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Review of the petroleum systems of the Iranian Zagros and Persian Gulf regions

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Abstract: This study provides a comprehensive review of the petroleum systems in the Iranian Zagros and Persian Gulf regions, spanning the Phanerozoic, with the objective of synthesizing geological, geochemical and basin-modelling data to enhance exploration strategies. Three primary petroleum systems are identified: Paleozoic–Triassic, Jurassic–Cretaceous and Cenozoic, each characterized by distinct source rocks, reservoirs and seals. The methodology integrates extensive literature reviews and original geochemical analyses, including Rock-Eval pyrolysis, vitrinite reflectance, biomarker studies, carbon isotope and kinetic modelling, to assess source-rock maturity, kerogen type and oil-source correlations. The main results highlight the Paleozoic–Triassic system, driven by Silurian Sarchahan 'hot shales', feeding gas-rich Permian–Triassic Dalan and Kangan reservoirs, sealed by Triassic Dashtak evaporites, but challenged by deep burial and high non-hydrocarbon content. The Jurassic–Cretaceous system, which contributes more than 50% of Iran's oil, features the oil-prone Sargelu, Garau and Kazhdumi source rocks, with reservoirs in the Khami and Bangestan groups, sealed by the Hith/Gotnia and Gurpi formations. The Cenozoic system, centred in the Dezful Embayment, relies on the Pabdeh source rock, Asmari reservoir and Gachsaran seal, with significant vertical migration from underlying Mesozoic systems. Chemometric classification of 21 oil samples revealed three distinct oil families that are genetically linked to these petroleum systems. Family A oils are attributed to Upper Jurassic–Miocene source rocks, characterized by a high C_{28}/C_{29} regular sterane ratio. Family B oils correlate to Jurassic or older source rocks, and are classified as high-maturity oils. Family C oils sourced from the Aptian–Albian Kazhdumi Formation and display biomarker parameters indicative of anoxic marine conditions.

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This study summarizes petroleum systems in the Iranian Zagros and Persian Gulf, highlighting factors behind major hydrocarbon accumulations. Decades of exploration spanning from Paleozoic–Cenozoic successions via numerous well penetrations and surface analogues provide a robust understanding of the subsurface geology and petroleum system evolution (Ko 2017; Alipour 2023). Figure 1 depicts the geographical distribution of oilfields and gas fields sourced from these petroleum systems.

Efficient petroleum systems across the Arabian Plate (Saudi Arabia, Iraq, United Arab Emirates (UAE) and Oman) result from ideal elements/processes, their systematic arrangement and the basin's vast scale, creating large drainage areas (Stoneley 1990; Beydoun 1991; Bordenave 2014). Regionally extensive source, reservoir and seal rocks, combined with large structural closures timed with peak oil migration, lead to significant accumulations (Esrafili-Dizaji and Rahimpour-Bonab 2019) (Fig. 2). Stratigraphic/compound traps are also explored (Mirzakhanian and Hashemi 2022).

The Paleozoic petroleum system is primarily sourced by the basal Silurian Sarchahan 'hot shales' (Fig. 3), feeding Paleozoic and basal Triassic reservoirs (Esrafili-Dizaji and Rahimpour-Bonab 2013; Bordenave 2014). These Lower Silurian shales, particularly the distinctive basal organic-rich ('hot') shale unit, are the primary source of most of Paleozoic-derived hydrocarbons in the North Africa and Arabian Plate. These shales supply hydrocarbons to both intra-Paleozoic and basal Triassic reservoirs (Alsharhan and Nairn 1997; Boote *et al*. 1998; Schenk *et al*. 2020). Minor contributions may also come from Carboniferous, Permian Faraghan and Lower Triassic Kangan source rocks (Sabbaghiyan and Aria-Nasab 2019; Sfidari *et al*. 2025). Burial depth (>6000 m) limits pre-Silurian exploration in the Zagros and Persian Gulf, while in the southern territories, such as Oman, there has been successful Precambrian and Lower Paleozoic exploration (Murris 1980; Droste 1997; Grosjean *et al*. 2009).

The Mesozoic system accounts for more than 50% of Iran's oil (Bordenave and Hegre 2005; Al-Husseini 2007; Esrafili-Dizaji and Rahimpour-Bonab 2019). Primary sources for this petroleum system include the Sargelu, Garau, Kazhdumi formations (equivalent to the Hanifa/Diyab, Sulaiy and Nahr-Umr formations in Saudi Arabia) (Bordenave and Huc 1995; Van Laer *et al*. 2014; Vahrenkamp *et al*. 2015*a*; Vincent *et al*. 2015; Alizadeh *et al*. 2017). Minor sources include Aghar Shale of the Dashtak Formation, lower Surmeh Shale, and Ahmadi and Gurpi shales (Bordenave and Hegre 2010; Lasemi and Jalilian 2010; Rabbani and Bagheri Tirtashi 2010; Alaei *et al*. 2012; Mashhadi and Rabbani 2015; Mashhadi *et al*. 2015*a*, *b*; Mirshahani *et al*. 2017; Alizadeh *et al*. 2020). The main reservoir rocks are found within the Khami Group and the Bangestan Group, while the most effective cap rocks include the Gotnia/Hith evaporites, as well as the Kazhdumi and Gurpi marls (Esrafili-Dizaji and Rahimpour-Bonab 2019) (Fig. 3). In addition, intra-formational shaly units can serve as subordinate seals within the Mesozoic petroleum system (Alsharhan and Nairn 2003*a*).

The Cenozoic petroleum system is characterized by the Pabdeh (source – immature/mature), Asmari (high-quality reservoir) and Gachsaran (effective seal) formations (Fig. 3) (Bordenave and Hegre 2010; Alizadeh *et al*. 2018; Rabbani *et al*. 2022). The Cenozoic petroleum system is primarily confined to the Dezful Embayment; however, substantial volumes of hydrocarbons have migrated vertically from the underlying Mesozoic system into the Asmari reservoir through the extensively fractured intervening strata (Alizadeh *et al*. 2012*b*; Kobraei *et al*. 2019; Rabbani *et al*. 2022;

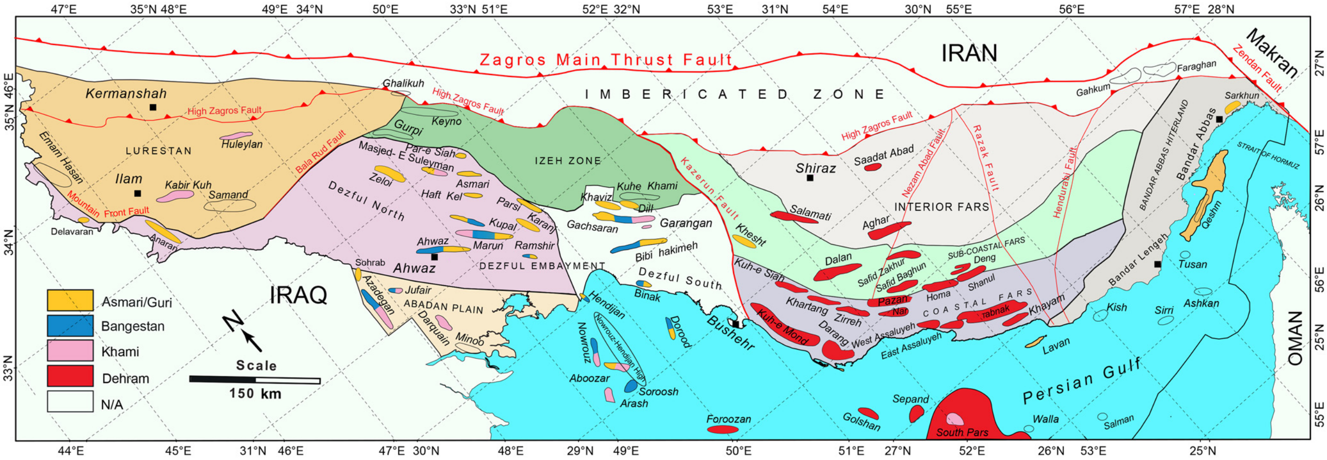

Fig. 1. Map of the Iranian Zagros and Persian Gulf regions showing the studied oilfields and gas fields colour coded by the age of the main producing reservoir interval: red, Permian–Triassic Dehram Group; pink, Jurassic–Aptian Khami Group; blue, Albian–Santonian Bangestan Group; and yellow, Oligo-Miocene Asmari Formation and Guri Member. Source: modified after Esrafili-Dizaji *et al.* (2013) and Bordenave (2014).

