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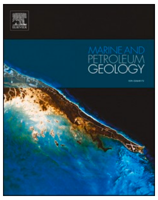

Relationship between structural style and the petroleum system in the siba gas field, southern Iraq

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ABSTRACT

The Siba gas field is the only non-associated gas field in southern Iraq, located in an area primarily for oil production. The study aimed to identify the reasons for gas generation and accumulation in the field's Lower Cretaceous Yamama reservoir and the source of the gas. The study focuses on seven wells from the field, namely Siba-1, 4, 5, 6, 7, 8, and 9, and the structural and tectonic settings of the field were studied by interpreting seismic data. Geometric analysis showed that the Siba field is a non-cylindrical, asymmetrical, open, anticlinal fold. The anticline is northeast-southwest-trending with two culminations, of which the northeastern one is the higher by about 100 m. The Siba field overlies deepest parts of the Mesopotamian foreland basin, almost adjacent to the Zagros orogenic front, where burial depth and thermal conditions were ideal for organic-matter maturation and increased pore pressures that lead to hydrocarbon migration from Middle Jurassic source rocks to the Lower Cretaceous Yamama Formation reservoir. The geochemical parameters of oils from the Yamama Formation are like those of oils from Sargelu Formation in adjacent fields, indicating that the Middle Jurassic Sargelu Formation is the most likely source of Siba hydrocarbons. Vitrinite reflectance and thermal analyses of oils from the Yamama reservoir (0.87% R0; 128.1 °C) and from the Sargelu Formation (1.36% R_0; 156.96 °C) show that only the Sargelu Formation had the right burial depths and temperatures in this area during Miocene deformation to source Yamama hydrocarbons in the Siba field. Although the anhydrites of the Upper Jurassic Gotnia Formation form a prominent regional seal separating Jurassic source rocks from Cretaceous reservoirs, structure-contour maps and seismic analyses indicate that many faults and fractures, mostly related to Miocene deformation, penetrate Gotnia anhydrites. Hence, the study interprets that these faults, as well as facies changes on the margin of the Gotnia basin, seriously impaired the Gotnia seal, allowing the vertical migration of hydrocarbons from the Middle Jurassic Sargelu Formation into the Lower Cretaceous Yamama reservoir in the Siba field.

1. Introduction

As natural resources, oil and gas play an important role, not only among individuals and companies in Iraq, but also among other countries around the world. Siba is a major gas field in southern Iraq and the only one producing natural gas from the Lower Cretaceous (Berriasian–Valanginian) Yamama reservoir. Yamama Formation is one of the most significant hydrocarbon reservoir formations in southern Iraq, containing significant amounts of oil in most fields of southern Iraq. Although clearly a prolific reservoir rock (Sadooni, 1993; Aqrawi et al., 2010; Chafeet, 2016), some researchers also consider the Yamama Formation to be a source rock (Handhal et al., 2020; Al-Khafaji et al., 2019).

This study deals with the origin of that gas, both from a structural point of view as well as from the view of its relationship to hydrocarbon migration and the high thermal maturation that led to gas generation.

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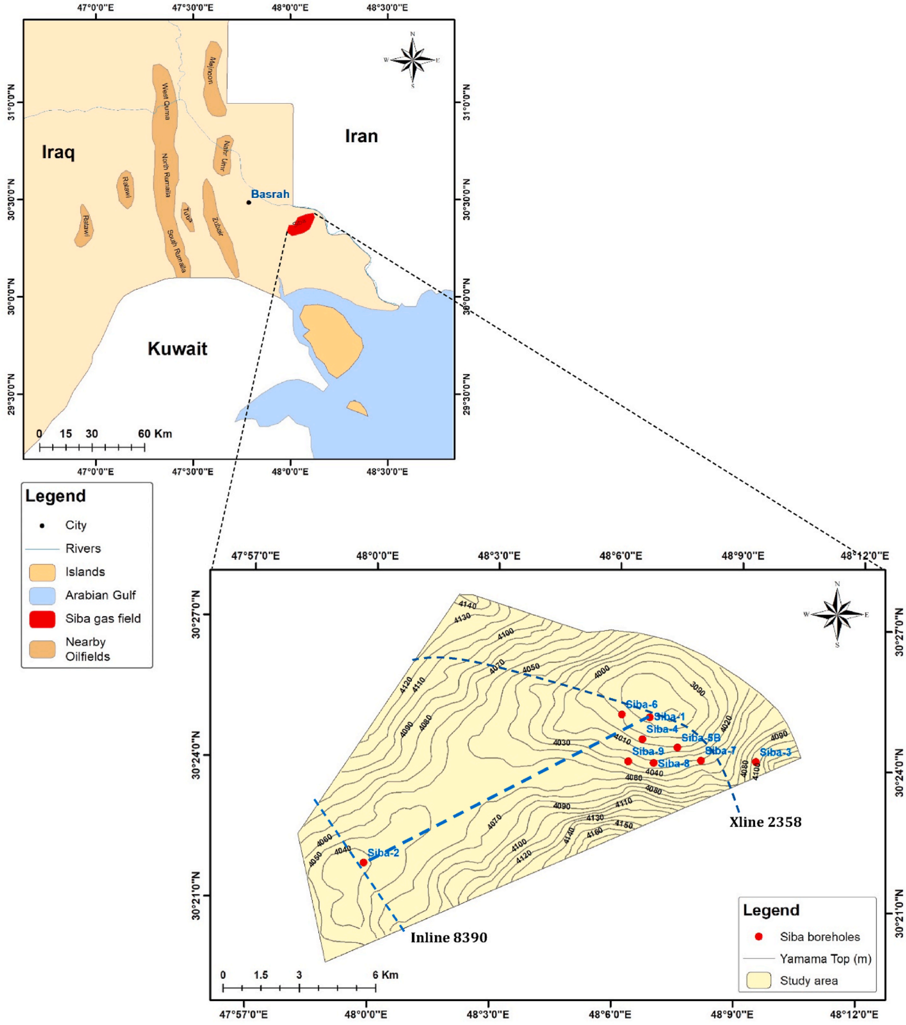


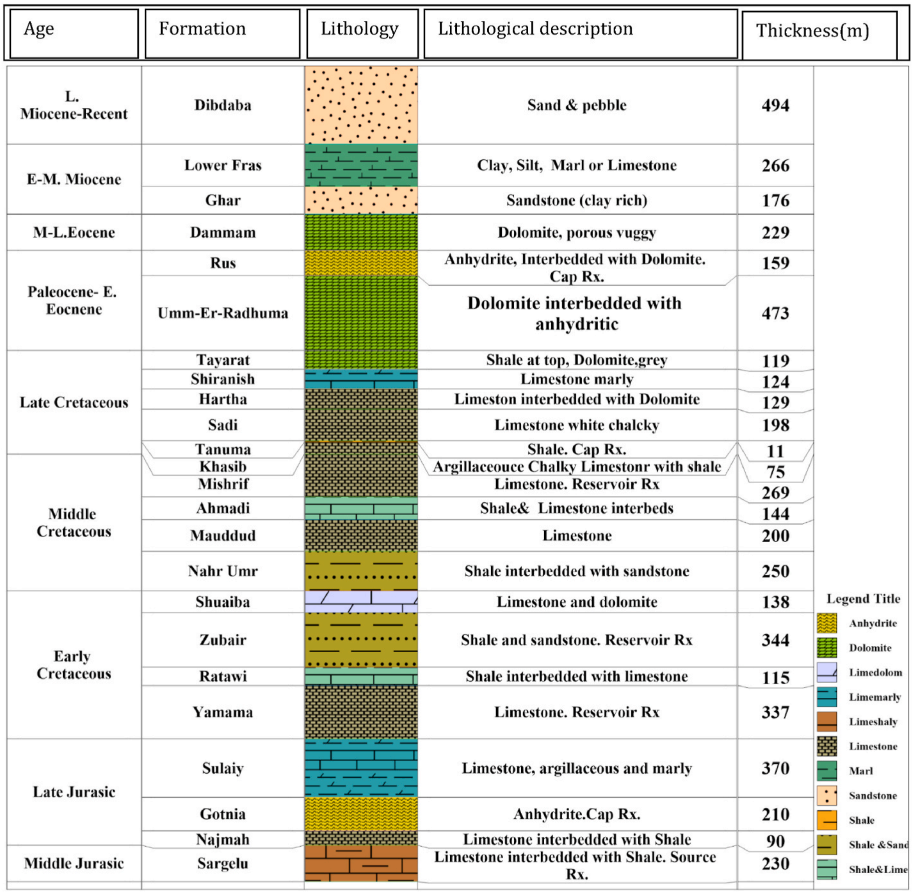
Fig. 1. Map of the study area. The left panel represents the oilfields in southern Iraq.

Consequently, the study will focus on two aspects. The first deals with the nature of the tectonic and structural factors that generated the field and their impact on gas generation. This will include origin of the sedimentary basin, impact of burial and temperature histories on the generation of oil and gas, and identification of the stages of oil and gas generation. The second aspect is a structural analysis of the sealing rocks, like the Upper Jurassic Gotnia Anhydrite Formation, and its role in the migration of hydrocarbons, as well as of source rocks like the Middle Jurassic Sargelu Formation and a comparison of the properties of its oil with that of the Yamama reservoir. This aspect also involves correlation of source rocks and oils from the two formations with those from adjacent fields to identify the geochemical properties of hydrocarbons in the study area.

The study area is in the Mesopotamian Basin of southern Iraq, which includes vast quantities of hydrocarbon resources developed through varying temperature and pressure processes during Jurassic and Cretaceous time (Pitman et al., 2004). Hence, determining maturity and temperature histories during Jurassic and Cretaceous times are important goals toward a better understanding of the development of thermal process through time in a sedimentary basin and the resulting generation of petroleum. In assessing the hydrocarbon-generating potential of source rocks like those noted above, petroleum-system generation models are commonly used, and the burial of source rocks from surface deposition to depths deep enough to initiate oil, and eventually gas, accumulation is tracked over geologic time (Martinelli, 2010).

