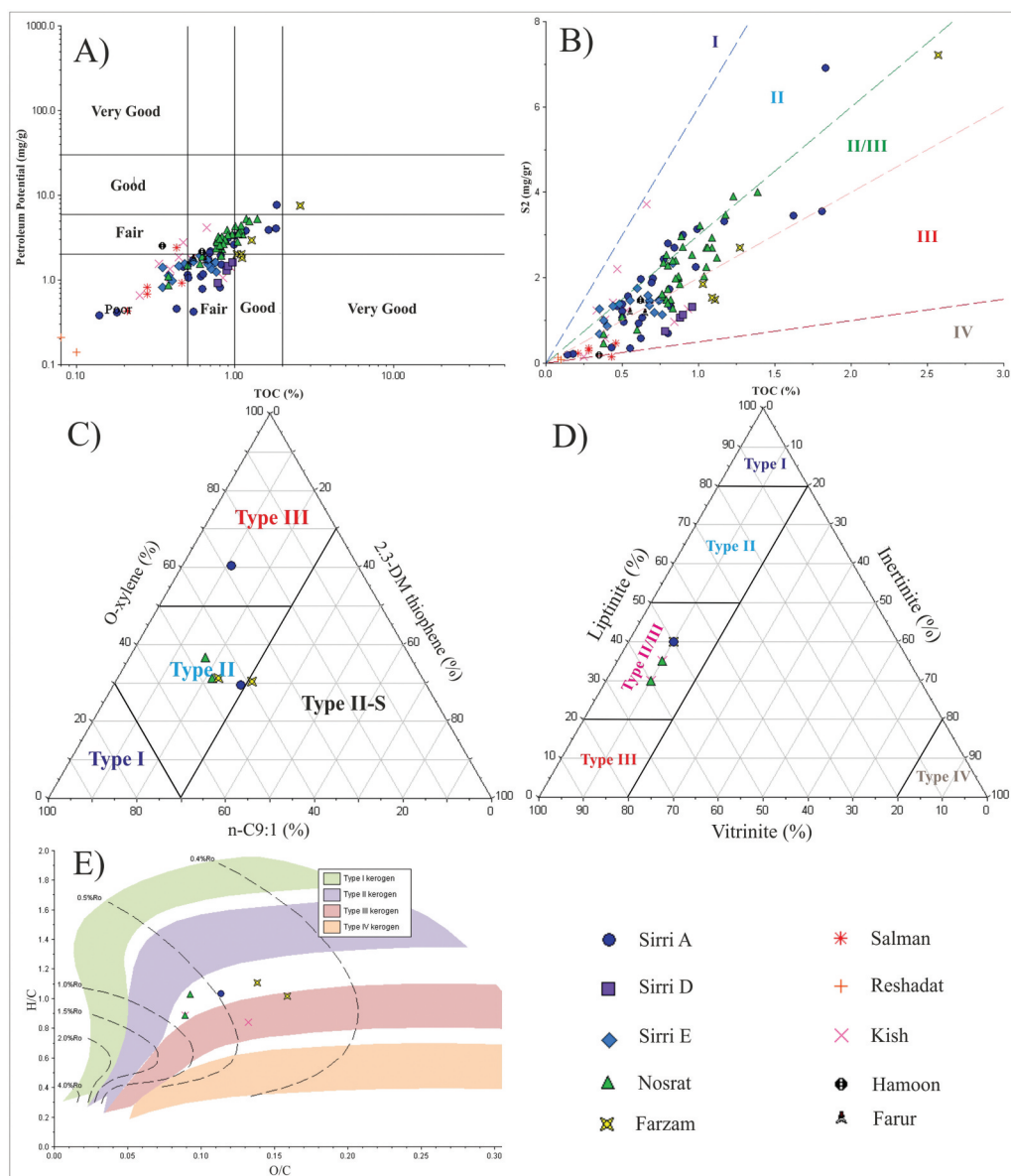


Figure 3. (A) Plot of petroleum potential vs TOC, (B) Plot of TOC vs S2, (C) Ternary diagram of n-C9:1, 2,3-dimethylthiophene, and o-xylene, (D) Ternary diagram of liptinite, vitrinite and inertinite, (E) The van Krevelen's diagram of H/C and O/C for Gurpi samples in the study area.

I (lacustrine) is strongly oil-prone, generating large volumes of paraffinic oil. Type II kerogen (marine) is moderately hydrogen-rich and yields oil and gas during maturation. Type III (woody, terrestrial) is hydrogen-poor and gas-prone and Type IV kerogen (oxidized/reworked) is essentially non-generative. The diagram of S2 against TOC reveals that samples with TOC > 0.5 have mainly kerogen type II/III (Langford and Blanc-Valleron 1990) (Figure 3B). The hydrogen index ($HI = S2/TOC \times 100$) varies from 34 to 565 mg HC/g

TOC (average = 221 mg HC/g TOC) (Table 1). The samples with fair and good quantity of organic matter are in the moderate range of HI (200–350 mg HC/g TOC). Therefore, they were deposited in a suboxic to weakly anoxic depositional condition, resulting in the predominant generation of gas and oil.

Kerogen type could be identified by the proportions of carbon, hydrogen, and oxygen. The diagram of van Krevelen applies atomic ratios of H/C and O/C to identify kerogen types and their maturity path (van Krevelen 1993). Accordingly, the atomic ratios of seven samples (Table 2) show type II/III kerogen within the Gurpi Formation (Figure 3E). Moreover, the distribution of *n*-non-1-ene, *o*-xylene and 2,3-dimethylthiophene components facilitates the assessment of the various types organic matter (I, II, II-S and III) (Eglinton et al. 1990). These components indicate concentration of aliphatic, aromatic, and sulfur-containing structures within the kerogen. Figure 3C shows low sulfur kerogen type II and III for six analyzed samples.

Besides chemical methods, optical methods are also used to determine the kerogen type. Macerals are microscopically recognized components of organic matter in kerogen. They are categorized into three main groups: liptinite, vitrinite, and inertinite (Sýkorová et al. 2005). The liptinite arises from lipid part of various plant and animal remains such as bacteria, algae, spore, pollen, cuticles, resin, and waxes. It is marked by a high hydrogen content and relatively higher oil generation. The vitrinite macerals consist of cell walls and woody plant tissue. The inertinite maceral group is mainly found in plant material transformed by severe degradation (Sýkorová et al. 2005). The organo-petrographic analysis of seven samples is reported in Table 2. The dominant maceral identified is vitrinite, followed by liptinite and inertinite. The ternary diagram of these macerals reveals that the Gurpi samples have kerogen type II/III (Figure 3D).

4.3. Maturity

The assessment of maturity level is the third step in the source rocks evaluation. Maturity parameters of Rock-Eval ($T_{\max}$ & PI), Vitrinite reflectance, biomarker ratios, and burial history have been used for this purpose.