Saadati *et al.* 2025). This system, yielding more than 43% of discovered oil, is the most studied system (Bordenave and Hegre 2005; Al-Husseini 2007; Esrafili-Dizaji and Rahimpour-Bonab 2019). The richest Pabdeh Formation source was deposited in the deep Khuzestan/Lengeh troughs during the upper Eocene–lowest Oligocene lowstand parts of sequences Pg25 and Pg30 (Piryaei and Davies 2024). The sandstones and carbonates of the Asmari Formation are is the key reservoir for the Cenozoic petroleum system, particularly in Khuzestan and the northwestern Persian Gulf. The Jahrum Formation and carbonates of the Pabdeh Formation, as well as the Guri Member of the Mishan Formation, are secondary reservoirs for this petroleum system (Rastegar Lari 2008; Esrafili-Dizaji and Rahimpour-Bonab 2019; Gholamalian *et al.* 2023; Piryaei and Davies 2024). These reservoirs are capped by extensive evaporitic deposits of the Gachsaran Formation (Fig. 3) (Bordenave and Hegre 2010; Alsharhan 2014; Maleki *et al.* 2021).

Hydrocarbon generation from potential source rocks in the Zagros Basin is significantly influenced by regional heat-flow patterns (Rudkiewicz *et al.* 2007). The composition of the generated hydrocarbons is determined by the kinetic properties of the source rocks, which govern the breakdown of associated kerogen (Tissot and Welte 1984; Tegelaar and Noble 1994; Pepper and Corvi 1995). Recent modelling studies have documented the timing of hydrocarbon generation from various source rocks in southwestern Iran (Karimi *et al.* 2016; Sfidari *et al.* 2016) and in the Persian Gulf (Mohsenian *et al.* 2014; Baniasad *et al.* 2016, 2017; Alipour *et al.* 2017*a*, 2019). A comprehensive study on source-rock maturation and the generated and expelled hydrocarbons was recently conducted as part of the Pearl Initiative Programme of the Persian Gulf region, which included a detailed 3D modelling study of the associated petroleum systems (NIOC 2016). This report reviews the petroleum systems in southwestern Iran and the adjacent offshore areas, with a particular focus on the remaining resources and evolving exploration and production trends.

Most accumulations are in NW–SE Zagros structural traps within the Oligo-Miocene Asmari, Mesozoic Bangestan and Khami groups and the Permian and Lower Triassic Dehram Group (Beydoun *et al.* 1992; Atashbari *et al.* 2018; Esrafili-Dizaji and Rahimpour-Bonab 2019; Vergés *et al.* 2024). Paleozoic traps are less developed due to their depth.

Conversely, structural traps linked to north–south orientated ‘Arab’ tectonism and halokinesis of the Infracambrian Hormuz Salt are more prevalent in the outer regions of the Iranian Zagros and the Persian Gulf regions (Orang *et al.* 2018; Faridi *et al.* 2021). Recent exploration efforts have increasingly targeted stratigraphic and combination traps around basement palaeohighs, such as the Hendijan and South Pars fields, particularly within the Late Cretaceous Sarvak and Ilam formations and the Oligocene–Miocene Asmari Formation. The former features rudist-dominated platform carbonates interbedded with muddy intrashelf basinal ‘Oilgostegina’ facies, notably observed in the Abadan Plain (e.g. Piryaei *et al.* 2010; Bromhead *et al.* 2022; Simmons *et al.* 2025).

Dataset and methodology

A synthetic and comprehensive understanding of the petroleum systems in the Iranian Zagros and Persian Gulf regions, focusing on the Paleozoic–Triassic, Jurassic–Cretaceous and Cenozoic systems, was carried out in this study. In this paper, an extensive review of published literature (e.g. Bordenave 2014; Esrafili-Dizaji and Rahimpour-Bonab 2019) and unpublished internal National Iranian Oil Company (NIOC) reports (e.g. NIOC Exploration

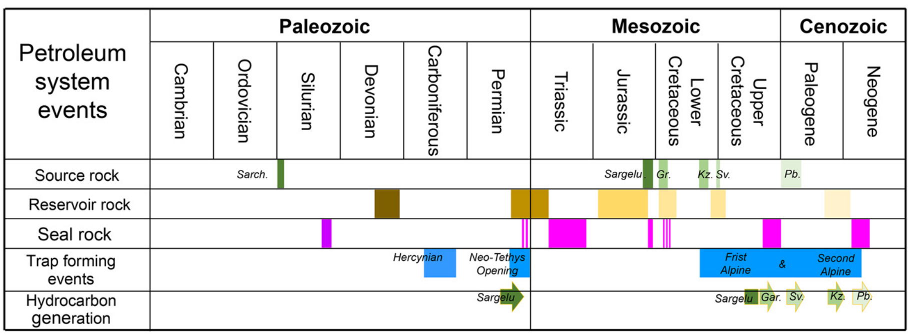

Fig. 2. Generalized event chart for the Paleozoic–Triassic, Jurassic–Cretaceous and Cenozoic petroleum systems of the study area. Source: modified after Esrafili-Dizaji *et al.* (2013).

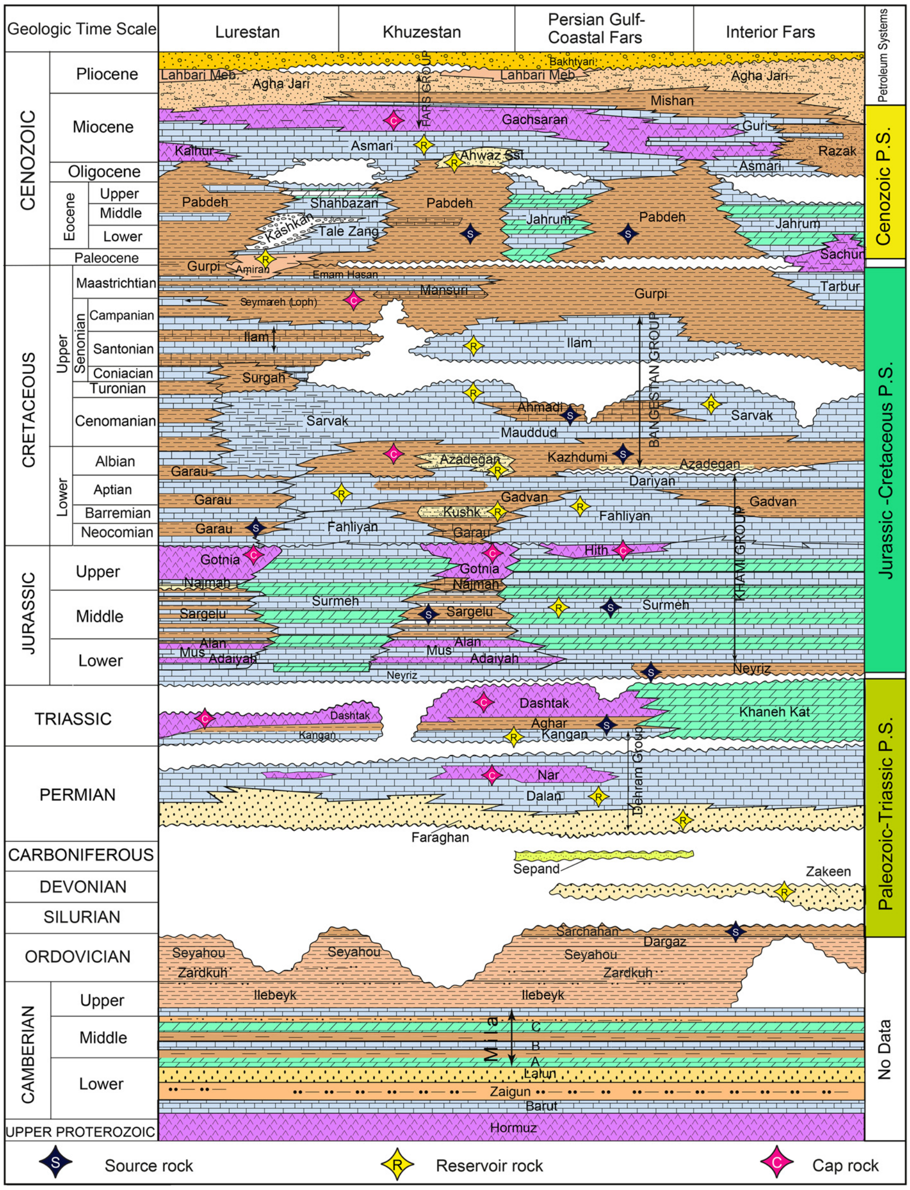

Fig. 3. Generalized stratigraphic column for the Iranian Zagros and Persian Gulf regions showing the petroleum system elements. Source: modified after James and Wynd (1965).