2. Location and geologic setting

The Siba gas field is located on the northern part of the Arabian Plate in southern Iraq, about 30 km southeast of Basra City, southeast of the Sindbad oil field and east of the Zubair oil field (Fig. 1) (Aljazaeri and Handhal, 2020). It is an anticlinal field, about 25-km long and 6-km wide (B.O.C., 2010). Tectonically, this field is located in the Zubair subzone of the Mesopotamia foredeep basin, part of the foreland basin associated with the Zagros orogen (Pitman et al., 2004; Fouad, 2010; Al-Kaabi et al., 2023). This foredeep is a southeast-northwest-elongated basin, the northeastern boundary of which stretches from Sinjar in northern Iraq to Buzurgan in southern Iraq along the first topographic and physiographic expression of the Zagros orogenic belt. On its southeastern margin, the elongate basin is bound by the stable interior of the Arabian Platform, delimited by the paralleling Anah and Abu-Jir fault systems (Fouad, 1999, 2007; Abdulnaby, 2019). Physiographically, the Mesopotamia foredeep is divided into two plains: the Al-Jazira plain to the northwest and the Mesopotamia plain to the southeast (Fouad, 2010). The foredeep basin is a highly mobile zone that contains a variety of buried tectonic structures, including folds, faults, and diapiric structures, which are buried below the Quaternary cover (Fouad, 2010). The trend of subsurface folds in the central and eastern parts of the Mesopotamia plain is northwest (in the same general trend as the Zagros fold-thrust belt), while in extreme southern parts of this plain, the trend is north-south (Fouad and Sissakian, 2011). These north-south-trending subsurface anticlines now represent major oil fields within the



Age	Formation	Lithology	Lithological description	Thickness(m)
L. Miocene-Recent	Dibdaba		Sand & pebble	494
E-M. Miocene	Lower Fras		Clay, Silt, Marl or Limestone	266
	Ghar		Sandstone (clay rich)	176
M-L.Eocene	Dammam		Dolomite, porous vuggy	229
Paleocene- E. Eocnene	Rus		Anhydrite, Interbedded with Dolomite. Cap Rx.	159
	Umm-Er-Radhuma		Dolomite interbedded with anhydritic	473
Late Cretaceous	Tayarat		Shale at top, Dolomite,grey	119
	Shiranish		Limestone marly	124
	Hartha		Limeston interbedded with Dolomite	129
	Sadi		Limestone white chalcky	198
	Tanuma		Shale. Cap Rx.	11
Middle Cretaceous	Khasib		Argillaceouce Chalky Limestonr with shale	75
	Mishrif		Limestone. Reservoir Rx	269
	Ahmadi		Shale& Limestone interbeds	144
	Mauddud		Limestone	200
	Nahr Umr		Shale interbedded with sandstone	250
Early Cretaceous	Shuaiba		Limestone and dolomite	138
	Zubair		Shale and sandstone. Reservoir Rx	344
	Ratawi		Shale interbedded with limestone	115
	Yamama		Limestone. Reservoir Rx	337
Late Jurasic	Sulaiy		Limestone, argillaceous and marly	370
	Gotnia		Anhydrite.Cap Rx.	210
	Najmah		Limestone interbedded with Shale	90
Middle Jurasic	Sargelu		Limestone interbedded with Shale. Source Rx.	230

Fig. 2. Stratigraphic column showing the succession of Jurassic, Cretaceous, and Tertiary units from the Siba gas field.

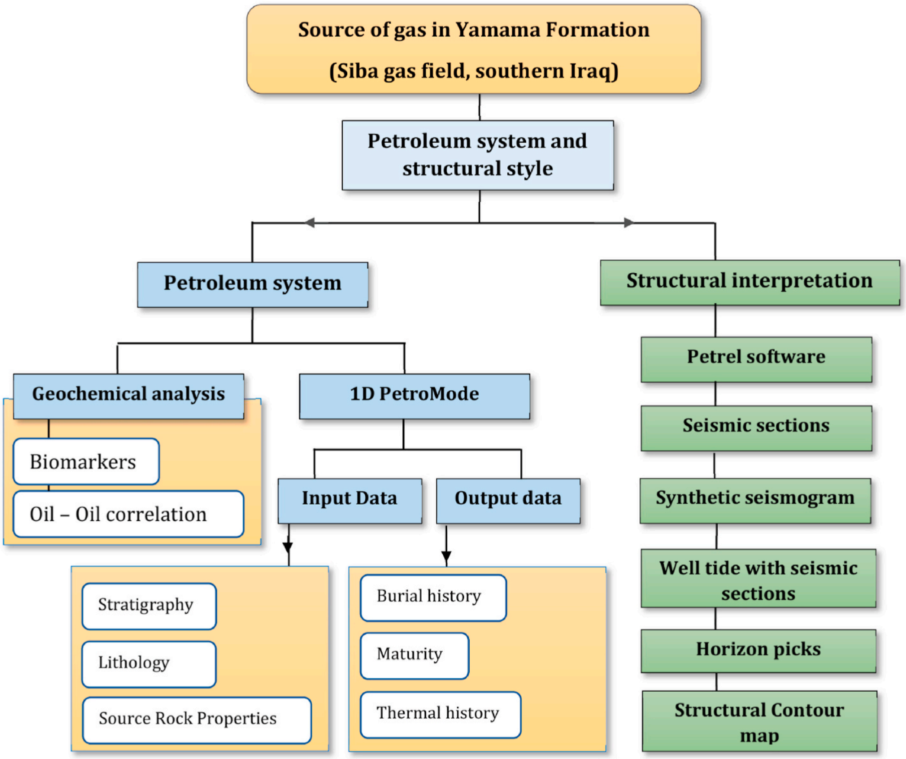
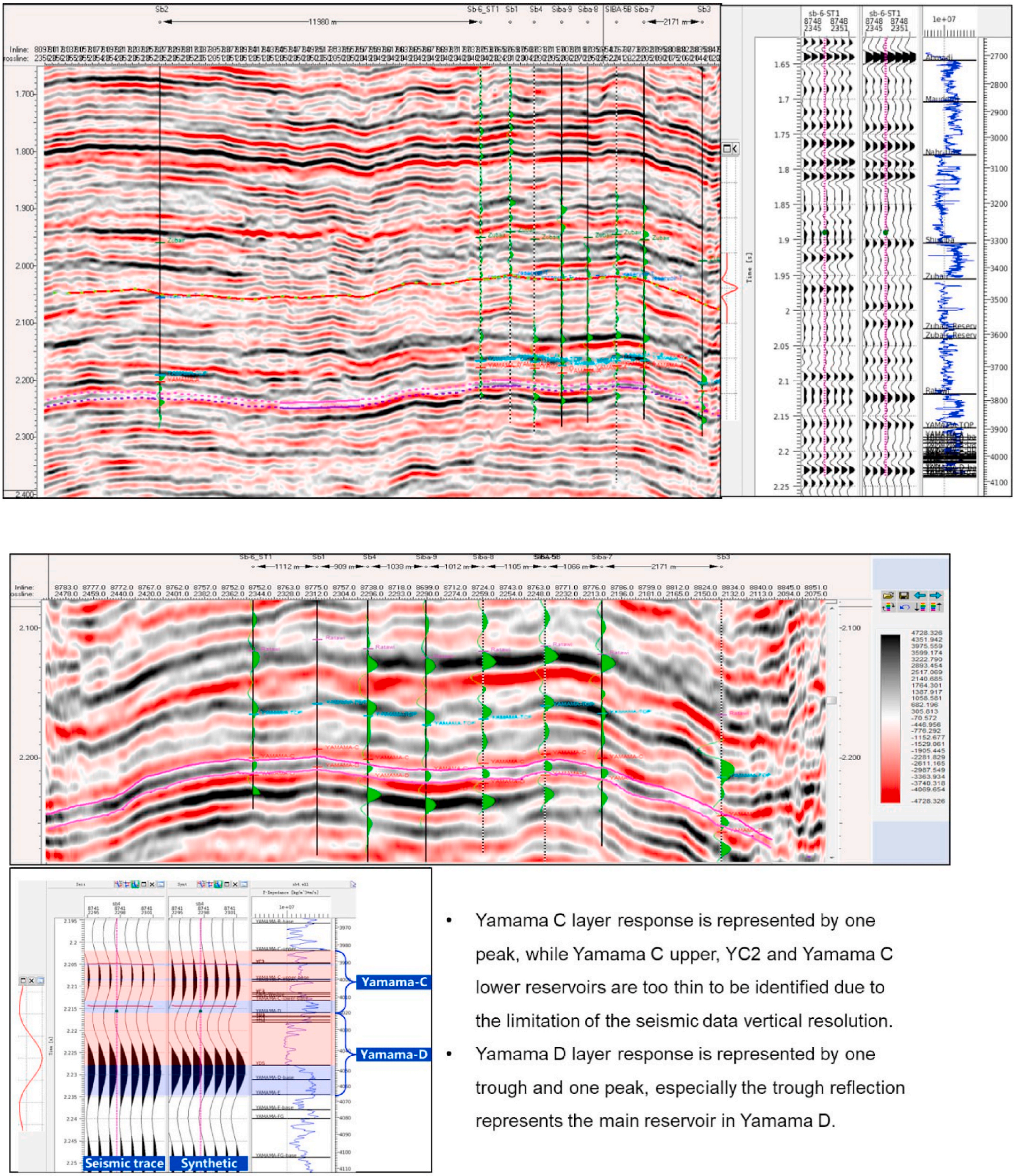


Fig. 3. Working flow of this study.