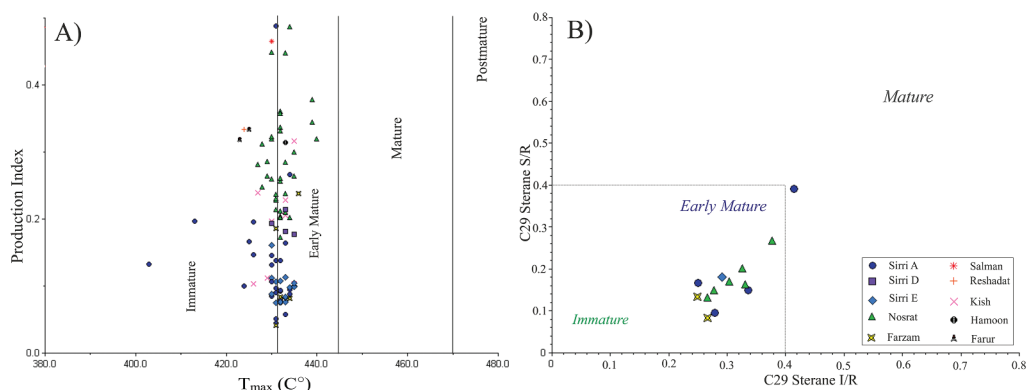


Figure 4. (A) Plot of $T_{\max}$ vs production Index, (B) Plot of C29 sterane I/R vs S/R for Gurpi samples in the study area.

Vitrinite reflectance (Ro%) quantifies the proportion of light that is reflected from the vitrinite surface. As the kerogen maturity increases, the vitrinite reflectivity increases. The onset of oil generation is around Ro% of 0.6% while the end of oil window is around 1.35% (Waples, Kamata, and Suizu 1992). The mean vitrinite reflectance varies between 0.3 and 0.61% in Gurpi Formation indicating immature and early mature of organic matters (Table 1). Furthermore, $T_{\max}$ supports this finding (Figure 4A). All $T_{\max}$ measurements are under 435°C, which suggests the Gurpi Formation is immature to early mature. A small number of samples have unusually low $T_{\max}$ values (337–349°C). These correspond to low TOC and low S2 yields (< 0.5 mg HC/g rock) and/or situations where S1 exceeds S2, indicating poor organic richness and low petroleum potential; in such samples, $T_{\max}$ is not a reliable indicator.

The C29 sterane isomerization of 20S/(20S + 20 R) and $\alpha\beta\beta/(\alpha\alpha\alpha + \alpha\beta\beta)$ and C31 and C32 homohopane isomerization of 22S/(22S + 22 R) are usually used to evaluate the maturity of oil and source rock (Peters and Moldowan 1993). These ratios reach an equilibrium value about 0.55, 0.7 and 0.6, respectively, during maturation. All samples have low ratio below the equilibrium value indicating low maturity level for Gurpi samples (Figure 4B). During maturity process, Moretane/Hopane ratio decreases and reaches approximately 0.05 during the initial phase of oil generation (Seifert and Moldowan 1980). The ratio ranges from 0.37 to 0.16 confirming low maturation level of Gurpi source rock (Table 3).

4.4. General sediment composition and depositional environment

It is well known that marine organic matter contains a high concentration of n-alkane from C15 to C25, while terrestrial organic matter with land plant origins exhibits a peak concentration of n-paraffin compounds between C25 and C29 (Tissot and Welte 1984). The short-chain n-C15 – 25 dominated the n-alkane pattern for most samples (Figure 5A).

The interplay between isoprenoids (Pr and Ph) and n-alkanes (n-C17 and n-C18) indicates kerogen types, maturity levels, and depositional condition of the source rock. The ratio of Pr/n-C17 and Ph/n-C18 in most samples fall in the marine environment near the border of mixed type region which indicate anoxic to suboxic condition. (Figure 6). Moreover, low values of Pr/n-C17 (< 0.5) indicate the influence of marine environment in depositional setting. In contrast, the high values (> 1) suggest terrigenous environment (Shanmugam 1985). Most samples have a ratio between 0.5 and 1 (Table 3).

The ratio of n-C27 to n-C17 is a commonly used indicator for determining the relative inputs from terrestrial and marine sources. High values (> 1) typically suggest a more outstanding contribution from terrestrial sources, while low values of this ratio (< 1) suggest a higher contribution from marine sources (Bourbonniere and Meyers 1996). In this study, we observed both low and high values of this ratio.

The Carbon-Preference Index (CPI) represents a ratio of odd to even n-alkanes and number of different formulae have been suggested (Bray et al. 1961). This index is often used to assign the contribution of land plants and microbial materials in immature source rocks. Hydrocarbons originated from land plants have CPI ~ 5–10, while hydrocarbons with more significant inputs marine micro-organisms have CPI approximating 1.0 (Bechtel et al. 2001; Samad et al. 2020). All samples have CPI values that approximate unity (Table 3).