Directorate and RIPI 2018; NIOC 2021) were conducted in the domains of geology, geochemistry and petroleum systems. This dataset provided critical data on source-rock properties, kinetic parameters and oil compositions. A comparison and regional integration have also been performed between the study area petroleum systems and neighbouring countries (e.g. Saudi Arabia, Iraq, UAE and Oman) within the broader Arabian Plate framework, drawing on references such as Abu-Ali *et al.* (1999) and Aqrawi and Badics (2015).

This review synthesizes geochemical data (Rock-Eval pyrolysis, vitrinite reflectance and biomarkers) from literature to assess source-rock maturity, kerogen type and generation potential (e.g. total organic carbon (TOC) content, hydrogen index (HI) and T_{max} for Sarchahan shales of the Sargelu Formation) (NIOC 2014; Saberi *et al.* 2016). Diagnostic biomarkers were identified in the source rocks of the Pabdeh, Kazhdumi, Garau and Sargelu formations. Compound-specific isotope analysis (CSIA) was performed on oils sourced from the Garau and Sargelu formations. In addition, the kinetic properties governing hydrocarbon generation from the source rocks of the Pabdeh, Garau and Sargelu formations were examined.

To characterize source rocks such as the Sarchahan Formation, we utilized direct geochemical measurements (TOC content and reflectance) from outcrop sections at locations including Kuh-e-Faraghan and Kuh-e-Gahkum, following the methodologies from Szabo and Kheradpir (1978) and Ghavidel-syooki *et al.* (2011). Separately, original chemometric analysis categorized 21 oil samples into three families (A, B and C) using biomarker indicators such as C_{28}/C_{29} sterane ratios. Statistical methods aided oil-source correlation. Biomarker and $\delta^{13}C$ isotope analyses (literature and original) established genetic links between oils and source rocks (e.g. the Kazhdumi and Pabdeh formations).

The Paleozoic–Triassic petroleum system

The Paleozoic–Triassic petroleum system is so named because of its age context and because of the Permian–Triassic uppermost reservoir succession, specifically the lower Triassic Kangan Formation, and its cap rocks, the middle–late Triassic Dashtak Formation (see Fig. 3). This Paleozoic–Triassic system in the Iranian Zagros and Persian Gulf holds significant economic value due to its vast reserves of natural gas, high gas/oil ratio (GOR), condensates and, in some instances, light oil (Bordenave 2014). However, accurately characterizing this system has proven challenging due to its considerable depth, which has resulted in limited direct sampling and suboptimal seismic data acquisition. Only a select few deep wells – such as those located in the Golshan, South Pars, Huleylan, Kabir Kuh, Kuh-e-Siah, Kuh-e Mond, Sepand,

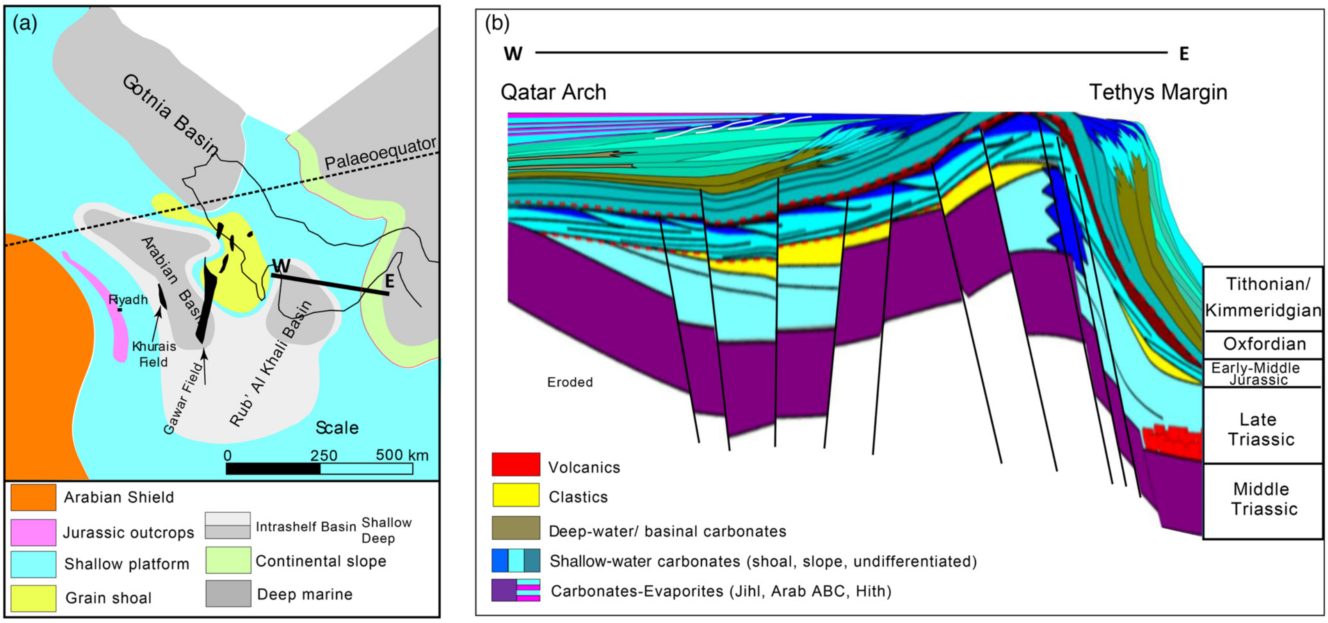

Fig. 4. (**a**) General palaeogeographical reconstruction of the Late Jurassic showing the development of anoxic intrashelf basins in the NE Arabian Plate. (**b**) Schematic west–east cross-section through the Diyab Basin from the Qatar Arch to the Neo-Tethys margin (profile line in Fig. 9a). Source: (a) modified from Vahrenkamp *et al.* (2015*b*) and Fox and Ahlbrandt (2002); (b) from Van Laer *et al.* (2014).

Khartang, Deng and Salman fields (see Fig. 1) – have successfully penetrated the pre-Permian strata. The presence of light oil and condensates within the Permian–Triassic Dalan–Kangan carbonates or the Permian Faraghan siliciclastics in the external Fars area and Persian Gulf suggests the effectiveness of the Paleozoic–Triassic petroleum system (Pollastro 2003; Aali and Rahmani 2011; Ahanjan *et al.* 2016, 2017). Below is a general overview of the key elements and processes that define this petroleum system based on the available data.

In contrast to regions such as Saudi Arabia (Hakami and İnan 2016), Iraq (Aqrawi and Badics 2015) and the UAE (Alsharhan 1993), the Triassic interval in the Iranian Zagros and Persian Gulf lacks the defining characteristics of an independent petroleum system (i.e. a cohesive source–reservoir–cap rock combination). For instance, in the Rub-Al-Khali Basin (Fig. 4), the Upper Triassic–Lower Jurassic siliciclastic succession has been found to host prolific gas reserves sourced from interbedded coal intervals (Stewart *et al.* 2016). This finding, alongside similar reports of coal-bearing intervals in Saudi Arabia's Triassic formations (Al-Mahmoud *et al.* 2014), suggest that the Triassic succession in the Zagros and Persian Gulf, especially offshore, may have significant exploration potential for natural gas. Onshore, the Lower Triassic Kangan Formation features high-quality reservoir rocks for hydrocarbons sourced from the Paleozoic, while the evaporites of the Upper Triassic Dashtak Formation act as an effective cap rock (Szabo and Kheradpir 1978; Insalaco *et al.* 2006; Bordenave 2008).

Given the limited hydrocarbon potential of the Triassic, the subsequent discussion will focus on the Mesozoic petroleum systems within the Jurassic and Cretaceous successions.