- Yamama C layer response is represented by one peak, while Yamama C upper, YC2 and Yamama C lower reservoirs are too thin to be identified due to the limitation of the seismic data vertical resolution.
- Yamama D layer response is represented by one trough and one peak, especially the trough reflection represents the main reservoir in Yamama D.

Fig. 4. Synthetic seismograms used to pick up the tops of the formations in the Siba structure.

Mesopotamia plain. The exception to these general trends is the Siba field, which is a gas field that reflects a northeast-southwest-trending structure (Fig. 1).

The stratigraphic column in southern Iraq consists of Jurassic, Cretaceous and Tertiary units (Fig. 2), including the Middle–Upper Jurassic Sargelu, Najmah, and Gotnia formations of the AP7 Megasequence (Sharland et al., 2001), the Upper Jurassic–Lower Cretaceous (upper Tithonian–lower Turonian) Sulaiy, Yamama, Ratawi, Zubair, Shuaiba, Nahr Umr, Muddud, Ahmadi, Rumila, and Mishrif formations of the AP8 megasequence, the Upper Cretaceous–lower Tertiary (upper

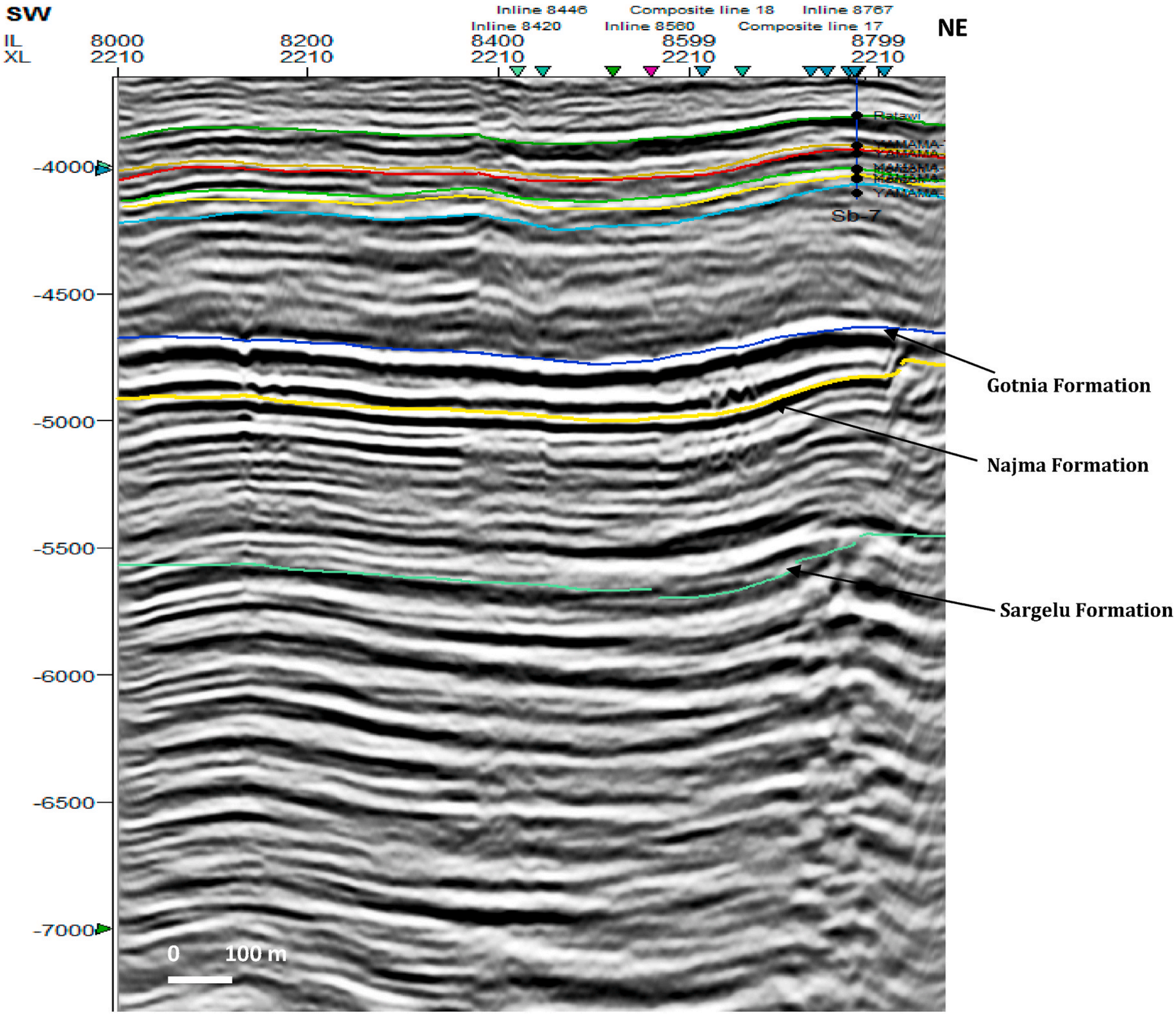


Fig. 5. Formation tops picked from the seismic section of the study area (Blue): Gotnia top; (Yellow): Najma top; (Green): Sargelu top.

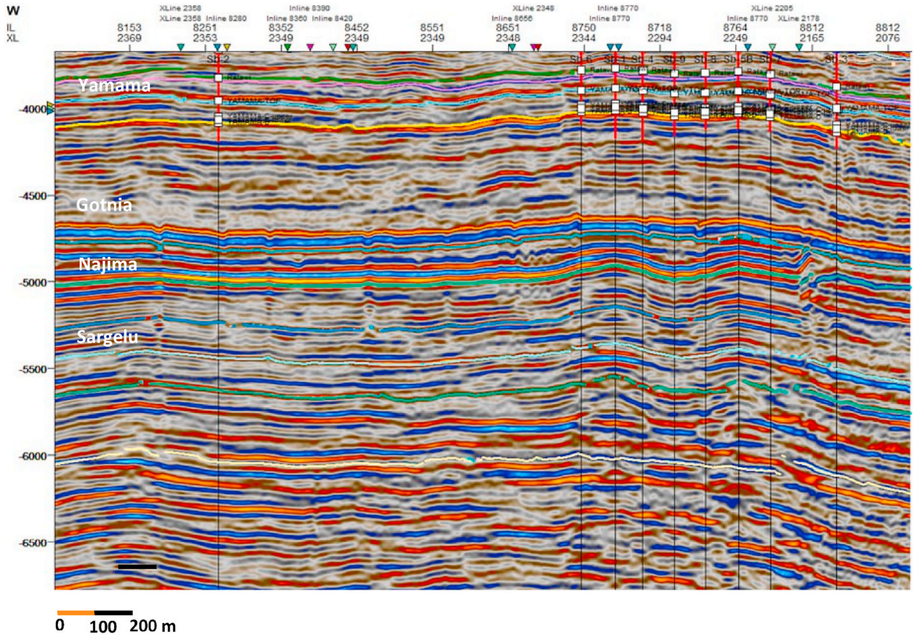


Fig. 6. Formation tops picked from the seismic section across the Siba field: Yamama top (yellow); Gotnia top (orange); Najmah top (dark blue); and Sargelu top (light blue).

Table 1
Parameters of geochemical analysis of crude oil (Yamama Formation, Siba field).

Well	Formation	Pr/Ph	Pr/nc17	ph/nc18	CPI	nc17/nc17 + nc27	nc18/nc18 + nc28	R_0
X-1	Sargelu	1.00	0.83	0.72	1.02	0.78	0.59	–
X-2	Sargelu	0.97	0.74	0.73	0.94	0.72	0.53	–
Siba 3 (4130.8 m)	Yamama	1.09	0.90	0.87	0.98	0.69	0.69	0.8
Siba 3 (4113.5 m)	Yamama	1.11	0.93	0.89	0.30	0.67	0.67	0.7
Siba 6 (4005 m)	Yamama	1.06	0.91	0.89	1.00	0.68	0.67	0.8
Siba 6 (4014.10 m)	Yamama	1.12	0.81	0.57	1.12	0.63	0.62	0.8
Siba 6 (4051.30 m)	Yamama	1.06	0.91	0.91	1.00	0.67	0.66	0.9
Siba 6 (4050 m)	Yamama	1.05	0.93	0.92	0.99	0.66	0.66	0.9
R-172	Yamama	0.52	0.24	0.4	1.04	–	–	–

Note: Pr: Pristine; Ph: Phytane; nc- normal alkane; CPI: Carbone Preference Index (CPI).

Table 2
Geochemical parameters of Yamama Formation at different oilfield of Iraq taken from previous studies (SOC, 2010; Amna M. Handhal 2013; Handhal et al., 2020).

Well No.	Formation	Sat/Aro	C34/C35	C29/C32	C29 S/S + R	% C27	% C28	% C29
NR-7	Yamama	0.78	0.93	1.54	0.59	35.9	22	42
WQ-15	Yamama	2.06	1	1.43	0.59	33.9	24.3	41.8
NR-9	Yamama	1.22	1.12	1.37	0.6	32	23.5	44.6
Zb-47	Yamama	2.6	0.47	0.46	0.6	30.7	20.5	48.8
WQ-60	Yamama	0.71	0.94	1.45	0.59	35.6	22.7	41.8
Zb-47	Yamama	2.63	0.43	0.44	0.61	31.9	20.9	47.2

Note: Sat: saturation; Aro: Aromatic; C34/C35: Hopanes ratio; C29/C32: Hopanes ratio; C29 S/S + R: C29 sterances isomerization; %C27, %C28, and % C29: regular sterances.

Turonian–Lower Paleocene) Khasib, Tanuma, Sadi, Hartha, Shiranish, and Tayarat formations of the AP9 Megasequence, the Middle Paleocene–Eocene Umm Er Radhuma, Rus, and Dammam formations of the AP10 Megasequence, and the upper Eocene–Recent Ghar, Lower Fars, and Diddiba formations of Megasequence AP11 (Jassim and Goff, 2006).