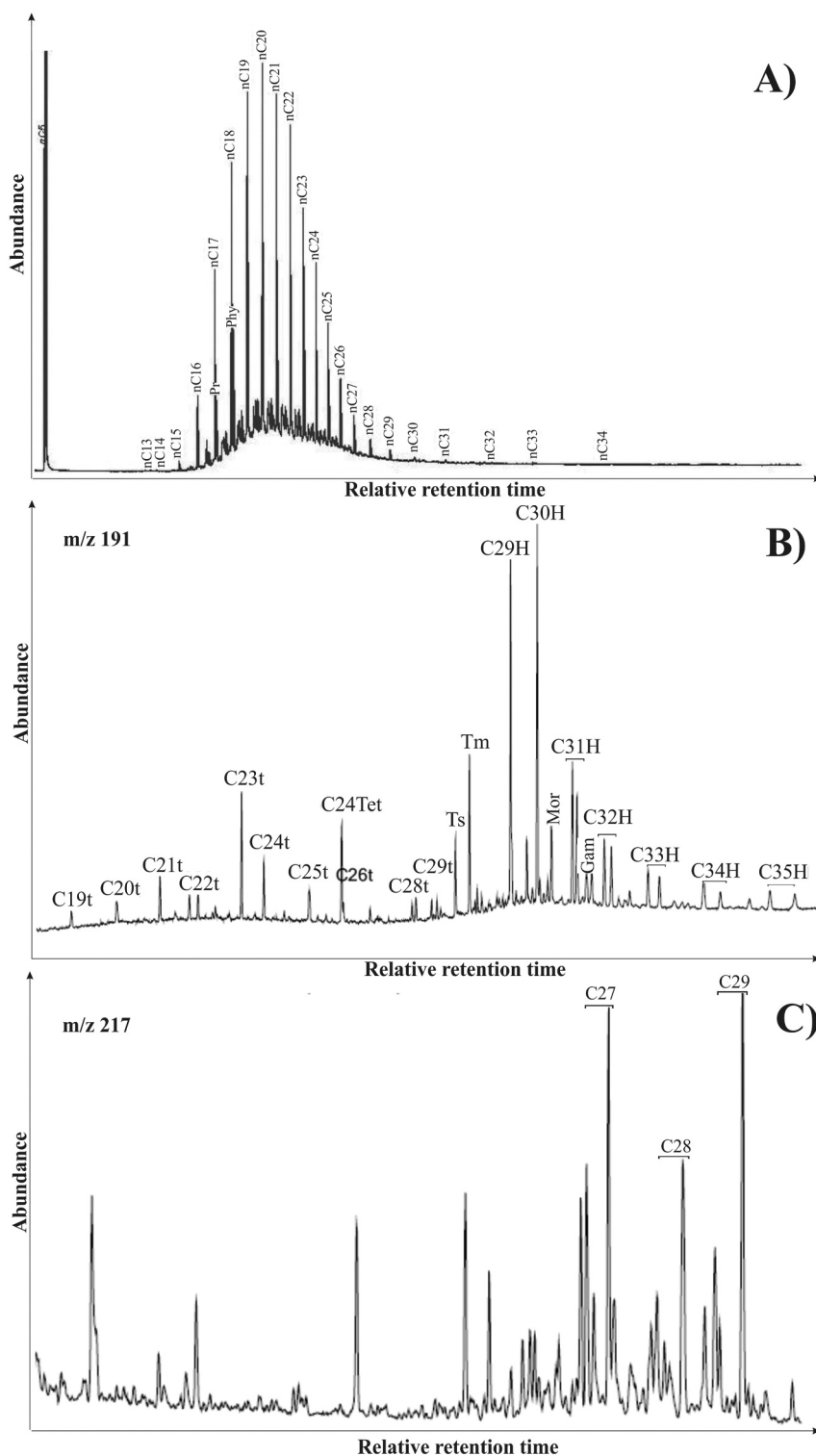


Figure 5. (A) Gas chromatogram, (B) m/z 191 and (C) m/z 217 fragmentogram of saturate fraction of Gurpi sample from Nosrat oil field.

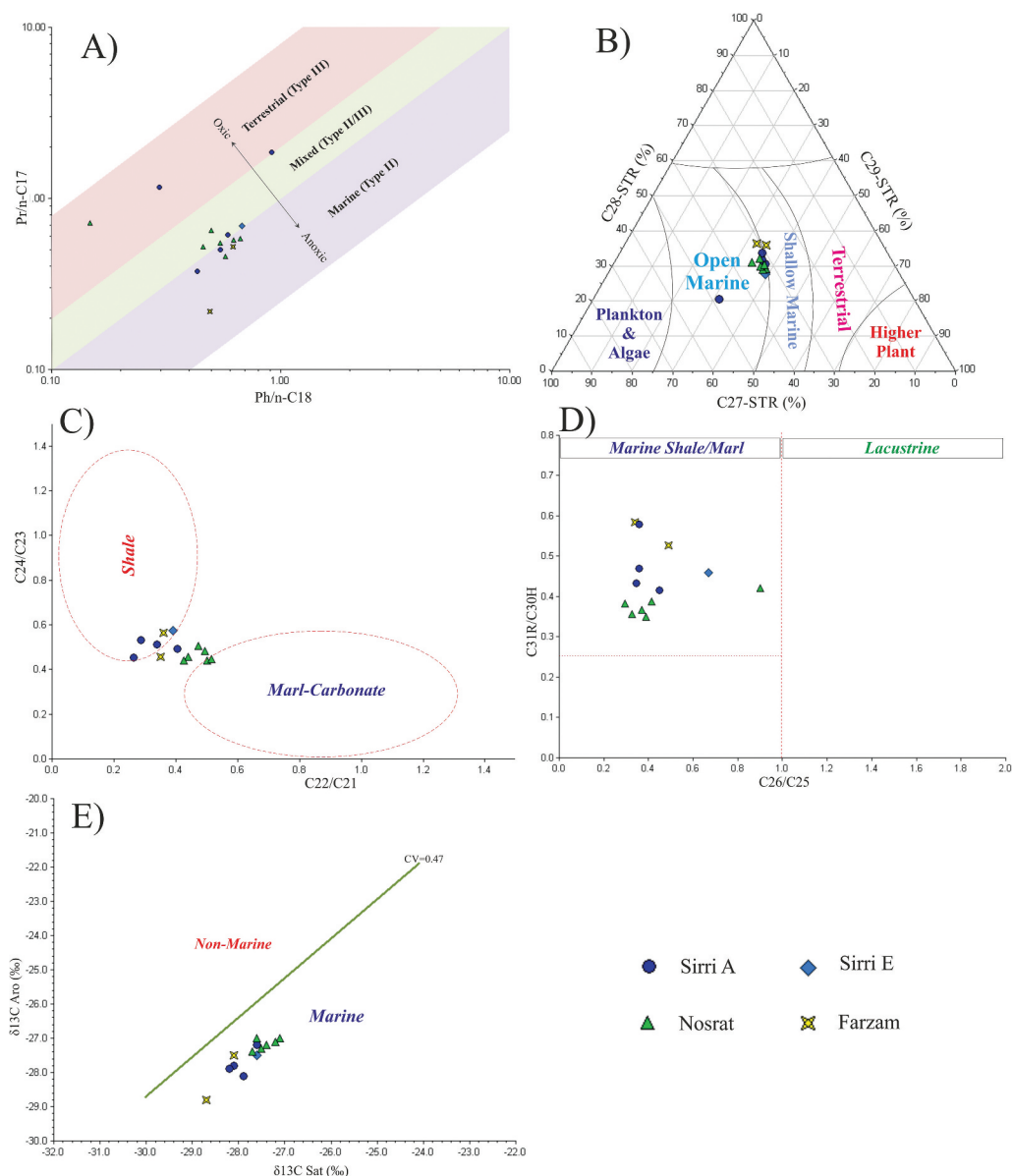


Figure 6. (A) Plot of $Pr/n-C17$ vs. $Ph/n-C18$, (B) Ternary diagram of C27, C28, C29 regular sterane, (C) Plot of $C22/C21$ vs. $C24/C23$ tricyclic terpanes, (D) Plot of $C31R/C30H$ vs. $C26/C25$ tricyclic terpanes, (E) Sofer plot of $\delta^{13}C$ for saturate and aromatic fraction for Gurpi samples in the study area.

In order to determine plants sources of lipid, Paq ratio was used. The land plants indicate values lower than 0.1, whereas emergent vegetation shows Paq ratio between 0.1 and 0.4, and values from 0.4 to 1 refer to submergent vegetation (Samad et al. 2020). This ratio for studied samples varies between 0.45 and 0.86 indicating organic matter contribution of submergent plants. Sediments with high submergent contribution commonly reflect sub-oxic to anoxic depositional conditions.

The relative amounts of steranes (C27, C28, and C29) furnish insights into the depositional environment of source rocks (Grantham and Wakefield 1988). C27 sterols are typically present in high concentrations within marine sedimentary environments. On the other hand, C28 are derived from marine phytoplankton and lacustrine algae, and C29 steranes are prevalent in terrigenous organic matters (Peters and Moldowan 1993) (Figure 5C). Figure 6A indicates that all samples were deposited in a marine setting.

Furthermore, biomarker ratios of terpanes are commonly utilized to ascertain the depositional condition and lithology of source rock. A high C19/C23 ratio (> 1) suggests a higher proportion of terrestrially derived organic matter, while a low value indicates a greater contribution from marine sources (Alberdi et al. 2001). All the studied samples have ratios below 1, indicating a high contribution of marine organic matters in Gurpi (Table 3 and Figure 5B).