Source rocks

The basal Silurian marine 'hot shales' of the Sarchahan Formation (Figs 3, 5 and 6a) are identified as the primary source rock within the Paleozoic petroleum system, accounting for more than 90% of the hydrocarbons generated in the Arabian Plate region and north Africa (Mahmoud *et al.* 1992; Aqrawi 1998; Jones and Stump 1999; Abu-Ali and Littke 2005; Grabowski 2005; Faqira *et al.* 2013; İnan *et al.* 2017). The term 'Silurian hot shale' refers to an organic-rich, lowermost Silurian (Rhuddanian Stage) shale, deposited during the early Silurian lowstand and early transgression stages following late Ordovician glaciation. This unit exhibits lateral discontinuity, with its distribution and thickness primarily influenced by early Silurian palaeorelief that was shaped by glacial processes during the late Ordovician ice age, as well as by Pan-African and infra-Cambrian compressional and extensional tectonism. This shaly interval is characterized by a high gamma-ray (GR) signature, typically ranging from 150 to 200° API or higher, reflecting an elevated uranium content associated with high TOC contents (3% for maturities around the oil window; lower TOC contents for higher maturities) and Type II (oil-prone) kerogen (Lüning *et al.* 2000; Saberi *et al.* 2016; Mehrabi *et al.* 2021). In the Arabian Plate, the Silurian shales are present in the Faydah-Jafurah and Nafud-Ma'aniya basins, separated by the Al-Batin Arch (Fig. 4). These basinal deposits have been truncated locally by the overlying Hercynian unconformity (Faqira *et al.* 2009). Geochemical fingerprinting links these shales to the non-associated gas in Qatar's North Field and the oil reserves in central Saudi Arabia (Alsharhan and Nairn 1997).

Although the Sarchahan Formation is exposed in limited areas within the interior parts of the Zagros, it remains deeply buried beneath the exterior parts of the Zagros and Persian Gulf regions (Figs 6a and 7). The organic geochemistry of these shales has been studied in outcrop sections in Kuh-e-Faraghan and Kuh-e-Gahkum, NE of Bandar Abbas in eastern Zagros (Szabo and Kheradpir 1978; Bordenave and Burwood 1990; Bordenave 2008; Ghavidel-syooki *et al.* 2011; Saberi *et al.* 2016). In these areas, the highly organic-rich hot shales at the base of the Sarchahan Formation are typically 30–50 m thick and exhibit average TOC content values of 5.27 wt%, an average T_{max} value of 459°C and average HI value of 72. 2 mgHC g^{-1} TOC – values consistent with a late mature source rock containing Type II/III organic matter. The Ordovician and early Llandoverian portions of the Sarchahan Formation contain Types II and III kerogen with TOC values ranging from 2.94 to 7.19 wt%, but the rest of the Sarchahan Formation (late Llandoverian) has lower TOC values (0.10–0.58 wt%). Therefore, the 'hot shales' interval in the Kuh-e-Faraghan section coincides with the Hirnantian and early Llandoverian (Rhuddanian) age, within which the GR response reaches *c.* 180° API (Saberi *et al.* 2016).

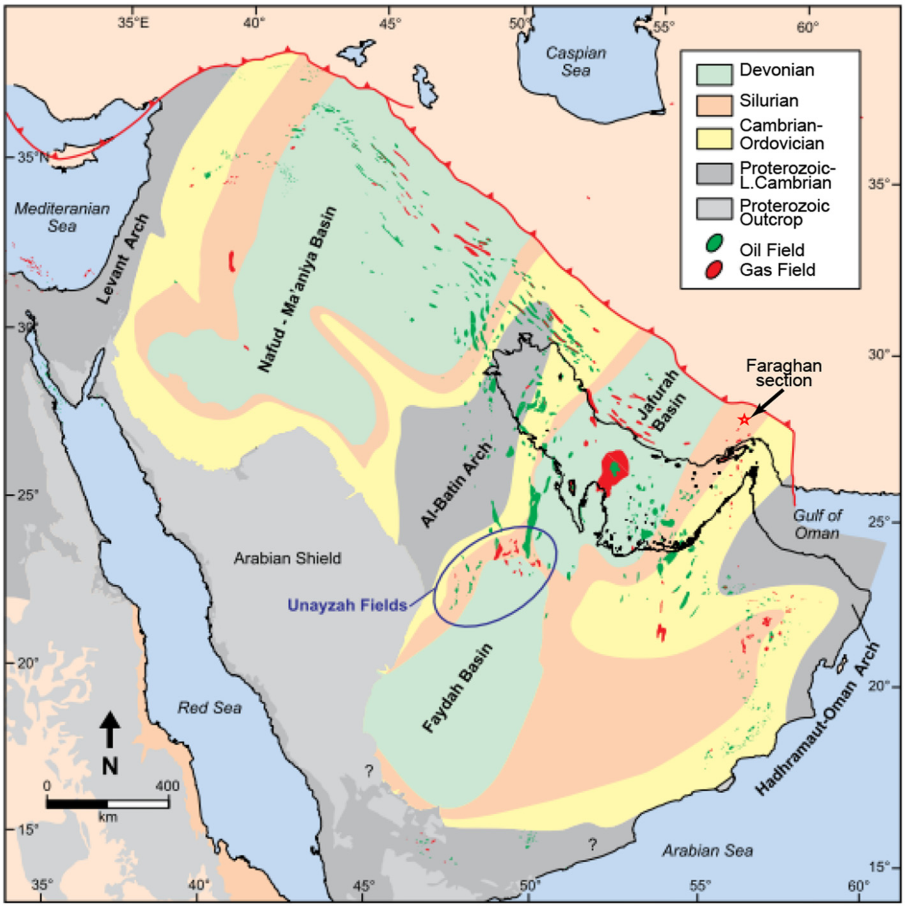

Fig. 5. Outline map showing the regional distribution of the basal Silurian organic-rich hot shales in the Arabian Plate. Source: from Faqira *et al.* (2009).

While the Silurian 'hot shales' in Iran remain unexplored in subsurface wells, the equivalent 'hot shales' at the base of the Qusaiba Formation in Saudi Arabia have been extensively studied due to their relatively shallow depths (see Figs 5 and 6c). These basal Qusaiba 'hot shales', ranging from 3 to 70 m in thickness, exhibit a pronounced high GR signature in well logs. They are characterized by Type II organic matter with TOC contents reaching up to 8 wt% and have excellent oil-generating potential (Mahmoud *et al.* 1992; Wender *et al.* 1998; Abu-Ali *et al.* 1999, 2001; Abu-Ali and Littke 2005). Upwards in the Qusaiba Formation are leaner shales with lower GR values that are referred to as 'warm shales' (e.g. Abu-Ali *et al.* 1991; Jones and Stump 1999; Lüning *et al.* 2000; Faqira *et al.* 2009, 2013; Le Heron *et al.* 2009). The kinetics of hydrocarbon generation from the Sarchahan shales in the Iranian Zagros and Persian Gulf areas are expected to be similar to those of the time-equivalent 'hot shales' at the base of the Qusaiba Formation in Saudi Arabia (e.g. Abu-Ali *et al.* 1999) (Fig. 6c).

Beyond the prominent basal Silurian source rock, other intervals within the Paleozoic succession of the Iranian Zagros – such as portions of the Zakeen, Sepand and Faraghan formations – may also possess source-rock potential. Notably, the recently identified Carboniferous Sepand Formation in the South Pars Field contains a 38 m-thick source-rock interval with average TOC and HI values of 3.87 wt% and 127 mgHC g^{-1} TOC, respectively (Fig. 7) (NIOC 2017). Moreover, parts of the Zakeen and Faraghan formations may also include source-rock intervals, as suggested by recently acquired geochemical data that include well logs, Rock-Eval pyrolysis data and kinetic measurements (Saberi and Jalilian 2018).

The organic-rich shales within the Lower Triassic Kangan Formation may exhibit moderate source-rock potential and could have contributed to charging several Triassic reservoirs located in the northern limb of the South Pars Palaeohigh in the Homa, Shanul, Tabnak, Khayam, Safid Baghun, Safid Zakhur, Dalan and Aghar fields (see Fig. 1 for their locations) (Ahanjan *et al.* 2017). Although the geochemical characteristics of these source rocks have not been extensively documented, it is noted that their organic matter differs isotopically and geochemically from that found in the basal Silurian shales (Ahanjan *et al.* 2017). For instance, condensates derived from the Early Triassic Kangan source rock display low concentrations of tetracyclic terpanes and high ratios of extended tricyclic terpanes, and are likely to contain predominantly marine algal-derived Type II kerogen, favouring the generation of high-quality oil and condensate under reducing depositional conditions. In contrast, the Sarchahan Formation shows a higher tetracyclic terpane content and lower extended tricyclic terpane ratios, suggesting a mixed organic input, possibly with a greater terrestrial influence and Type II/III kerogen, which leads to a broader hydrocarbon spectrum including oil, condensate and significant natural gas generation (Ahanjan *et al.* 2017).