The considered units in this study, the Sargelu, Najmah, Gotnia, and Yamama formations, are parts of the Mesozoic–Cenozoic Composite Total Petroleum System (TPS) (Pitman et al., 2004; U.S.G.S., 2012). The Sargelu Formation comprises up of 115 m of thin-bedded, black, bituminous, dolomitic limestones and black papery shales with streaks of thin, black chert; it is interpreted to represent deeper, restricted, sometimes euxinic, outer-ramp environments in a subsiding intra-shelf basin (Yousif and Nouman, 1997; Jassim and Goff, 2006; Aqrawi et al., 2010). The Najmah Formation is a widely diachronous formation, comprising limestones with dolomite, some of which are organic-rich, with thin anhydrite beds that represent inner-to outer-ramp, lagoonal conditions in a shallowing intra-shelf basin (Bellen et al., 1959; Yousif and Nouman, 1997; Jassim and Goff, 2006; Aqrawi et al., 2010). The overlying Gotnia Formation includes bedded anhydrites and salt with occasional limestones, which represent very restrictive, sabkha and lagoonal environments that effectively filled the intra-shelf basin (Yousif and Nouman, 1997; Aqrawi et al., 2010). The formation's southern depocenter stretches into Kuwait, where the average thickness exceeds 700 m (Yousif and Nouman, 1997; Aqrawi et al., 2010).

3. Materials and methods

Understanding the nature and origin of the gas in the Siba gas field is the major objective of this study and necessitated the following steps (Fig. 3): (i) A structure-contour map on top of the Yamama Formation in the Siba field (Fig. 1) was generated based on seismic data using Petrel software. A synthetic seismogram was firstly generated from sonic, acoustic-impedance, and density logs, as well as through multi-averaged wavelet extraction of the seismic data (Fig. 4). On this seismogram, top horizon picks for the main Cretaceous geological markers (Mishrif, Ahmadi, Maudud, Nahr Umr, Zubair, and Yamama formations) were made (Fig. 5). However, those deeper Jurassic formation tops that were not reached by drilling were generally picked based on control points in

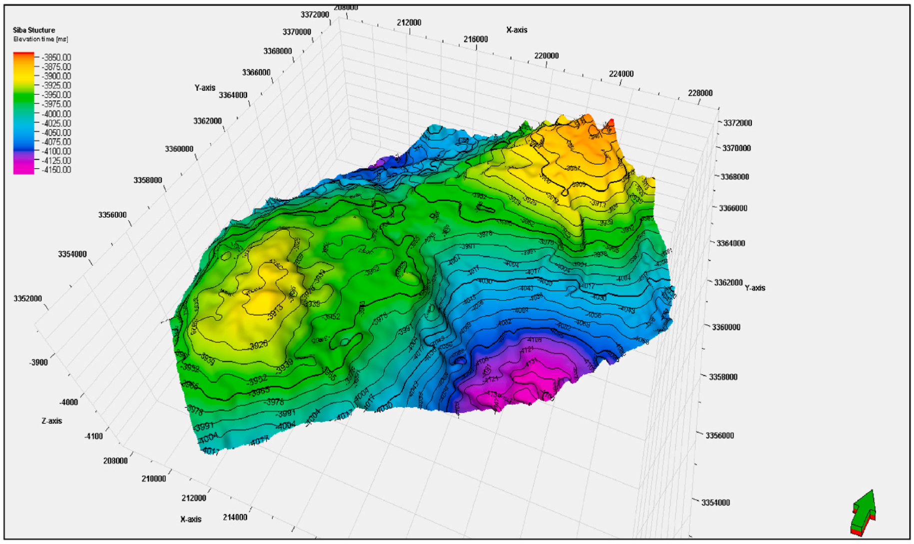


Fig. 7. Three-dimensional contour map of the top of Lower Cretaceous Yamama Formation in southern Iraq (Fig. 1) with sectional view, showing two domal culminations on the northeast-southwest-trending anticline that comprises the Siba gas field.

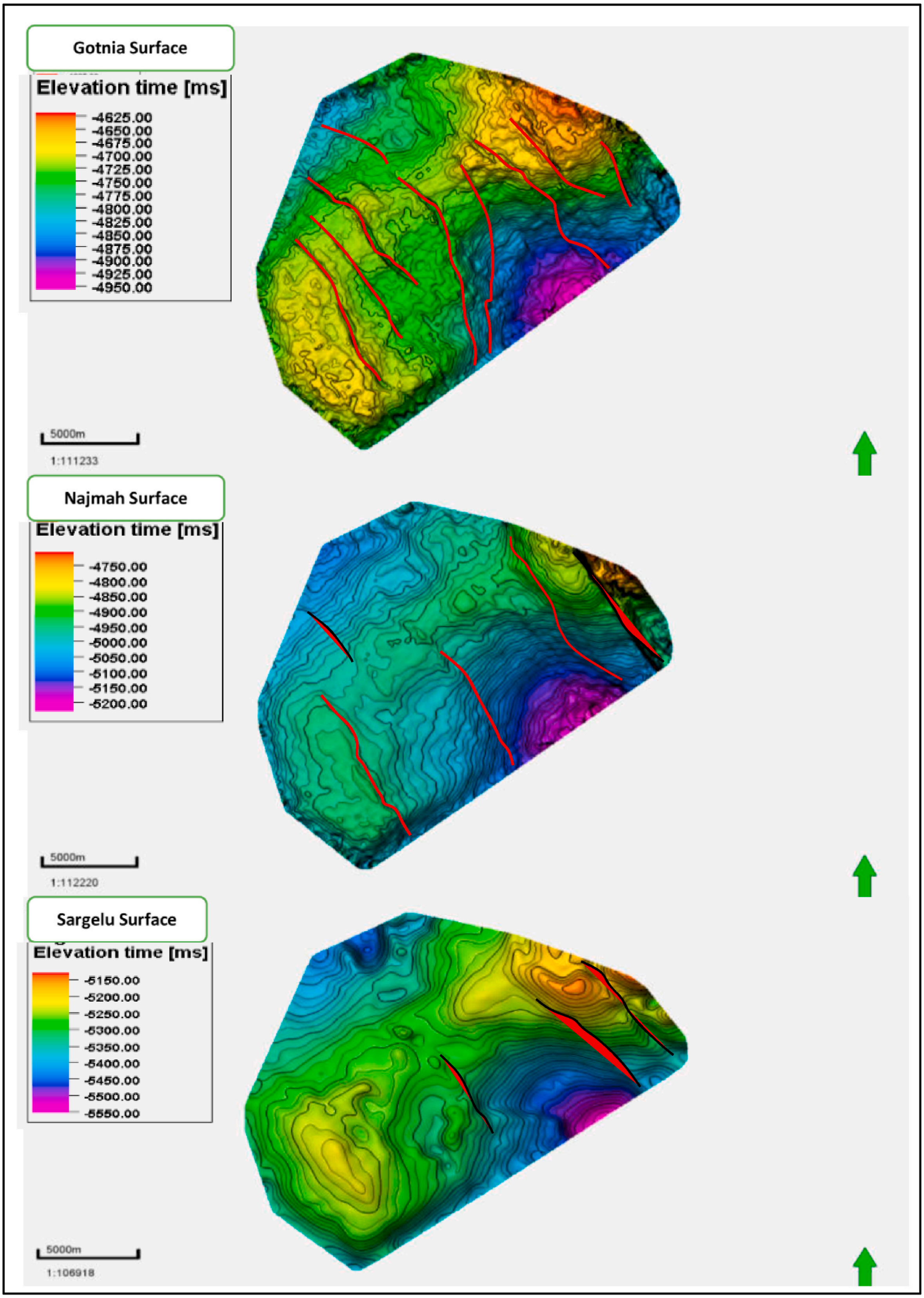


Fig. 8. Structural-contour maps on top of the Middle and Upper Jurassic Sargelu, Najmah, and Gotnia formations from the Siba field, showing various fissures and faults. The green arrows represent true North. (Red lines refer to probable faults).