The tricyclic terpene ratios of C22/C21 and C24/C23 are helpful tools for distinguishing between carbonate- and shale-source rocks. The high amount of C22/C21 (> 0.5) and low amount of C24/C23 suggest the lithology of marl-carbonate for source rock(s) (Peters, Walters, and Moldowan 2005). Accordingly, Figure 6C confirms lithology of shale and marl for Gurpi samples.

In order to distinguish marine and lacustrine paleo-environment, C26TT/C25TT tricyclic terpene and C31 22 R homohopane/C30 hopane are commonly used. The C26TT/C25TT tricyclic terpene ratio below 1 indicates the domination of marine environment, while the value greater than one evidences lacustrine environment (Holba et al. 2000). Moreover, oils from marine marl and shale source rock generally have C31R/C30 hopane ratio above 0.25 (Peters, Walters, and Moldowan 2005). Figure 6D shows the marine environment for almost all samples.

Another terpene ratio often employed to differentiate between carbonate and clay-rich source rock is C29 norhopane to C30 hopane (Peters and Moldowan 1993). The values above 0.7 imply carbonate source rock, whereas the values between 0.4 and 0.75 imply shale source rock. This ratio varies from 0.58 to 0.9 which indicate both carbonate and shale for Gurpi samples. Marine shale and marl typically deposited in low energy offshore settings that experience suboxic to anoxic conditions. Moreover, the C35S/C34S homophone ratio of studied samples ranges between 0.54 and 1.13 which indicates Gurpi Formation was deposited in an anoxic to suboxic condition (Table 3). Normal salinity condition during Gurpi deposition could be deduced due to low values of Gammacerane/hopane ratio for all samples (Table 3).

The stable carbon isotope of the saturate and aromatic fractions provides further evidence for the origin of the organic matter. Sofer (1984) suggests a plot of saturate fraction carbon isotopes versus aromatic ones to determine the paleo-environment of source rock. The $\delta^{13}\text{C}_{\text{sat}}$ values for the analyzed Gurpi samples range from -28.7‰ to -27.1‰ , while $\delta^{13}\text{C}_{\text{aro}}$ values range from -28.8‰ to -27.0‰ (Table 3). Figure 6E indicates that all Gurpi samples deposited in a marine environment corroborating the depositional setting inferred from biomarker distributions.

4.5. Burial history reconstruction

1D models of two wells and two pseudo-wells were created to provide a summary of the burial, thermal, and maturity history of Gurpi source rock, in addition to delineate the

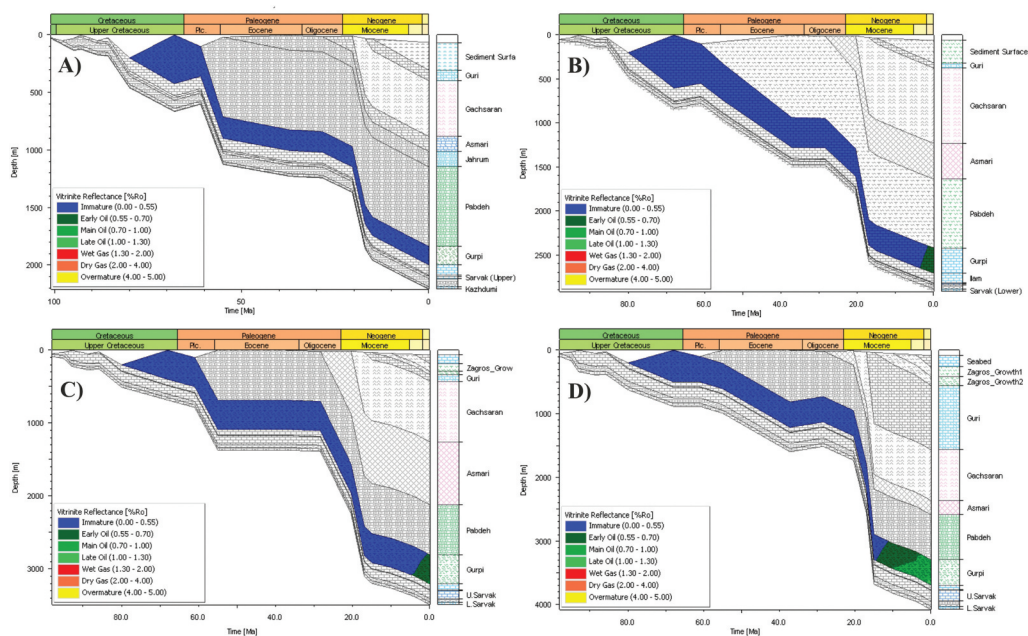


Figure 7. Burial and thermal modeling of (A) Sirri A, (B) Sirri E, (C) pseudo-well_1, and (D) pseudo-well 2.

temporal framework of its hydrocarbon generation across the Sirri A, Sirri E, and two pseudo-wells in the depression of the eastern study area (Figure 7). According to 1D burial profile, the Gurpi Formation is at the maximum depth in present days (Figure 7D). Its depth approach to near 3700 m in the depression in the east of Sirri district. The stratigraphic information and paleo-water depth (PWD) values were obtained from well and regional geological reports. The PWD is dependent on relative sea level changes. The depositional setting of each formation was used to infer paleo-water depth (PWD). A pronounced sedimentation rate (m/Ma) is noticeable during the Pabdeh and Gachsaran Formations. The temperature at the boundary between sediment and water (SWIT) was estimated from the time-latitude diagrams (Wygrala 1989). Heat flow is a critical input parameter for basin modeling; however, its reliable estimation for past geological periods remains a significant source of uncertainty. The present-day and paleo-heat flow values (in mW/m^2) were derived from and subsequently calibrated against bottom-hole temperature (BHT) and vitrinite reflectance (VR) measurements (Figure 8). This calibration yields a present-day heat flow of $\sim 68 \text{ mW/m}^2$ and reconstructed paleo-heat flow ranges from 50 to 70 mW/m^2 throughout the modeled history.

The thermal maturity was estimated by Sweeney and Burnham's (1990) method. The modeled vitrinite reflectance for the Gurpi in the Sirri A, Sirri E and pseudo-well 1 and 2 is estimated to be 0.47%, 0.62%, 0.64% and 0.92%, respectively. It entered the oil window about 3.5 and 4.5 million years ago in Sirri E well and pseudo-well 1. In pseudo-well 2, the Gurpi was entered in the main oil window about 9.5 million years ago (Figure 7).