Shale-rich mudstones within the K2 unit at the base of the Kangan Formation demonstrate fair to good source potential, with TOC values reaching up to 2.15 wt% and organic matter mainly composed of Type II kerogen (some levels show Type II/III kerogen). However, the hydrocarbon generation kinetics and geographical extents of the Lower Triassic source rocks are poorly known, and they are thought to have generated relatively minor volumes of hydrocarbons compared with the basal Silurian source rock (Bordenave 2008).

Reservoir rocks and seals

Reservoirs

The Permian–Triassic carbonates and siliciclastics of the Middle Permian–Lower Triassic Dehram Group – including the Faraghan, Dalan and Kangan formations – serve as the primary reservoir rocks

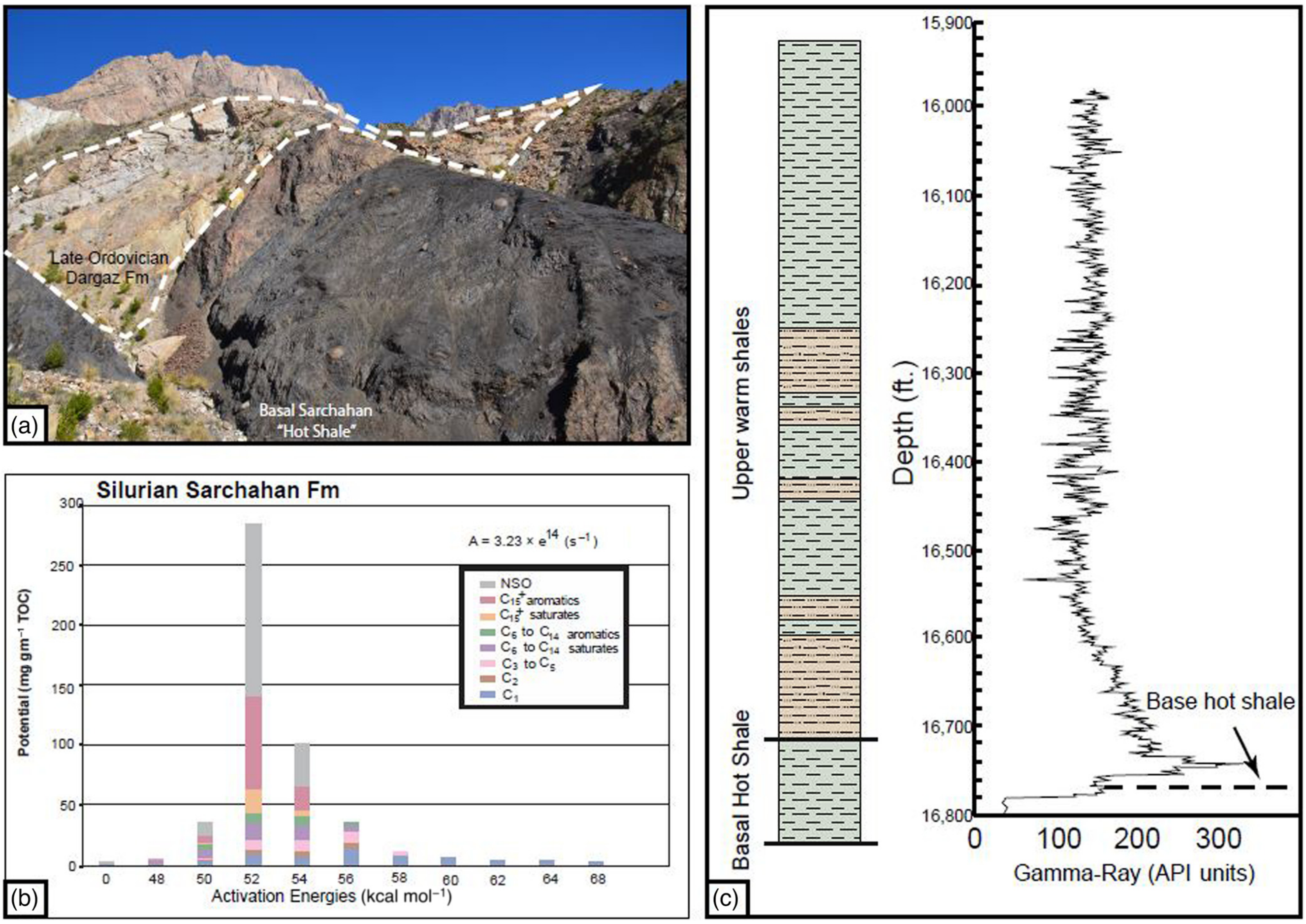

Fig. 6. (**a**) Outcrop view of the basal Silurian hot shale of the Sarchahan Formation in the Tang-e Zakeen section of the Faraghan Mountains. (**b**) Kinetic properties of the petroleum formation from the Silurian Qusaiba Formation source rock. (**c**) Gamma-ray profile v. depth for the basal Silurian hot shale intervals from a well in the Saudi Arabia. Source: (b) from Abu-Ali *et al.* (1991); (b) from Jones and Stump (1999).

charged by the Paleozoic source rocks in the Iranian Zagros and Persian Gulf regions (Bashari 2005; Insalaco *et al.* 2006; Bordenave and Hegre 2010; Esrafili-Dizaji *et al.* 2013; Ahanjan *et al.* 2016). Gas occurrences within the siliciclastics of the Faraghan Formation have been reported at several locations in the Fars area and Persian Gulf (e.g. the Khartang, Sepand and Salman fields), where overlying Dalan and Kangan reservoirs may facilitate multi-reservoir systems. For instance, significant gas accumulations have been identified in the sandstones of the Faraghan Formation in the Khartang Field (Vennin *et al.* 2015). The uppermost section of the Faraghan Formation, which corresponds to the 'Basal Khuff' clastics, is predominantly muddy and exhibits limited reservoir potential. In contrast, the 'Basal Khuff' clastics serve as significant gas reservoirs in Saudi Arabia and the UAE (Ali and Silwadi 1989; Fox and Ahlbrandt 2002; Taher *et al.* 2012; Al-Johi and Al-Laboun 2015).

The Dalan and Kangan formations are characterized by thick, dolomitized carbonates that host some of the largest gas reserves globally (Amel *et al.* 2015). Specifically, the upper sections of these formations within the Dehram Group are the primary reservoirs for the Paleozoic petroleum system in the South Pars Field and its extension into Qatar, known as North Dome (Esrafili-Dizaji *et al.* 2013; Bordenave 2014). These reservoirs have been confirmed in the outer Fars area, including notable fields such as Aghar, Dalan, Tabnak and Nar. Conversely, in the Lurestan area – in fields like Huleylan, Kabir Kuh and Samand – these reservoirs contain non-commercial gas reserves characterized by a high nitrogen content (Bordenave 2008). These intervals correspond to the Khuff A, B and C reservoirs found in Saudi Arabia (Alsharhan and Nairn 2003*a*; Alsharhan 2006).

The Nar Member, which delineates the Lower and Upper Dalan formations (Fig. 3), is characterized lithologically by a combination of evaporites and carbonates. Notably, the carbonates in the lower and middle sections of the Nar Member are gas-producing in certain locations, such as in the Kish and Safid Zakhur fields.

While the Dashtak Formation generally acts as an effective seal, carbonate intervals in its lower section, specifically between the Aghar Shale Member and the S6 unit, exhibit non-commercial gas accumulations.

Seals

The shaly and argillaceous intervals between the Faraghan and Dalan formations, corresponding to the basal Khuff clastics of Saudi Arabia, provide a robust seal for the underlying Faraghan reservoirs (Asghari 2014). The evaporitic Nar Member (Fig. 3), which separates the Lower and Upper Dalan formations, has been recognized as an impermeable unit across the Persian Gulf and Coastal Fars regions (e.g. the Kish, Golshan, Pazan, Khayam and Homa fields). This impermeability effectively prevents the upward migration of Paleozoic-sourced hydrocarbons (Insalaco *et al.* 2006; Amel *et al.* 2015). However, this regional cap rock thins or transitions into solution breccia and dolomitic units towards the northeastern Zagros, leading to a loss of sealing efficiency. Consequently, the Faraghan, Dalan and Kangan formations – collectively referred to as the Dehram reservoirs – form a continuous reservoir unit in the Fars area, exemplified by fields such as Safid Zakhur and West Assaluyeh.