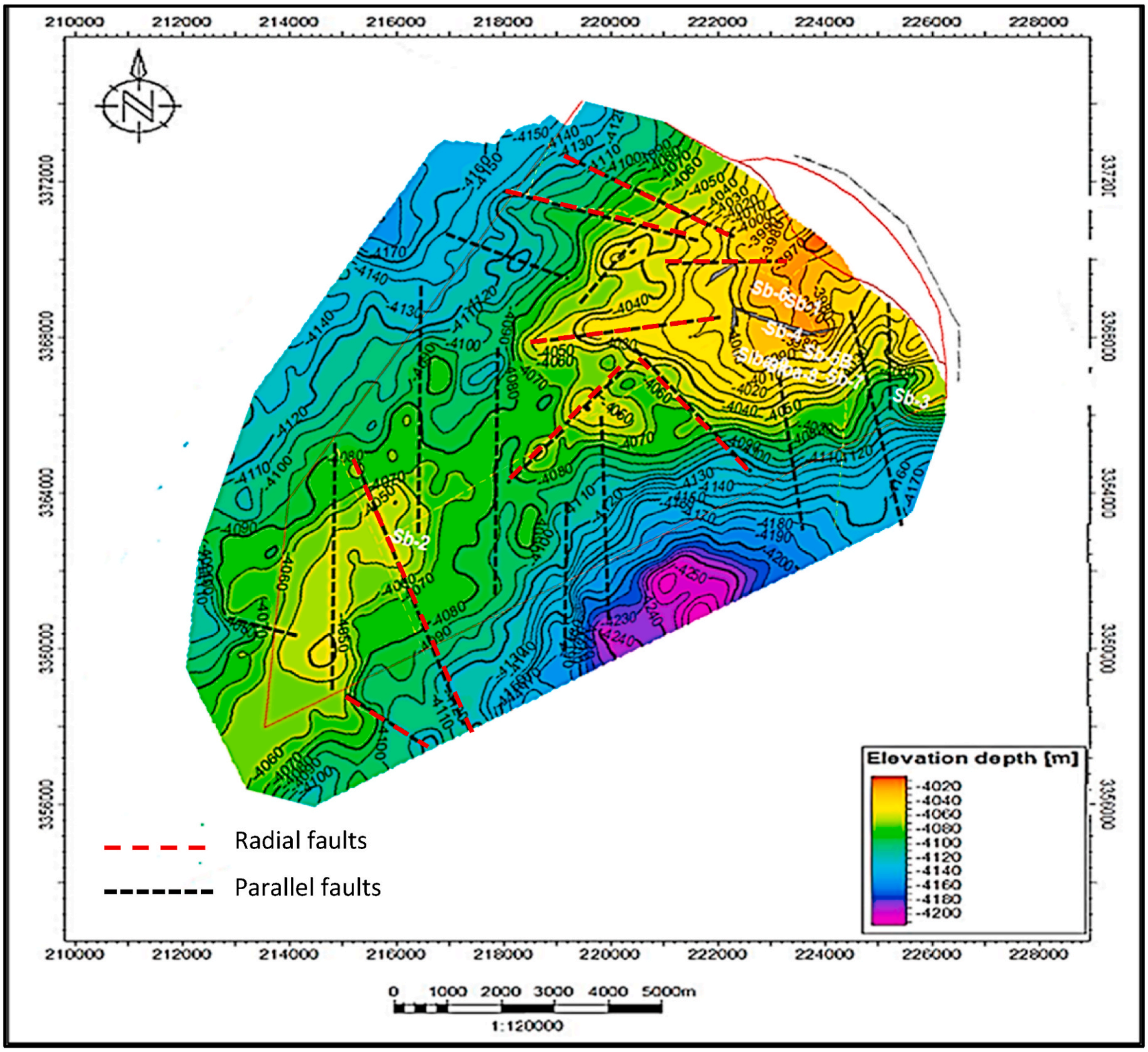


Fig. 9. Structure-contour map on top of the Yamama Formation in the Siba field, showing the distribution of parallel and radial faults determined from well data and seismic sections.

2D/3D seismic and on datasets from deep wells in oil fields adjacent to the Siba field (Fig. 6). (ii) Data from wireline logs data were later used to identify formation tops and make correlations with seismic data. (iii) Six crude oil samples were sampled from different Siba wells to identify oil properties and make oil-oil correlations. The authors of this study performed geochemical analyzes of the Yamam Formation in the Siba field at the Southern Oil Company (SOC) laboratory (Table 1) using Gas Chromatography instrument (GC), while other geochemical analyzes (Table 2) were taken from the previous studies and SOC final report (Amna M. Handhal, 2013; Handhal et al., 2020; SOC, 2010). (iv) Using the above data, the nature and timing of hydrocarbon generation were approximated using 1D PetroMod software. PetroMod 1D is a comprehensive software package that integrates seismic and geological interpretation with multi-dimensional simulation of thermal 3-phase fluid and petroleum migration histories in sedimentary basins (Handhal and Mahdi, 2016). The software requires a significant amount of input data, including deposition, porosity determination, eroded thickness, sediment decompaction, and heat flow. The software calculates various parameters, such as thermal conductivity, porosity, heat flow, pressure, burial history, thermal history, and vitrinite reflectance, to evaluate the petroleum system (Jia, 2010).

4. Results and discussion

4.1. *Geometric analyses of structure in the siba field*

Geometrical analysis of subsurface features of the Siba gas field, based on seismic interpretations using Petrel software, produced two-dimensional (Fig. 1) and three-dimensional (Fig. 7) structural-contour maps on top of the Lower Cretaceous Yamama Formation, the major reservoir in the field. Plotted data from the Yamama Formation is based on seismic and wireline data from nine wells (Fig. 1), but data for the deeper Middle Jurassic Sargelu Formation is based wholly on seismic interpretations, because this formation was not penetrated by drilling. The three-dimensional structural map and resulting sectional view of the field is shown in Fig. (7), and the geometrical analyses of structure in the Siba field is explained in the sections below.

4.1.1. *Fold analyses*

A fold is defined as a bent or curved structural feature that results from the distortion of a planar surface (Park, 2013), whereas a dome is an anticlinal uplift that has no separate tendency (Billings, 1972). The structure on top of the Yamama Formation (Fig. 7) is used herein to study the nature of the Siba structure. Geometric analysis of the structure shows that the Siba field is an anticline based on the fold facing, a

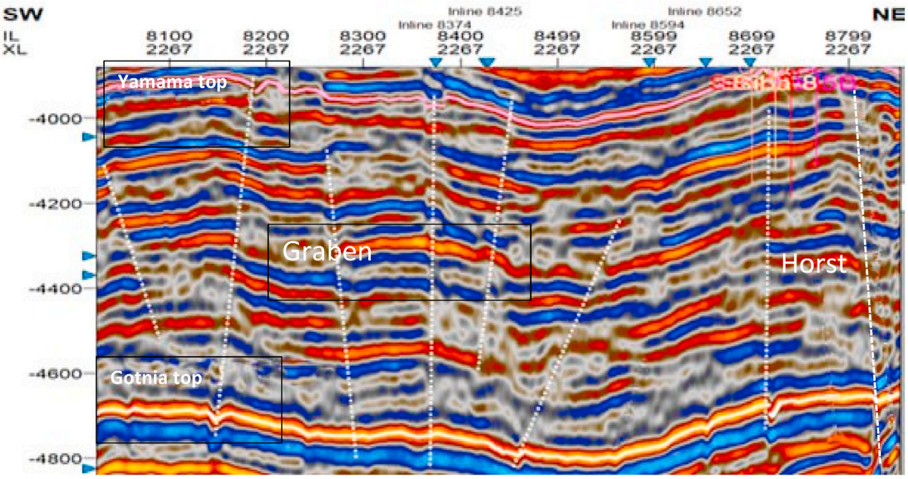


Fig. 10. SW-NE seismic section across the Siba field, showing the likely tops of the Gotnia and Yamama formations as well as the distribution of major faults across the Siba field. Note the large horst that defines the top of the northeastern culmination and the complex graben structure that underlies the southeastern culmination.

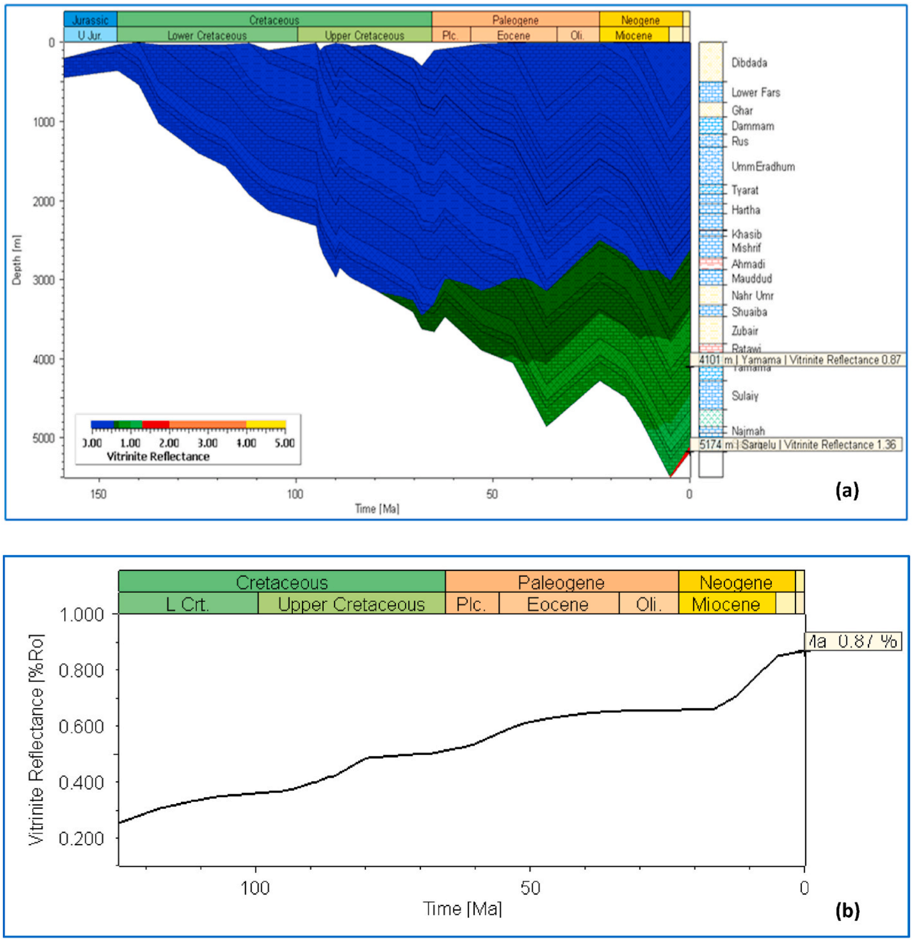


Fig. 11. (a) Development of vitrinite reflectance relative to burial depth and (b) time for the study area.

non-cylindrical fold based on three-dimensional analysis, an asymmetrical fold based on fold orientation, and an open fold based on the inter-limb angle of about 100° from the cross-section profile. Moreover, the analyses show that the northeast-southwest-trending anticline exhibits two domal culminations, each of which has an elliptical shape with a northwest-southeast elongation (Fig. 1). Moreover, the northeast dome is larger and higher in relief by about 100 m (Figs. 1 and 7).