Hydrocarbon generation in the Gurpi source rock is defined through transformation ratios in the model. In low transformation ratios, less than 10%, oil production is minimal. However, as the transformation ratio increases, the oil generation process becomes more

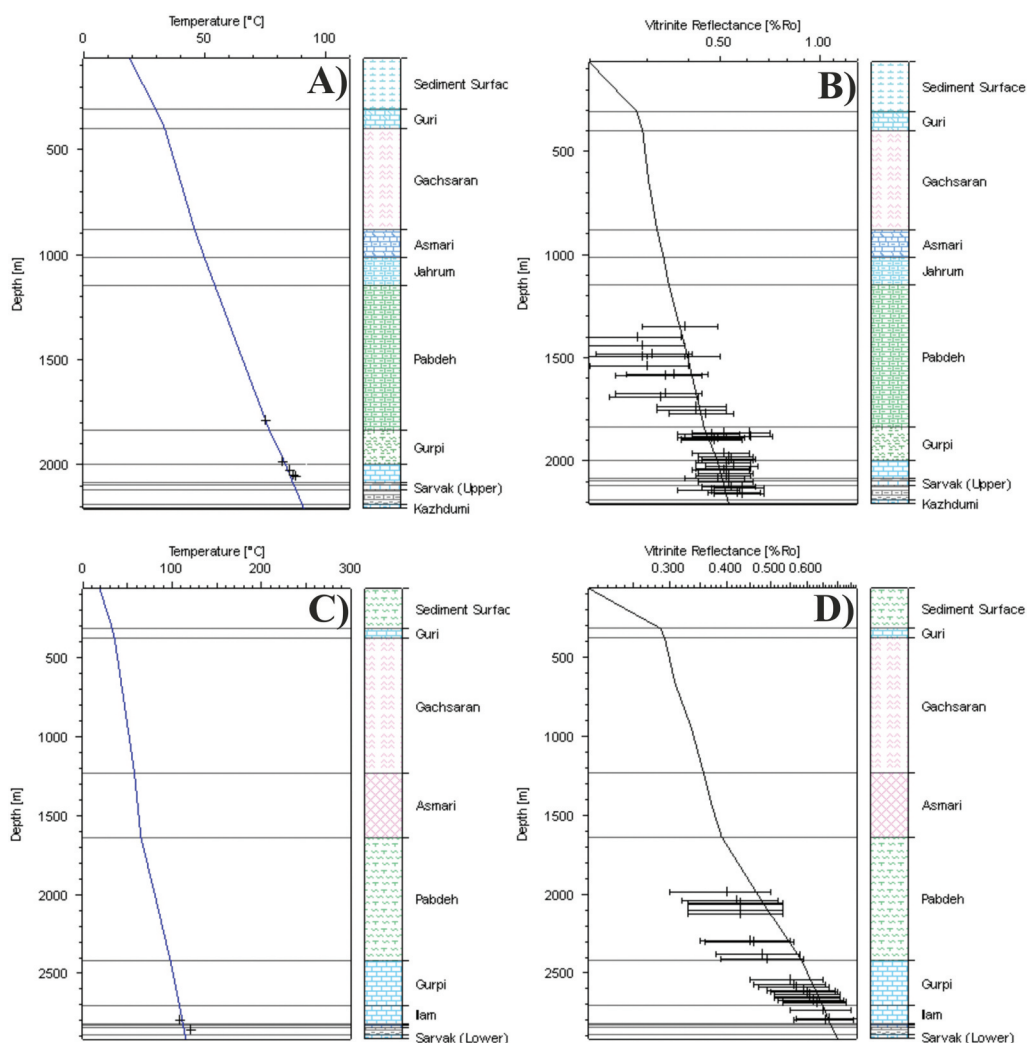


Figure 8. The calibrations of the thermal and maturity models with corrected bottomhole temperature and measured vitrinite reflectance in (A) Sirri A and (B) Sirri E.

active, with noticeable amounts of oil expelled from the rock when the ratio reaches about 30%. Moreover, peak oil generation occurs when the transformation ratio reaches 50% (Makeen et al. 2016). The transformation ratio of Gurpi in Sirri A, Sirri E, and pseudo-well 1 is less than 10%, while the TR in middle Gurpi at pseudo-well 2 is about 45% (Figure 9).

5. Discussion

The results of this study provide a comprehensive understanding of hydrocarbon generation potential, depositional environment, burial and thermal history of Gurpi in the eastern Persian Gulf.

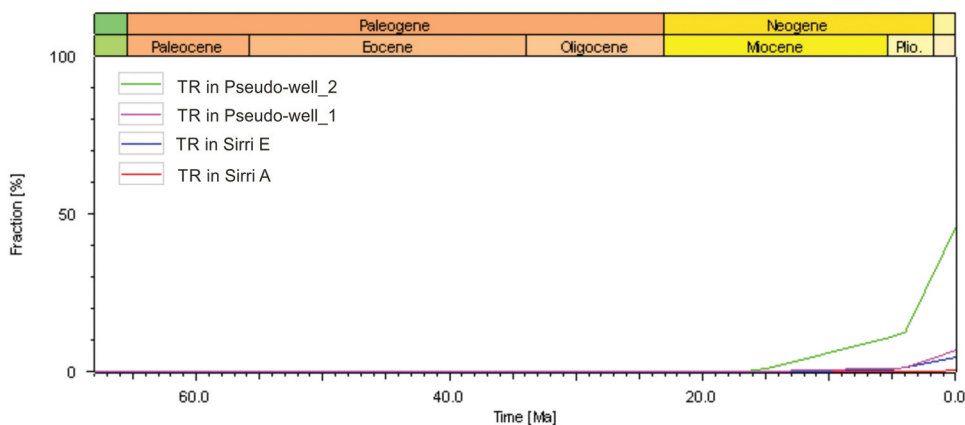


Figure 9. Evolution of transformation ratio along geological time for gurpi in Sirri A, Sirri E, pseudo-well_1 and pseudo-well 2.

The Gurpi Formation exhibits variable source rock potential across the study area. The observed TOC values generally indicate a poor to fair petroleum generation potential. This result aligns well with earlier research in the southwest Iran and northwest Persian Gulf (Hosseiny, Karmalachab, and Barati Boldaji 2020; Karami et al. 2017; Karimi et al. 2016; Moosavi et al. 2012; Vatandoust et al. 2020) that recognized poor to fair potential for Gurpi. The southeastern study region, particularly the Sirri district, shows the highest Total Organic Carbon (TOC) contents and S2 peak. This suggests localized areas within the study region offer a fair hydrocarbon prospects, despite most areas falling into the poor hydrocarbon generation capabilities.

The predominant kerogen type is II/III, as evidenced by multiple analytical methods including Rock-Eval pyrolysis, van Krevelen diagram, and organo-petrographic analysis. This kerogen type is consistent with the published results from the Gurpi Formation in the Dezful Embayment (Figure 2A) in southwestern Iran (Moosavi et al. 2013; Vatandoust et al. 2020). This mixed kerogen type indicates a combination of marine and terrestrial organic matter inputs with the potential for both oil and gas generation. The observation that samples with higher TOC values mainly consist of kerogen type II/III aligns with existing literature that correlates the quantity of organic matter with its quality. The Fiqa Formation (its equivalents in the UAE and Oman) in some wells within Abu Dhabi areas is dominated by kerogen Type III and IV with mean vitrinite reflectance of $\sim 0.43\%R_o$, indicating immaturity and limited generative potential (Lijmbach et al. 1992). In contrast, several exploratory wells in northeast offshore Abu Dhabi contain more sapropelic organic matter with moderate maturity, which could have generated or contributed to petroleum charge (Alsharhan 1995).