A regional seal is further provided by the anhydrites and shales of the Triassic Dashtak Formation, which serve as an effective cap rock

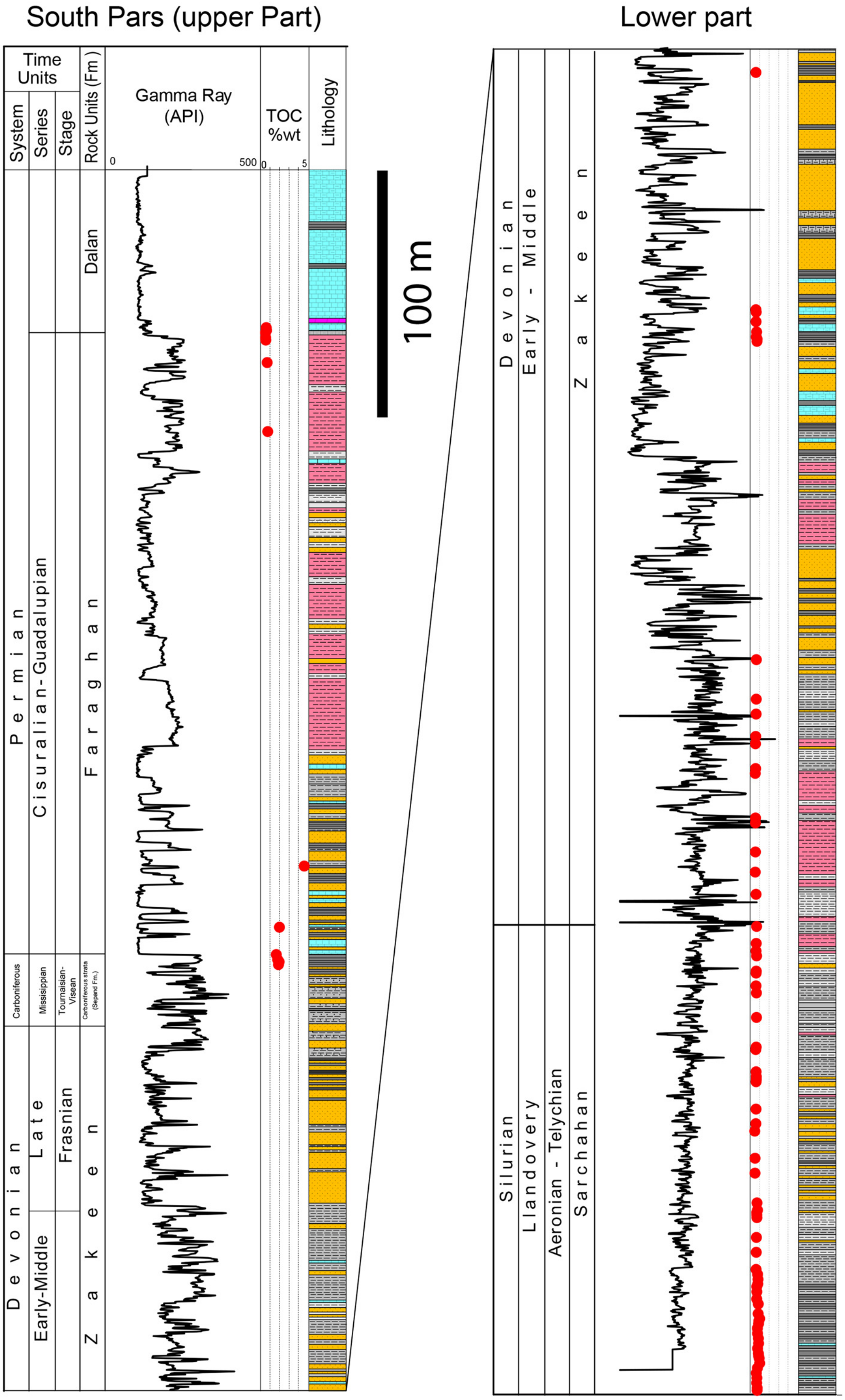

Fig. 7. Well section through the Paleozoic stratigraphic units of the Sarchahan, Zakeen, Sepand, Faraghan and Dalan formations in the South Pars Field. The TOC values of the different source-rock intervals are shown in red solid circles.

for reservoirs in the Upper Dalan and Kangan formations (Szabo and Kheradpir 1978; Sadooni and Alsharhan 2004; Bordenave 2008). Nonetheless, in certain fields in the western Fars area (e.g. the Nar and Aghar fields: Fig. 1), the Dashtak Formation functions as both a reservoir and a cap rock. The proportion of evaporitic facies within the Dashtak Formation diminishes towards the internal and eastern Zagros regions, facilitating the upward migration of hydrocarbons from the Dehram reservoirs (e.g. Alipour 2024).

The ‘Aghar Shale’ at the base of the Dashtak Formation and its time-equivalent Sudair shales in the Arabian Peninsula can be regarded as regional seals for the underlying oolitic carbonates and dolomitic Dalan–Kangan reservoirs in the Fars and Persian Gulf areas (e.g. the North Dome, South Pars and Tabnak gas fields) (Bashari 2005).

Understanding reservoir quality and seal efficiency is crucial for assessing the risks associated with the Paleozoic petroleum system in southwestern Iran. A comprehensive grasp of the areal extent of porous, grain-dominated facies in the Dalan–Kangan reservoirs will reveal future exploration trends within this petroleum system (Bordenave 2008, 2014; Alipour 2024).

Hydrocarbon generation and migration

Basal Silurian Sarchahan source at Kuh-e-Faraghan and Kuh-e-Gahkum was buried to a depth of 6 km before its subsequent exposure during the Cenozoic Zagros orogeny (Kamali and Rezaee 2003). The burial maturity of these shales to gas-window levels has

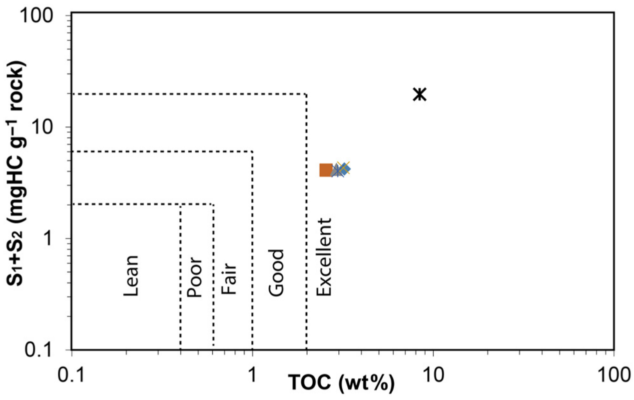

Fig. 8. TOC v. S1 + S2 diagram showing the abundance of organic matter in the Silurian Sarchahan Formation source rocks in the South Pars Field.

led to the formation of significant natural gas reserves within the Permian–Triassic Dalan Formation and Kangan Formation reservoirs (Ala *et al*. 1980; Bordenave and Hegre 2010; Ghavidel-syooki *et al*. 2011; Alipour 2024). An organic petrographical analysis of the organic matter present in these 'hot' shales, primarily utilizing graptolite reflectance, has validated their elevated thermal maturity, indicating a dry-gas window (Khani *et al*. 2016). This conclusion is further supported by the average Rock-Eval T_{max} values of 459°C documented for this basal Silurian Sarchahan source rock from the Kuh-e-Faraghan outcrop section (Saberi *et al*. 2016).

Deep drilling into the Sarchahan Formation, particularly in the South Pars, Golshan and Zirreh fields, has not reached the basal 'hot-shale' interval. However, the maximum vitrinite reflectance (VR_o) values obtained from one well at the South Pars Field, where VR_o is *c*. 1.33% at a depth of 4488 m – align with the gas-generation window (Fig. 7). The maturity (R_o) of the Sarchahan hot shale in this well (189 m drilled to a depth of 4488 m) is constrained to ≤2% based on a comparison to the formation's regional thickness (Lüning *et al*. 2000), placing it firmly in the wet-gas window (South Pars Field). Excellent hydrocarbon generation potential is also indicated for Carboniferous shales and the Lower Permian section within this well, supported by TOC values of more than 2% and high S1 + S2 values (Fig. 8). 1D and 2D petroleum system modelling studies of the Paleozoic petroleum system (Kamali and Rezaee 2003; Rudkiewicz *et al*. 2007; Bordenave and Hegre 2010) indicate that the Sarchahan source rock entered the oil window during the Early Cretaceous in the northwestern regions of the Fars Platform, particularly at Salamati. In addition, shales within the Kangan Formation are modelled to have commenced oil generation in the Late Cretaceous, especially in the northern part of the South Pars Palaeohigh. The basal section of the Kangan Formation is situated within the oil window in some fields such as East Assaluyeh and Khayam fields in the subcoastal Fars area, as well as in the northern and central sectors of the South Pars High (Ahanjan *et al*. 2017).