Unlike the north-south orientation of most other anticlinal fields in southern Iraq (Fig. 1), the Siba anticlinal field is oriented in a northeast-southwest direction (Figs. 1, 7 and 8). This orientation is parallel to a series of "transversal system" faults that cross Iraq (Jassim and Buday, 2006; Aqwari et al., 2010). In the study area, the Siba field occurs between the Basrah-Zubair and Jal Az-Zor transverse faults. Most of these faults exhibit evidence of strike-slip movement, and according to

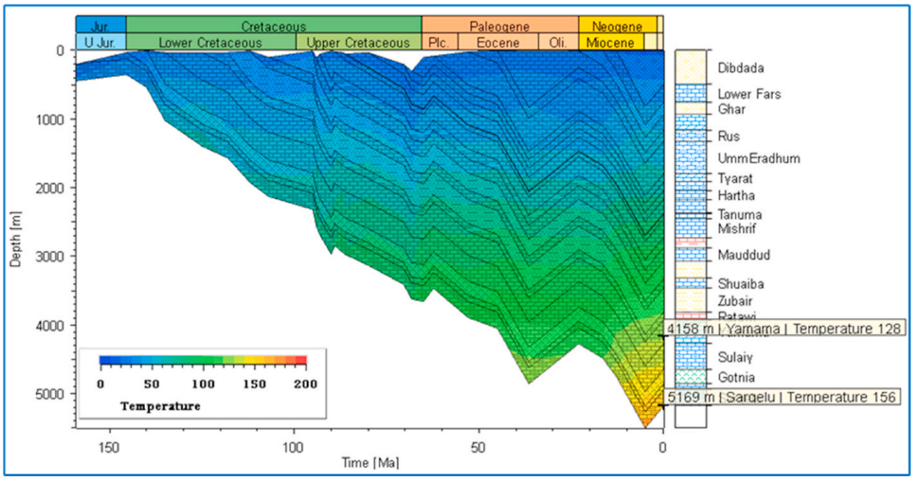


Fig. 12. Thermal history of formations in the study area relative to time and depth.

Sissakian et al. (2014) and Al-Bahadily and Al-Rahim (2022), they formed by compressional forces along zones of weakness, commonly marked by shear zones. In the study area, however, similarly oriented structures like the Siba field are apparently related to piercement by salt along the zones of weakness (Abdulnaby,2019; Al-Kaabi et al., 2023).

4.1.2. *Fracture analyses*

A fracture can be defined as any planar or sub-planar break that is extremely thin in one dimension compared to the other two and forms because of external forces (tectonic) or inner (thermal or residual) potential stress (Fossen, 2016). According to Fossen (2010), fractures can be classified as joints, fissures, veins, and faults, and based on the seismic profiles from the study area (Figs. 5 and 6), subsurface faults and fissures have been identified from Jurassic units as deep as the Sargelu Formation up through the Lower Cretaceous Yamama Formation. These faults and fissures are also identifiable on structural-contour maps from the deep Sargelu Formation through the Yamama Formation (Fig. 8). These structures are most likely related to closure of the Neotethys and formation of the Zagros fold belt and probably played a major role in hydrocarbon flow and accumulation (Sadooni, 1997; Pitman et al., 2004; Fouad, 2010). Understanding the nature of faults and fissures across a reservoir like Yamama Formation can be critical, as faults may compartmentalize the reservoir, impacting positively or negatively the volume of producible hydrocarbons (Jolley et al., 2015).

4.1.3. *Geometric analysis of the faults of study area*

Faults may be classified relative to their spatial distribution on a larger structure or relative to their displacing movements (Billings, 1972). Based on the available datasets from wells and seismic sections across the Siba field, a series of faults were identified based on their distribution pattern, which includes both parallel and radial faults (Fig. 8). Billings (1972) indicated that domal structures are typically broken by normal faults arranged in a radial pattern, whereas parallel faults more likely represent horsts and grabens. The faults in the study area can be characterized as both parallel and radial faults (Fig. 9). In particular, radial faults characterize the northeastern culmination of the Siba field, suggesting that it is a dome-shaped structure, whereas those faults across southwestern parts of the structure are more parallel in orientation, suggesting that southwestern parts of the structure represent a series of more or less parallel horsts and grabens (Fig. 9).

Faults can also be classified based on relative movement into dip-slip faults (normal and reverse), strike-slip faults (dextral and sinistral), and oblique-slip faults (normal-dextral, normal-sinistral, reverse-dextral, reverse-sinistral, and scissors or rotational faults (Ragan, 1985; Ghosh, 2013). In our two-dimensional, seismic sections (Figs. 5, 6 and 10), numerous normal and reverse faults are visible. Whether any of these faults have lateral components of movement is difficult to assess, but the three-dimensional structure-contour maps in Fig. 8 do suggest the possibility of such movement. The density of faults across the structure is shown in Figs. 5, 9, and 10, and based on Figs. 6 and 9, most of the faults occur across the northeastern culmination. However, Fig. 10 clearly shows the northeastern and southwestern culminations and suggests that the northeastern culmination is largely rooted in a horst, whereas the southwestern culmination is fixed on a complex graben structure.

4.2. *Hydrocarbon generation*

This section aims to examine the generation and migration of hydrocarbons from Middle Jurassic to Lower Cretaceous source rocks, using petroleum-modeling software (1D). These source rocks were largely deposited as deeper-water, outer-ramp, bituminous carbonates, and dark, organic-rich shales deposited in anoxic circumstances. The thickness of this sequence exceeds 600 m in southern Iraq (Sadooni, 1993; Yousif and Nouman, 1997; Jassim and Goff, 2006).

4.2.1. *Vitrinite reflectance* (R_0)

Vitrinite reflectance is used extensively to detect the maturity of organic matter (Allen and Allen, 2005). It is an optical factor indicated by VR or R_0 (reflectance in oil). Sweeney and Burnham (1990) developed a simple model of R_0 estimation based on chemical processes, noting that the maturation of vitrinite is a kinetic process dependent on time and burial depth (Fig. 11a and b). The maturation of vitrinite in the Yamama Formation began in the early oil-window phase in the Paleocene Epoch and continued maturation until it reached the stage of the main oil generation (0.87%) (Fig. 11a and b). This value is comparable to the measured R_0, which ranges between 0.7 and 0.9. (Table 1). In contrast, maturation of vitrinite in the Middle Jurassic Sargelu Formation began in Late Cretaceous time and has now reached the wet gas stage (1.36%), as illustrated in Fig. 10. Based on these results (Fig. 11a), it is most likely that the Sargelu Formation (U.S.G.S., 2015) is the source of the gas present in the Yamama reservoir, as the Yamama Formation never reached the stage of gas generation, while Sargelu Formation had entered the stage of gas generation by Miocene time (Fig. 11a). Although the Yamama Formation itself may have contributed some as a source (Handhal et al., 2020; Al-Khafaji et al., 2019), biomarker and carbon-isotope analyses of oils from nearby fields suggest that the Sargelu Formation was the principal source for the Yamama reservoir in southern Iraq (Al-Khafaji et al., 2015).

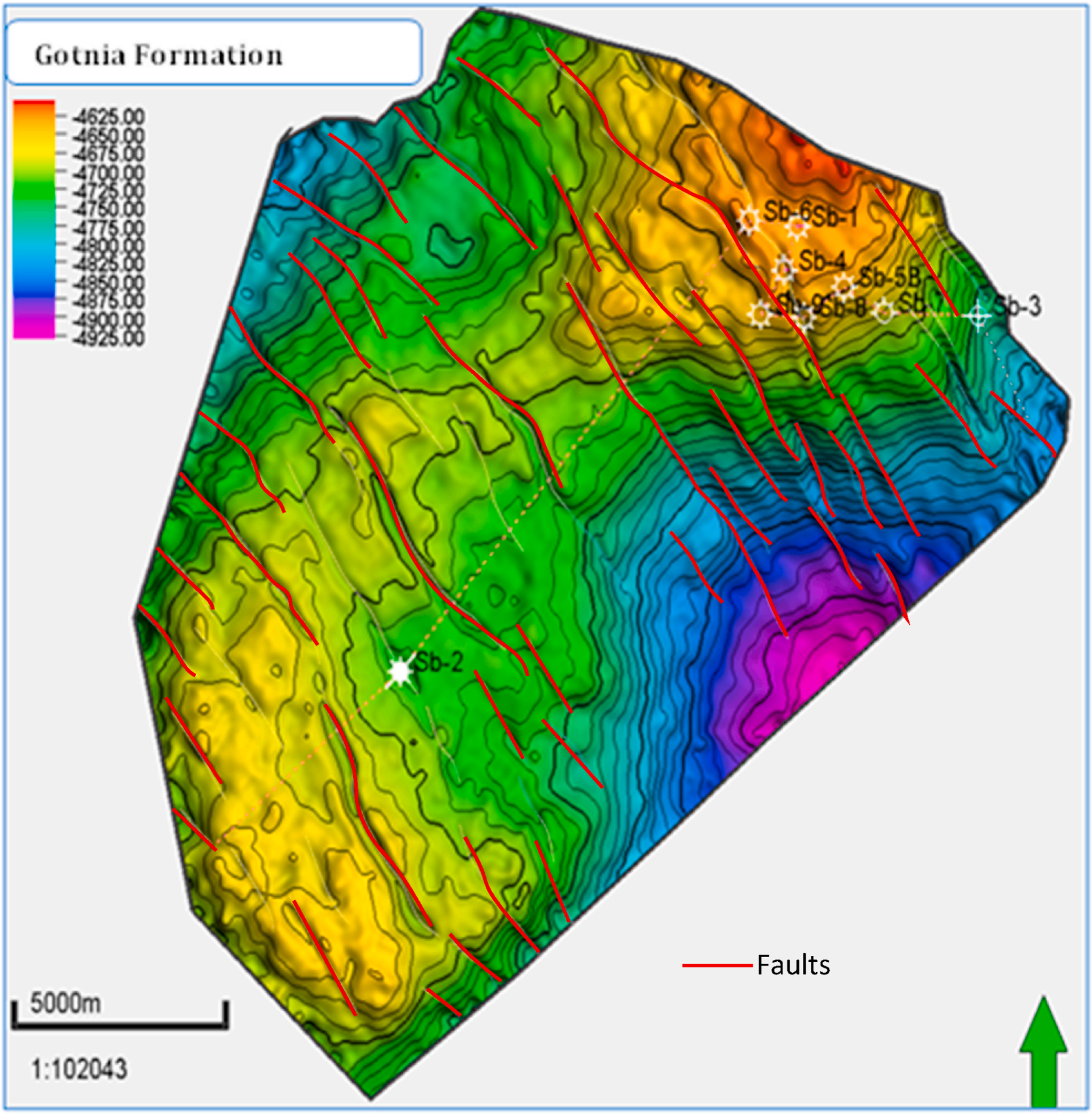


Fig. 13. Structure-contour map on top of the Gotnia Formation in the Siba field, showing several northwest-southeast-trending faults that apparently penetrate the top of the formation (compare with Figs. 7 and 13).