Several biomarker and geochemical indicators consistently point to a marine depositional environment for the Gurpi Formation. However, there are indications of some terrestrial input, as evidenced by the mixed kerogen type II/III. The depositional condition falls in suboxic to anoxic. This is consistent with the preservation of organic matter required to form potential source rocks. Moreover, biomarker ratios indicate that the Gurpi

Formation consists of both shale and marl lithology. These geochemical results show good consistency with geological evidence (Bordenave and Hegre 2010; Gowhari et al. 2020).

The assessment of maturity through various parameters indicates that the Gurpi Formation is largely in an immature to early mature state. This suggests that the Gurpi has reached varying degrees of maturity across different locations, which is crucial for understanding its hydrocarbon generation capabilities. The western region is characterized as immature, while the eastern region is in the early mature stage. The Van Krevelen's diagram showed in Figure 3E confirms this result. Moreover, this trend aligns with geological expectations (Figure 1), where depth and thermal gradient contribute significantly to the maturation process. It is important to note that the analyzed samples were from structural crests, suggesting that maturity levels may be higher in synclines and depressions, particularly in the eastern Sirri fields.

Based on the evaluation of the source rock in the previous paragraphs, the Gurpi in the southeastern part of the studied area has a moderate potential for oil and gas generation and its early mature status suggests that significant hydrocarbon generation may only occur in deeper, more thermally mature parts of the basin. The transformation ratio analysis confirms above conclusion and reveals that while the Gurpi Formation in Sirri A, Sirri E, and pseudo-well 1 has low transformation ratios (less than 10%), indicating limited oil generation, the significantly higher transformation ratio of approximately 45% in pseudo-well 2 and entering the main oil window approximately 9.5 million years ago suggests that this area has been more conducive to hydrocarbon generation. Accordingly, some hydrocarbon could have been generated and expelled from Gurpi and migrated downward to Ilam Formation. This proposition is presented as a qualitative inference grounded in (a) the demonstrated petroleum potential and maturity of Gurpi source rock from 1D models, (b) regional stratigraphic relationships and structural proximity between Gurpi depocenters and the Ilam reservoir. The implications of these findings are significant for hydrocarbon exploration and production strategies in the region. The potential downward migration of hydrocarbons from the Gurpi Formation to the Ilam Formation, particularly impacting the Mubarak and Sirri E areas, underscores the need for targeted exploration in these locations. In future, more research (Oil-Source correlation, 2D/3D petroleum system modeling) is necessary to examine the spatial variability in hydrocarbon potential and to improve models of hydrocarbon generation and migration within this formation.

6. Conclusion

In a comprehensive investigation aimed at assessing the hydrocarbon generation capability of the Gurpi Formation and its contribution to charging the Ilam reservoir in the eastern region of the Persian Gulf, a total of 111 rock samples were procured from 10 oilfields within the study area. The total organic carbon values fluctuate between 0.06 and 2.57 wt%, with a mean value of 0.76 wt%. Notably, the highest values of TOC are found in the south-eastern study area (Sirri A, D, E, Nosrat, and Farzam), showcasing fair petroleum generation potential. The samples with fair to good quantity of organic matter fall within the moderate range of HI (200–350 mgHC/gTOC). Kerogen type analysis predominantly reveals type II/III in the Gurpi Formation. The vitrinite reflectance varies from 0.3 to 0.61%. The maturity parameters increase from immature in the west to early oil window in the east of the investigation area. Moreover, the modeled

vitrinite reflectance values in the Sirri A, Sirri E, and pseudo-wells 1 and 2 are estimated at 0.47%, 0.62%, 0.64%, and 0.92%, respectively. Gurpi has reached the main oil window approximately 9.5 million years ago in pseudo-well 2. The transformation ratio in Sirri A, Sirri E, and pseudo-well 1 is less than 10%, while the transformation ratio in pseudo-well 2 is around 45%.

Nomenclature

1D	1 Dimension
GC	Gas chromatography
GC-MS	Gas chromatography-mass spectrometry
Py-GC-MS	Pyrolysis-gas chromatography-mass spectrometry
PDB	Pee Dee Belemnite
TOC	Total Organic Carbon
HI	Hydrogen Index
OI	Oxygen Index
PI	Production index
Pr	Pristane
Ph	Phytane
CPI	The Carbon-Preference Index
Paq	Proxy aqueous
$C_{19}/C_{23}t$	C_{19}/C_{23} tricyclic terpanes
$C_{22}/C_{21}t$	C_{22}/C_{21} tricyclic terpanes
$C_{24}/C_{23}t$	C_{24}/C_{23} ricyclic terpanes
$C_{26}/C_{25}t$	C_{26}/C_{25} tricyclic terpanes
$C_{30}H$	C_{30} hopane
$C_{29}H$	C_{29} 30-norhopane
$C_{31}HR$	C_{31} homohopane 22R
$C_{34}H$	C_{34} homohopane
$C_{35}H$	C_{35} homohopane

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

All data during this study are given in this article.