Previous research has established that the burial history and hydrocarbon generation behaviour of the Sarchahan source rock were influenced by a series of basement highs, with the South Pars Palaeohigh being the most significant (Bordenave 2008; Faqira *et al*. 2009, 2013; Alipour 2024). Early generated oil appears to have migrated toward these highs, filling broad, gentle closures and forming 'pre-Zagros' oil and gas accumulations (Fig. 9a) (Bordenave and Hegre 2005, 2010; Rudkiewicz *et al*. 2007; Bordenave 2008). Despite their considerable size, these accumulations were later redistributed into younger anticlines created during Zagros Orogeny folding (Fig. 9b). This process involved an initial phase of lateral migration towards the giant pre-Zagros structures, followed by vertical remigration during the Zagros Orogeny (Alsharhan and Kendall 2021; Alipour 2024). The geochemistry of gas reserves within the Paleozoic reservoir rocks was shaped by both fractionation during migration and subsequent mixing of multiple hydrocarbon charges (Ahanjan *et al*. 2017). While some geochemical evidence suggests that secondary cracking of oil contributed to the occurrence and geochemistry of Paleozoic gas (Aali and Rahmani 2011), it is also likely that hydrocarbons in the Dehram Group (i.e. Dalan and Kangan formations) were primarily generated through kerogen cracking rather than oil cracking (Dessort *et al*. 2006; Ahanjan *et al*. 2017). Nevertheless, a detailed understanding of the migration dynamics of Paleozoic gas in southwestern Iran and the associated light-oil play fairways remains elusive (Alipour 2024).

Recent studies in northwestern and east-central Saudi Arabia have identified potential for unconventional gas and oil resources (shale gas and shale oil) within the Silurian 'hot shales' (Inan *et al*. 2016, 2017). Similarly, multidimensional modelling of petroleum system in offshore Iran has indicated that the maturity required for shale gas development has been achieved in the equivalent Sarchahan 'hot shales' located in the southern Persian Gulf (Alipour *et al*. 2021). Both the basal Silurian 'hot shales' and the immediately overlying 'warm shales' (Fig. 3) are promising candidates for unconventional resource exploration in southwestern Iran (Alipour *et al*. 2021; Inan *et al*. 2017). However, given the significant depths of the basal Silurian 'hot shales', the current

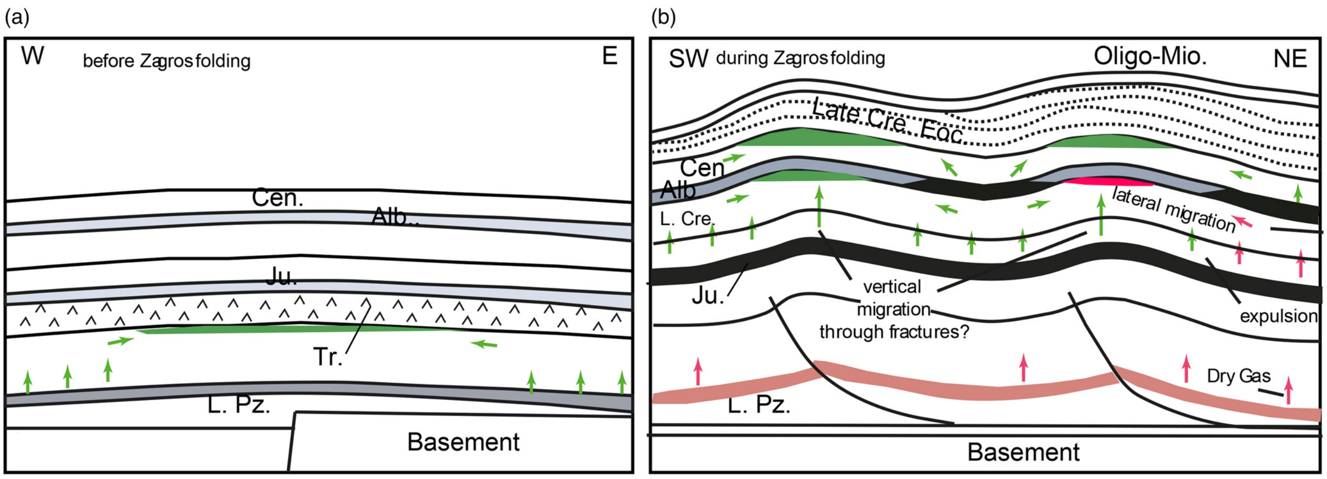

Fig. 9. (**a**) Schematic cartoon showing initial entrapment of oil derived from the Paleozoic–Triassic petroleum system in large-scale, gentle structures before the Zagros Orogeny. (**b**) Remigration causing the mixing of multiple charges within younger structures formed as a result of the Zagros Orogeny. Source: Rudkiewicz *et al*. (2007).

economic viability of developing these reserves remains questionable at present.

The Paleozoic–Triassic petroleum system in the Lurestan area is notable for high concentrations of nitrogen gas, particularly in fields such as Kabir Kuh and Huleylan, where nitrogen levels range from 60 to 94% across different wells. However, the sources and mechanisms behind nitrogen formation in this region have yet to be thoroughly investigated.

In summary, there is a significant uncertainty regarding the dynamics of the Paleozoic–Triassic petroleum system in south-western Iran, particularly concerning the spatial distribution and maturity evolution of its source rocks. Further investigations of basin-scale migration mechanisms, potential stratigraphic traps and the notably high nitrogen concentrations observed in some Permian–Triassic reservoirs in the Lurestan area are needed to clarify this uncertainty. Future exploration efforts, particularly through the drilling of deeper wells targeting the pre-Permian succession, will enhance our understanding of this system. Despite being poorly understood compared with other petroleum systems in the region, the Paleozoic may contain considerable undiscovered hydrocarbon reserves in Iran.

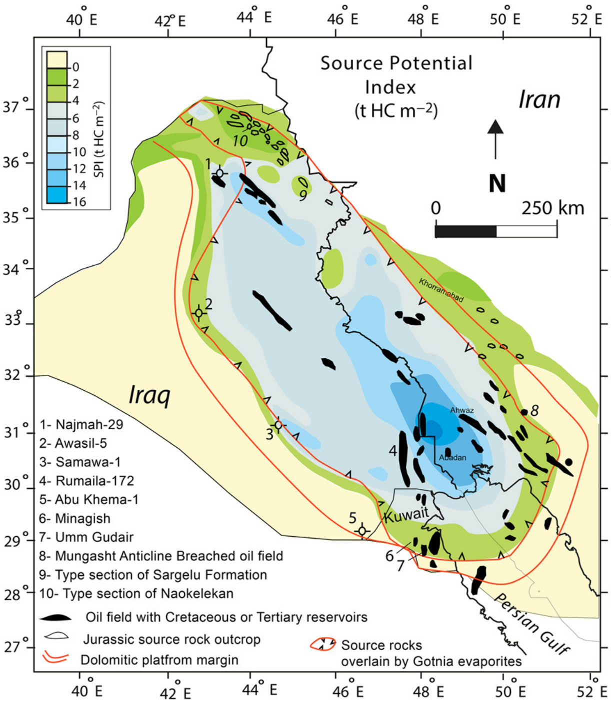

Fig. 10. General map of the intrashelf basin in the NW Zagros area in which the Middle Jurassic Sargelu Formation source rock was deposited. The colour scale shows the formation's source-rock potential index (t HC m^{-2}). The barbed red line shows the area in the centre of the intrashelf basin where the Sargelu Formation is overlain by Gotnia Formation evaporites; elsewhere it is surrounded by dolomitized platform margin facies. Source: modified from Goff (2005) and Aqrawi and Badics (2015)

Jurassic–Cretaceous petroleum system

The Jurassic and Cretaceous successions are characterized by rich hydrocarbon contents due to the presence of highly organic-rich source rocks that have reached optimal thermal maturation. These source rocks have generated substantial volumes of oil and gas, filling a variety of traps.

Jurassic

Source rocks

The Lower Jurassic Neyriz Formation (Fig. 3) is reported to extend across much of the Iranian Zagros Basin and Persian Gulf (Alavi 2004). However, its organic geochemistry and hydrocarbon potential in this study area remain poorly understood. While organic-rich facies have been identified in its time-equivalent strata in Abu Dhabi, their contribution to the Jurassic petroleum system is regarded as minor and primarily gas focused (Taher *et al*. 2012).