4.2.2. *Thermal history*

Fig. 12 shows the thermal history of the Yamama and Sargelu formations. At the present time, the Yamama Formation has reached the temperature of 128.1 °C, just at the margin of the gas-generation window, whereas the Sargelu Formation, at 156.96 °C, is well within the gas-generation window (Bjørlykke, 1989).

It is probably no coincidence that the Siba gas field is located on the eastern margin of the fold belt, proximal to the Zagros orogenic front, because this is where the foreland basin is deepest and the sediment load greatest (Pitman et al., 2004; Fouad, 2010; Sissakian et al., 2020, 2021). The great burial depth, increasing temperatures, and advanced geologic age here, and only here (Fig. 12), would have been sufficient to begin the thermal degradation and cracking in which the heavy components of oil are broken up into lighter molecules of gas.

4.3. *Regional seals and the impairment of sealing capacity*

The anhydrite layers of the Gotnia Formation are well-known as an active regional seal between fractured Middle–Upper Jurassic source rocks and the Cretaceous limestone reservoirs of central and southern Iraq (Fox and Ahlbrandt, 2002; Pitman et al., 2004; Jassim and Goff, 2006; Aqrawi et al., 2010; Abeed et al., 2013). Although the thickness of the Gotnia Formation varies throughout southern Iraq, the average thickness of the unit is about 200 m, and the thickness decreases toward northeastern Kuwait (close to the study area) and increases toward western Kuwait (Yousif and Nouman, 1997). Ali and Al-Husseini (1995) proposed that the differences in Gotnia thickness are associated with a period of synsedimentary structural development and basin subsidence, whereas Yousif and Nouman (1997) observed thinning of the Gotnia toward northeastern Kuwait where the basin margin was located.

Most research into the petroleum systems of southern Iraq interprets the presence of two major total petroleum systems, a Jurassic TPS and Mesozoic–Cenozoic TPS, separated by a large regional seal, the evaporites of the Gotnia Formation (Ahlbrandt et al., 2000; Pitman et al., 2004; Lučić and Bosworth, 2018). Pitman et al. (2004), however, questioned the integrity of the Gotnia Formation as sealing bed in the Majnoon area. They called the seal “semi-permeable” and “ineffective” because of facies changes among the varied formation lithologies (salt,

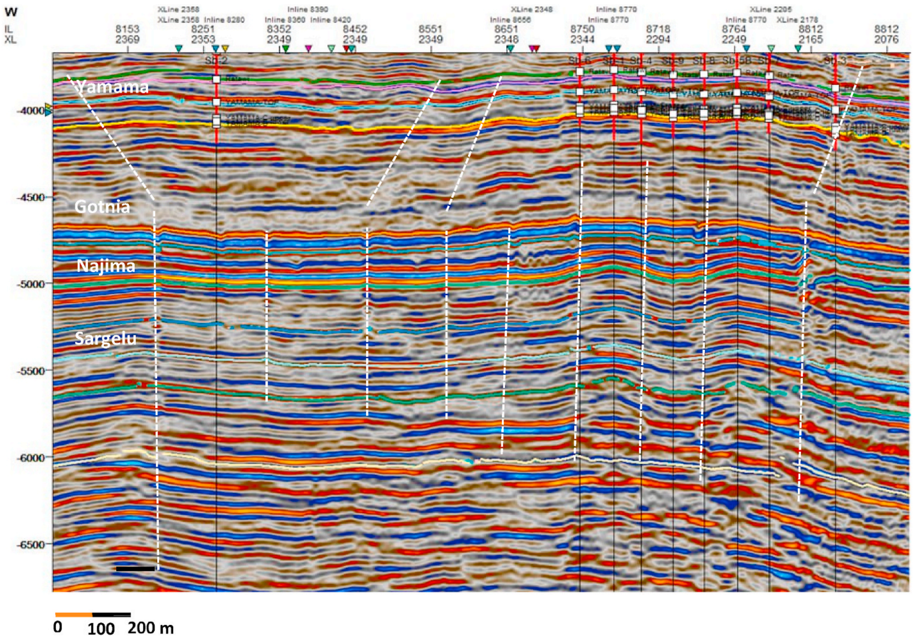


Fig. 14. Seismic section across the Siba field (see Fig. 4), showing several likely faults (white dashed lines) that cross the Gotnia Formation, potentially linking the Jurassic petroleum system below to the Lower Cretaceous petroleum system above. These faults may be major contributors to the ineffectiveness of the Gotnia Formation as a seal in the Siba field.

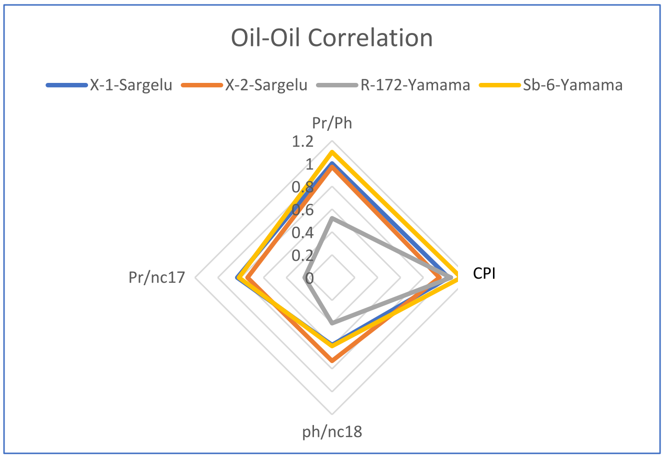


Fig. 15. Star plot showing oil-oil correlation between geochemical properties of oils from the Yamama Formation in the Siba field and North Rumaila oilfield and properties of oils from the Sargelu Formation in nearby fields.

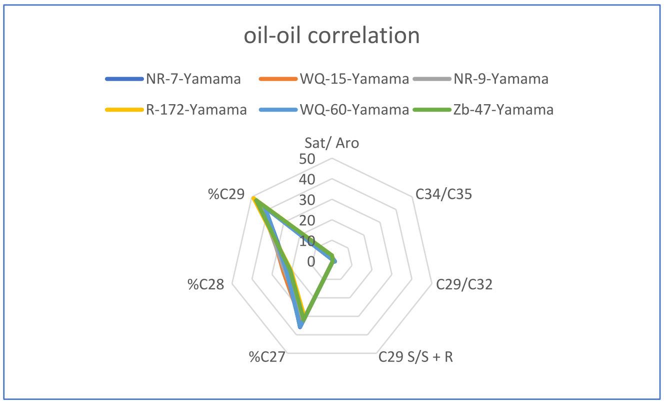


Fig. 16. Star plot showing oil-oil correlation between geochemical properties of oils from the Yamama Formation in the different oil field in Iraq.

anhydrite, shale, dolostone, and limestone; e.g., Ibrahim, 1983) and basement-related faulting and fractures that penetrate the formation (Fig. 13).

The impairment of the Gotnia Formation as an extensive seal is related to two issues: facies changes, especially those involving carbonates, and penetrating faults and fractures. Relative to facies, Roychoudhury and Handoo (1980) described the Gotnia Formation of southern Iraq as mostly anhydrite and chalky limestone, but porous, bioclastic and oolitic limestones are also present, especially on the basin margins (Aqwari et al., 2010), above which the Siba field is located. Moreover, an unconformity caps the Gotnia Formation in southern Iraq (Sharland et al., 2001; Aqwari et al., 2010), and so, the possibility of primary carbonate porosity along with secondary porosity due to dolomitization and karstification along the unconformity (Aqwari et al., 2010; Pitman et al., 2004) is a significant reason why the Gotnia seal failed in the Majnoon field (Pitman et al., 2004), and likely in the Siba field. Yet another reason for failure of the Gotnia seal in the Majnoon field is the presence of faults and fractures that penetrate the seal (Pitman et al., 2004). The Gotnia seal of thick halite and anhydrite is also present below Cretaceous reservoirs in parts of northern Kuwait as well as below reservoirs like those in the Rumaila field in southern Iraq, and seismic interpretation of the Gotnia in Kuwait indicates that similar faulting with folding there is related to synsedimentary movement along basement lineaments that occurred during Kimmeridgian deposition of the evaporites (Carmen, 1996). Structure-contour mapping on top of the Gotnia (Fig. 13) and a seismic section from the Siba field show similar faults and fractures. So, it is very likely that they contributed to failure of the seal.