References

- Alberdi, M., J. Moldowan, K. Peters, and J. Dahl. 2001. "Stereoselective Biodegradation of Tricyclic Terpanes in Heavy Oils from the Bolivar Coastal Fields, Venezuela." *Organic Geochemistry* 32 (1): 181–191.
- Al Rawahi, Z., and T. D. Jones. 2019. "Calcareous Nannofossil Assemblages of the Late Cretaceous Fiqa Formation, North Oman." *Journal of Micropalaeontology* 38:25–54. <https://doi.org/10.5194/jm-38-25-2019>.
- Alsharhan, A. S. 1995. "Sedimentology and Depositional Setting of the Late Cretaceous Fiqa Formation in the United Arab Emirates." *Cretaceous Research* 16:39–51. <https://doi.org/10.1006/cres.1995.1003>.
- ASTM-D7708-14. 2014. "Standard Test Method for Microscopical Determination of the Reflectance of Vitrinite Dispersed in Sedimentary Rocks." ASTM International, Annual Book of ASTM Standards: 823–830.
- Bechtel, A., W. Gruber, R. F. Sachsenhofer, R. Gratzner, and W. Püttmann. 2001. "Organic Geochemical and Stable Isotopic Investigation of Coals Formed in Low-Lying and Raised Mires Within the Eastern Alps (Austria)." *Organic Geochemistry* 32 (11): 1289–1310. [https://doi.org/10.1016/S0146-6380\(01\)00101-2](https://doi.org/10.1016/S0146-6380(01)00101-2).
- Bordenave, M., and J. Hegre. 2010. "Current Distribution of Oil and Gas Fields in the Zagros Fold Belt of Iran and Contiguous Offshore as the Result of the Petroleum Systems." *Geological Society, London, Special Publications* 330 (1): 291–353. <https://doi.org/10.1144/SP330.14>.
- Bourbonniere, R. A., and P. A. Meyers. 1996. "Sedimentary Geolipid Records of Historical Changes in the Watersheds and Productivities of Lakes Ontario and Erie." *Limnology and Oceanography* 41:352–359. <https://doi.org/10.4319/lo.1996.41.2.0352>.
- Bray, E. E., E. D. Evans, E. E. Bray, and E. D. Evans. 1961. "Distribution of N-Paraffins as a Clue to Recognition of Source Beds." *Geochimica et Cosmochimica Acta* 22 (1): 2–15. [https://doi.org/10.1016/0016-7037\(61\)90069-2](https://doi.org/10.1016/0016-7037(61)90069-2).
- Eglinton, T. I., J. S. Sinninghe-Damsté, M. E. L. Kohnen, and J. W. de Leeuw. 1990. "Rapid Estimation of the Organic Sulphur Content of Kerogens, Coals and Asphaltenes by Pyrolysis–Gas Chromatography." *Fuel* 69 (11): 1394–1404. [https://doi.org/10.1016/0016-2361\(90\)90121-6](https://doi.org/10.1016/0016-2361(90)90121-6).
- El-Nemr, A., A. A. Moneer, S. Ragab, and A. El-Sikaily. 2016. "Distribution and Sources of N-Alkanes and Polycyclic Aromatic Hydrocarbons in Shellfish of the Egyptian Red Sea Coast." *Egyptian Journal of Aquatic Research* 42:121–131. <https://doi.org/10.1016/j.ejar.2016.05.003>.
- Ficken, K. J., B. Li, D. L. Swain, and G. Eglinton. 2000. "An N-Alkane Proxy for the Sedimentary Input of Submerged/Floating Freshwater Aquatic Macrophytes." *Organic Geochemistry* 31:745–749. [https://doi.org/10.1016/S0146-6380\(00\)00081-4](https://doi.org/10.1016/S0146-6380(00)00081-4).
- Ghazban, F. 2007. *Petroleum Geology of the Persian Gulf*. Tehran: Tehran University and National Iranian Oil Company Publications.
- Ghosh, K. K., K. Das, S. Bhattacharyya, and C. P. Ramteke. 2022. "Characterization of Shale Gas Reservoir of Lower Gondwana Litho-Assemblage at Mohuda Sub-Basin, Jharia Coalfield, Jharkhand, India." *Journal of Natural Gas Science and Engineering* 97:104316. <https://doi.org/10.1016/j.jngse.2021.104316>.
- Gowhari, S. A., V. Ahmadi, H. Saroea, and K. Yazdgerdi. 2020. "Depositional Environment, Sequence Stratigraphy and Biostratigraphy of the Gurpi Formation in Fars Zone, Zagros Basin (SW Iran)." *Carbonates and Evaporites* 35:86. <https://doi.org/10.1007/s13146-020-00620-6>.
- Grantham, P. J., and L. L. Wakefield. 1988. "Variations in the Sterane Carbon Number Distributions of Marine Source Rock Derived Crude Oils Through Geological Time." *Organic Geochemistry* 12:61–73. [https://doi.org/10.1016/0146-6380\(88\)90115-5](https://doi.org/10.1016/0146-6380(88)90115-5).
- Hakimi, M.H., Kumar A., Lashin A., Rahim A., Varfolomeev M.A., Abdulmumini Yelwa N., Mustapha K.A., 2023. "Geochemistry and organic petrology of the bituminite shales from the Kapurdi mine, Rajasthan of NW India: implications for waxy oil generation potential." *Journal of Petroleum Exploration and Production Technology* 13:505–521.

- Hatem, B. A., M. H. Hakimi, K. A. Mustapha, W. H. Abdullah, and A. Kumar. 2026. "Shale–Oil Potential in Shabwah Depression, Southeast Yemen: A Geochemical and Basin Modeling Perspective." *Journal of African Earth Sciences* 233:105848.
- Holba, A. G., E. W. Tegelaar, L. Ellis, M. S. Singletary, and P. Albrecht. 2000. "Tetracyclic Polyprenoids: Indicators of Freshwater (Lacustrine) Algal Input." *Geology* 28:251–254. [https://doi.org/10.1130/0091-7613\(2000\)28<251:TPIOFL>2.0.CO;2](https://doi.org/10.1130/0091-7613(2000)28<251:TPIOFL>2.0.CO;2).
- Hosseiny, E. 2024. "Geochemical Variability of Oils from Jurassic Petroleum System in the East of Persian Gulf." *Petroleum Science and Technology* 42 (1): 102–121. <https://doi.org/10.1080/10916466.2022.2118776>.
- Hosseiny, E., and S. Barati Boldaji. 2020. "Evaluation of Hydrocarbon Generation Potential of Sargelu Source Rock in the Southwestern Iran and Northwestern Persian Gulf." *Journal of Analytical and Numerical Methods in Mining Engineering (In Persian)* 10 (23): 79–89.
- Hosseiny, E., M. Karmalachab, and S. Barati Boldaji. 2020. "Hydrocarbon Generation Potential of Gurpi Formation in the Southwestern Iran and Northwestern Persian Gulf." National Conference on Knowledge-Based Research in Oil, Gas, Refining and Petrochemical Industries, Ahvaz, Iran.
- Hosseiny, E., A. R. Rabbani, and S. A. Moallemi. 2016. "Source Rock Characterization of the Cretaceous Sarvak Formation in the Eastern Part of the Iranian Sector of Persian Gulf." *Organic Geochemistry* 99:53–66. <http://dx.doi.org/10.1016/j.orggeochem.2016.06.005>.
- Hosseiny, E., A. R. Rabbani, and S. A. Moallemi. 2017. "Oil Families and Migration Paths by Biological Markers in the Eastern Iranian Sector of Persian Gulf." *Journal of Petroleum Science and Engineering* 150:54–68. <http://dx.doi.org/10.1016/j.petrol.2016.11.031>.
- James, G. A., and J. G. Wynd. 1965. "Stratigraphic Nomenclature of Iranian Oil Consortium Agreement Area." *AAPG Bulletin* 49 (12): 2182–2245. <https://doi.org/10.1306/A663388A-16C0-11D7-8645000102C1865D>.
- Karami, A., M. Memariyani, M. R. Kamali, and E. Hosseiny. 2017. "Investigating the Geochemical Characteristics and Evaluating the Hydrocarbon Generation Potential of Gurpi and Pabdeh Formations in a Number of Fields Located in the Northwest of the Persian Gulf." *Iranian Journal of Petroleum Geology* 13 (7): 63–77.
- Karimi, A. R., A. R. Rabbani, M. R. Kamali, and M. H. Heidarifard. 2016. "Geochemical Evaluation and Thermal Modeling of the Eocene–Oligocene Pabdeh and Middle Cretaceous Gurpi Formations in the Northern Part of the Dezful Embayment." *Arabian Journal of Geosciences* 9:1–16. <https://doi.org/10.1007/s12517-016-2370-5>.
- Kumar, A., K. A. Mustapha, V. P. Singh, B. Hazra, P. Gopinathan, and R. P. Mathews. 2025. "Paleodepositional Environment and Source Rock Potential of Paleogene Lignite and Shale Horizons in the Saurashtra Basin, Western India." *International Journal of Coal Science & Technology* 12:69. <https://doi.org/10.1007/s40789-025-00810-4>.
- Langford, F. F., and M. M. Blanc-Valleron. 1990. "Interpreting Rock-Eval Pyrolysis Data Using Graphs of Pyrolyzable Hydrocarbons vs. Total Organic Carbon." *AAPG Bulletin* 74:799–804. <https://doi.org/10.1306/0C9B238F-1710-11D7-8645000102C1865D>.
- Lijmbach, G. W. M., J. M. A. Buiskool Toxopeus, T. Rodenburg, and L. J. P. C. M. Hermans. 1992. "Geochemical Study of Crude Oils and Source Rocks in Onshore Abu Dhabi." Abu Dhabi Petroleum Conference, Abu Dhabi, SPE-24513–MS.
- Makeen, Y. M., W. H. Abdullah, M. J. Pearson, M. H. Hakimi, O. M. A. Elhassan, and T. A. H. Yousif. 2016. "Thermal Maturity History and Petroleum Generation Modelling for the Lower Cretaceous Abu Gabra Formation in the Fula Sub-Basin, Muglad Basin, Sudan." *Marine and Petroleum Geology* 75:310–324. doi:10.1016/j.marpetgeo.2016.04.023.
- Moosavi, M. H., S. Abdolzadeh, M. R. Kamali, M. Shayesteh, A. Ahmadi, and A. Kaabimofard. 2013. "Organic Geochemistry of Upper Cretaceous (Gurpi Formation) and Paleogene (Pabdeh Formation) Source Rocks in Par-E-Siah Field, NW Izeh, Iran." *Journal of Stratigraphy and Sedimentology Researches* 28 (4): 1–24.
- Moosavi, M. H., H. Amiribakhtiar, M. Shayesteh, S. Abdolzadeh, M. Gholamalemmammad, and N. Moslemzadeh. 2012. "Study and Investigation of Potential Source Rocks in the Masjed Soleiman Oil Field Using Pyrolysis and Thermal Modeling." *Journal of Stratigraphy and Sedimentology Researches* 27 (4): 65–84.