4.4. *Possible hydrocarbon migration through faults and fractures*

The Gotnia Formation is considered to be an excellent regional seal between an over-pressured Jurassic petroleum system below and the normally pressured Cretaceous reservoirs above (Al-Hajeri and Bowden, 2017). However, between these two petroleum systems, the pressure

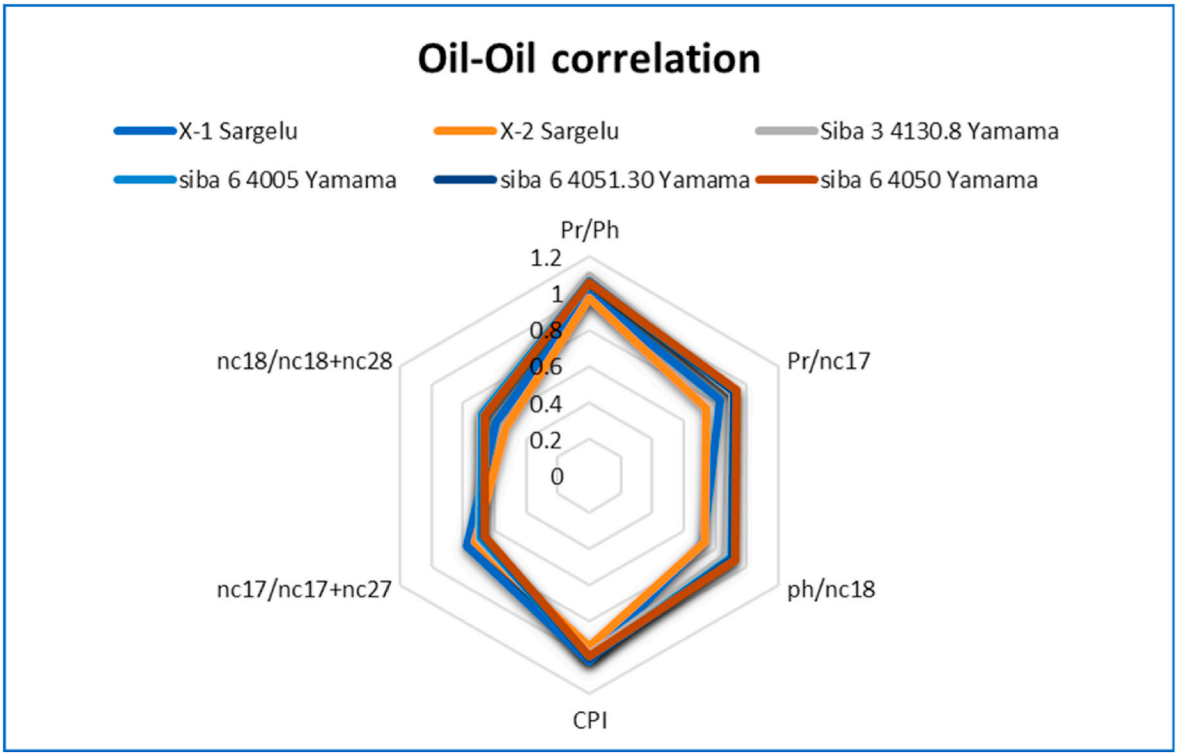


Fig. 17. Star plot showing oil-oil correlation between geochemical properties of oils from the Yamama Formation in the Siba field and properties of oils from the Sargelu Formation in nearby fields. Note the similarity of patterns among all the oils, suggesting similar origins.

change appears to occur in the Gotnia Formation, indicating that it was not always a perfect seal (Al-Hajeri and Bowden, 2017) and allowed liquids to migrate through an otherwise tight formation. Faults and fractures penetrating the Gotnia seal in Kuwait have been interpreted to represent pathways through which fluids could migrate from pre-Gotnia sources to post-Gotnia reservoirs (Al-Hajeri and Bowden, 2017), and similar faults and fractures can be seen breaching the Gotnia seal in the Siba field (Figs. 13 and 14). Late Cretaceous and Neogene compressional forces related to coeval Zagros tectonism reactivated many of these faults, discharging abnormal pressures and allowing fluids to move upward along them (Corely et al., 2006). Because few of these faults reached the surface and erosion in southern parts of the basin was minimal, only small amounts of hydrocarbons were lost from either of the petroleum systems (Pitman et al., 2006).

Similar formation-breaching faults have been noted in Kuwait along anticlinal lineaments like the Kuwait Arch, allowing pre-Gotnia, Jurassic fluids to mix with Cretaceous fluids in north Kuwait (Al-Hajeri and Bowden, 2017). Modeling in southern Iraq (Abeed et al., 2012; 2013) suggests a comparable situation with low to moderate pressures in post-Gotnia formations and abnormally high pressures in pre-Gotnia formations and vertical migraton paths along the faults from source rock to reservoir. Moreover, the migration process was facilitated by the fact that the Jurassic source rocks lie directly below the Cretaceous reservoirs in southern Iraq (Pitman et al., 2006; Abeed et al., 2012; 2013). As has been suggested elsewhere in nearby parts of southern Iraq and Kuwait, faults and fractures through the Gotnia Formation (Figs. 6, 10 and 14) very likely facilitated the vertical, up-fault migration of fluids (Pitman et al., 2006; Abeed et al., 2012,2013; Al-Hajeri and Bowden, 2017) from the pre-Gotnia, Jurassic Sargelu Formation into the post-Gotnia, Cretaceous Yamama reservoir in the Siba field. Hence, development of migration pathways and the inefficiency of the Gotnia seal are clearly related to the Late Cretaceous and Neogene tectonism that reactivated the many basement faults throughout the area (Figs. 6, 10 and 14).

4.5. *Oil-oil correlation*

Petroleum geochemical correlation, using a star plot, is a valuable tool to identify similarities or differences in the compositions of crude oils and rock extracts. The correlations can be used to differentiate oils from dissimilar sources or oils affected by secondary developments, such as biodegradation and thermal maturation (Peters et al., 2007). When Yamama oil in the Siba and North Rumaila fields is compared to Sargelu oil in fields nearby the Siba field, it is clear that the oil in the Yamama Formation is identical to the oil in the Sargelu Formation and does not match the oil in the Yamama formation in the North Rumaila field (Table 1 & Table 2). It is also clear that the oils in the Yamama Formation in the North Rumaila field do not match the oils in the neighboring fields, Fig (15). When comparing the oils of the Yamama Formation in different fields in Iraq (Nahr Umr (NR-7,9), North Rumaila (R-172), West Qurna (WQ-15,60) Zubair (Zb-47) oil fields) it becomes clear that they are identical in the rest of the fields and differ in the Siba field (Fig. 16). Fig. 17 shows a star-plot, oil-oil correlation between crude oil samples from the Yamama Formation in the Siba gas field and from the Sargelu Formation in neighboring oil fields. Based on the near coincidence of patterns shown in Fig. (17), the geochemical properties of oils from the Yamama Formation in the Siba gas field are very similar to the geochemical properties of oils from the Sargelu Formation in the neighboring fields, suggesting that the Sargelu Formation sourced hydrocarbons in the Siba field.

5. Conclusions

The Siba gas field in southern Iraq is Iraq's only producing, non-associated, gas field, but it occurs in an area where mainly oil production predominates. To understand reasons for gas generation and accumulation within the field's Lower Cretaceous Yamama reservoir, investigation of structural style and regional geologic history are critical. The salient points of this investigation are concluded below. (1) A structure-contour map generated on top of the field's Yamama reservoir shows that the Siba field developed on an asymmetrical, northeast-southwest-oriented, anticlinal fold with two domal culminations. The northeastern dome is higher than the southwestern dome by about 100 m, and both domes exhibit elliptical shapes with northwest-southeast-oriented axes. (2) The northeast-southwest orientation of the Siba field contrasts markedly with the predominantly north-south-oriented anticlinal fields that characterize southern Iraq. The Siba field's orientation parallels other "transversal" faults and lineaments throughout Iraq, and in southern Iraq this orientation is apparently related to piercement by salt along these zones of weakness. (3) Structure-contour maps and seismic data show that the Siba anticlinal field is cut by both radial and parallel faults, most of which are concentrated around the northeastern dome. Seismic sections also indicate that the northeastern culmination is largely rooted in a horst, whereas the southwestern culmination is fixed on a complex graben structure. (4) Many precursor faults and zones of weakness are present throughout southern Iraq and adjacent areas, and they cut an important regional seal, the Upper Jurassic Gotnia anhydrite. Reactivation of these faults by Cretaceous and Tertiary tectonic events has not only contributed to the compartmentalization of reservoirs, but more importantly, has most likely allowed the migration of hydrocarbons from high-pressure areas below the Gotnia seal to low-pressure areas above the seal. (5) Oil-oil correlations from this study, as well as previous biomarker and carbon-isotope studies, indicate that hydrocarbons from the Yamama reservoir in the Siba field were sourced from the underlying Sargelu Formation below the Gotnia seal. However, hydrocarbons from other nearby fields may have had different Jurassic source rocks. (6) Clearly, the Gotnia anhydrite in the study area is an impaired seal. Structure-contour maps, combined with seismic sections, show the presence of faults that crossed both formations, allowing the vertical migration of hydrocarbons from the Sargelu Formation to the Yamama reservoir. (7) Vitrinite reflectance and thermal analyses of oils from the Yamama reservoir (0.87% R_0; 128.1 °C) and from the Sargelu Formation (1.36% R_0; 156.96 °C) show that only the Sargelu Formation had the right burial depths and temperatures in this area during Miocene deformation to source Yamama hydrocarbons in the Siba field. It is most likely that the Sargelu Formation is the sole source of the gas present in the Yamama reservoir, as the Yamama Formation (0.87 R_0) never reached the stage of gas generation, while Sargelu Formation (1.36 R_0) had entered the stage of gas generation by Miocene time. (8) Inasmuch as gas-generating parts of the Sargelu Formation occur in deepest parts of the Mesopotamian foreland basin just below the Siba field, vertical movement of hydrocarbons from the high-pressure Sargelu source across a regional seal, impaired by Miocene deformation, is the mostly likely means of migration into the low-to-moderate-pressure Yamama reservoir of the Siba field.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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