- Packer, S. R. 2002. *Fiqa Formation Study IV: Biostratigraphic Analysis of Selected Intervals from PDO Wells Qalah-2, Burhaan-5, Hanya-1, Wadi Umayri-1, Wadi Umayri-2 and Jahiz-1, North Oman*. Internal Millennia Report for PDO.
- Peters, K. E., and J. M. Moldowan. 1993. *The Biomarker Guide: Interpreting Molecular Fossils in Petroleum and Ancient Sediments*. Englewood Cliffs, New Jersey: Prentice-Hall.
- Peters, K. E., C. C. Walters, and J. Moldowan. 2005. *The Biomarker Guide, 1*. New York: Cambridge University Press.
- Rabbani, A. R., M. J. Kotarba, A. R. Baniasad, E. Hosseiny, and D. Wieclaw. 2014. "Geochemical Characteristics and Genetic Types of the Crude Oils from the Iranian Sector of the Persian Gulf." *Organic Geochemistry* 70:29–43.
- Rahmani, A., M. Naderi, and E. Hosseiny. 2023. "Shale Gas Potential of the Lower Silurian Hot Shales in Southern Iran and the Arabian Plate: Characterization of Organic Geochemistry." *Petroleum* 9:499–507. <https://doi.org/10.1016/j.petlm.2022.03.004>.
- Samad, S. K., D. K. Mishra, R. P. Mathews, S. Ghosh, V. A. Mendhe, and A. K. Varma. 2020. "Geochemical Attributes for Source Rock and Palaeoclimatic Reconstruction of the Auranga Basin, India." *Journal of Petroleum Science and Engineering* 185:106665. <https://doi.org/10.1016/j.petrol.2019.106665>.
- Seifert, W. K., and J. M. Moldowan. 1980. "The Effect of Thermal Stress on Source-Rock Quality as Measured by Hopane Stereochemistry." *Physics and Chemistry of the Earth* 12:229–237. [https://doi.org/10.1016/0079-1946\(79\)90107-1](https://doi.org/10.1016/0079-1946(79)90107-1).
- Sfidari, E., S. M. Zamanzadeh, A. Dashti, A. Opera, and M. H. Tavakkol. 2016. "Comprehensive Source Rock Evaluation of the Kazhdumi Formation, in the Iranian Zagros Foldbelt and Adjacent Offshore." *Marine and Petroleum Geology* 71:21–40. <https://doi.org/10.1016/j.marpetgeo.2015.12.011>.
- Shanmugam, G. 1985. "Significance of Coniferous Rainforests and Related Organic Matter in Generating Commercial Quantities of Oil, Gippsland Basin." *AAPG Bulletin* 69:1241–1254. <https://doi.org/10.1306/AD462BC3-16F7-11D7-8645000102C1865D>.
- Shekarifard, A., M. Daryabandeh, M. Rashidi, M. Hajian, and J. Röth. 2019. "Petroleum Geochemical Properties of the Oil Shales from the Early Cretaceous Garau Formation, Qalikh Localities, Zagros Mountains, IRAN." *International Journal of Coal Geology* 206:1–18.
- Sofer, Z. 1984. "Stable Carbon Isotope Compositions of Crude Oils: Application to Source Depositional Environments and Petroleum Alteration." *AAPG Bulletin* 68 (1): 31–49. <https://doi.org/10.1306/AD460963-16F7-11D7-8645000102C1865D>.
- Sweeney, J., and A. K. Burnham. 1990. "Evaluation of a Simple Model of Vitrinite Reflectance Based on Chemical Kinetics." *AAPG Bulletin* 74:1559–1570. <https://doi.org/10.1306/0C9B251F-1710-11D7-8645000102C1865D>.
- Sýkorová, I., W. Pickel, K. Christanis, M. Wolf, G. H. Taylor, and D. Flores. 2005. "Classification of Huminite—ICCP System 1994." *International Journal of Coal Geology* 62:85–106. <https://doi.org/10.1016/j.coal.2004.06.006>.
- Tissot, B. P., and D. H. Welte. 1984. *Petroleum Formation and Occurrence*. 2nd ed. Berlin: Springer-Verlag.
- van Krevelen, D. W. 1993. *Coal: Typology–Physics–Chemistry–Constitution*, 979. Amsterdam: Elsevier.
- Vatandoust, M., A. Faghih, S. Asadi, A. M. Azimzadeh, and M. H. Heidarifard. 2020. "Study of Hydrocarbon Generation and 1D-2D Modeling of Hydrocarbon Migration at the Karanj and Parsi Oilfields, Southern Dezful Embayment, SW Iran." *Marine and Petroleum Geology* 113:104095.
- Waples, D. W., H. Kamata, and M. Suizu. 1992. "The Art of Maturity Modeling: Part 1. Finding a Satisfactory Geological Model." *AAPG Bulletin* 76:31–46. <https://doi.org/10.1306/BDFF875E-1718-11D7-8645000102C1865D>.
- Wygrala, B. P. 1989. "Integrated Study of an Oil Field in the Southern Po Basin, Northern Italy Berichte der Kernforschungsanlage Jülich 2313, 226 p." :. (Jülich, Germany: Zentralbibliothek der Kernforschungsanlage) <http://hdl.handle.net/2128/6740>
- Ziegler, M. 2001. "Late Permian to Holocene Paleofacies Evolution of the Arabian Plate and Its Hydrocarbon Occurrences." *GeoArabia* 6: 445–504. <https://doi.org/10.2113/geoarabia0603445>