The organic-rich layers of the Middle Jurassic are predominantly located in the western parts of the Zagros in Iraq (e.g. Aqrawi and Badics 2015), with significant source rocks being represented by the Middle Jurassic Sargelu Formation. This formation was deposited within a deep, anoxic intrashelf basin, known as the 'Sargelu Basin', which trends SE–NW across the northwestern Persian Gulf, encompassing the Khuzestan and Lurestan areas before extending into Iraq (Szabo and Kheradpir 1978) (Fig. 10). In Iran, the organic-rich Sargelu facies predominantly cover much of Lurestan and the Abadan Plain, reaching eastwards into the northern Dezful Embayment, where they extend laterally into the Surmeh Formation's platform carbonates (Rudkiewicz *et al.* 2007; Bordenave 2008; Aqrawi and Badics 2015) (Fig. 10).

Within the Zagros region, only a limited number of wells, such as those in the Gurpi, Azadegan, Darquain and Asmari fields, have successfully penetrated the Sargelu Formation. However, a newly drilled well in the Abadan Plain has encountered a substantial section of this formation, as illustrated in Figure 11.

The organic matter within the Sargelu Formation source rock is primarily composed of oil-prone Type IIS kerogen (Aqrawi *et al.* 2010; Aqrawi and Badics 2015; Khani *et al*. 2018). The TOC values range from 1.5 to 5 wt%, with Rock-Eval S2 yields of 1.5–13.2 mgHC g^{-1} rock and HI values of 100–600 mgHC g^{-1} TOC (Aqrawi and Badics 2015). Kinetic analysis of representative samples reveals a broad spectrum of activation energies, spanning 39–60 kcal mol^{-1}, with a predominant activation energy of 54 kcal mol^{-1} (NIOC 2014) reflecting heterogeneous organic matter decomposition characteristics (Fig. 12). The Sargelu Formation exhibits TOC values between 0.28 and 11.18, with an average of 2.82 wt%. The HI values range from 56 to 378 mgHC g^{-1} TOC, averaging 197 mgHC g^{-1} TOC. T_{max} values for the Sargelu Formation source rock demonstrate a significant variability, ranging from 427 to 478°C across the examined wells, with an average temperature of 444°C (NIOC 2014; Kobraei and Rabbani 2018). In addition, T_{max} values of 427–478°C (average 444°C) illustrate diverse thermal maturity levels within the formation, underscoring the complexity of its petroleum generation kinetics and maturation history.

Characteristically, the Sargelu Formation is marked by a predominance of C_{29} steranes, indicating a significant contribution from higher plants, alongside lower concentrations of C_{28} steranes, C_{23} tricyclic terpanes and methylhopanes, as well as a high diasterane content in the kitchens that supply various producing fields (NIOC 2025). As a result, oils exhibiting C_{28} sterane content below 20% are likely to have been derived from the Sargelu Formation source rock (Fig. 13a, b), such as those in the Azadegan, Jufair, Sohrab and Foroozan fields. The elevated diasterane content observed in the source kitchens supplying multiple producing fields further reflects an advanced thermal maturation and anoxic or reducing depositional environment (Peters *et al*. 2005). Compound-specific isotope analysis of produced oil samples has revealed a zigzag pattern in carbon isotopic values for C_{12}–C_{31} alkanes, ranging mainly from −29 to −27‰ (Fig. 13c) (NIOC 2021). In addition, a notable trend in the Sargelu Formation-sourced oil is the progressive lightening of carbon isotope values in higher molecular weight normal alkanes (Fig. 13d) (NIOC 2021) such as in the Salman, Walla and Foroozan fields.

Geochemical investigations indicate that the thermal maturity of the Sargelu Formation increases from the main oil window (0.7–

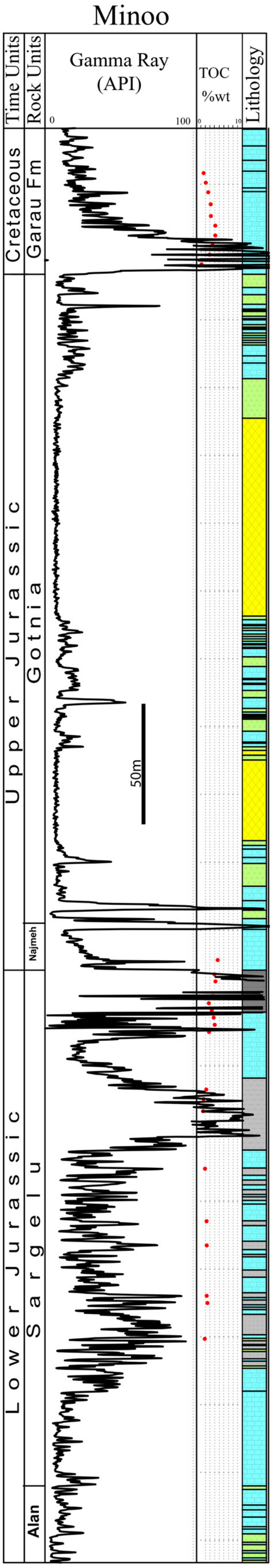

Fig. 11. Well section of the Jurassic strata in the Abadan Plain showing the Sargelu Formation source rock and the Gotnia Formation cap rock. The TOC values are plotted in red solid circles for the Sargelu Formation and lower parts of the Garau Formation.

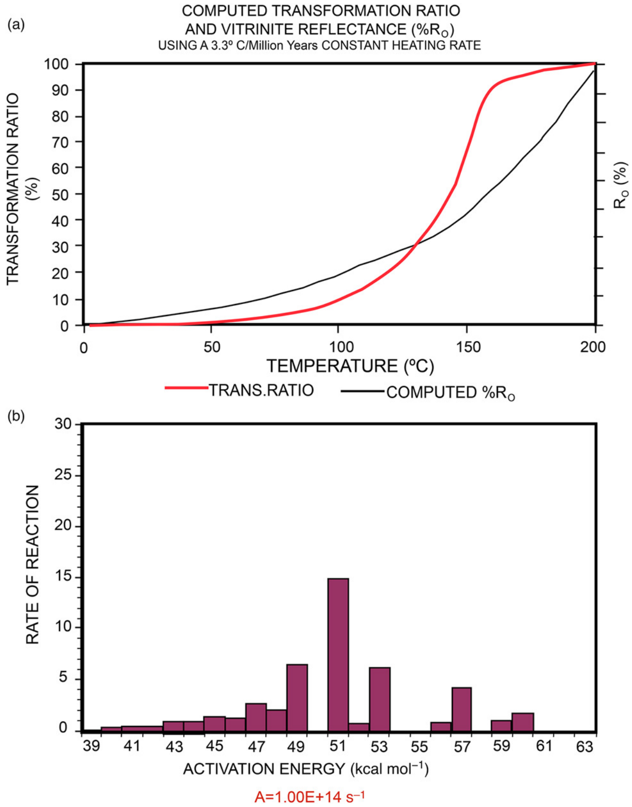

Fig. 12. (**a**) Transformation and vitrinite reflectance evolution of the Sargelu Formation source rock with increasing temperature. (**b**) The distribution of activation energies defining petroleum generation from the Sargelu Formation source rock in the Dezful Embayment.

1% VR$_o$) to the late oil window (1–1.3% VR$_o$) as one moves from the NW Persian Gulf Basin towards the Abadan Plain (Kobraei and Rabbani 2018; Kobraei *et al*. 2019). The highest thermal maturity is observed towards the Dezful Embayment and Lurestan area, where this source rock moved from the wet-gas to dry-gas window (2–4% VR$_o$) (Ghavami *et al*. 2015; Sadouni and Rabbani 2018). This trend is inversely related to the TOC and the HI distribution, with higher maturity in the Abadan Plain and Dezful Embayment reflecting an increased hydrocarbon generation over geological time.

The Sargelu Formation source rock is believed to have generated substantial volumes of hydrocarbons, up to 5600 MMbbl of oil equivalent, within the Zagros region, with considerable remaining potential for shale gas resource development (Aqrawi and Badics 2015; Khani *et al*. 2018). Recent studies have also highlighted the shale gas potential of the Sargelu Formation source rocks in Iraq (Aqrawi and Badics 2015; Schenk *et al*. 2015), as well as that for its age-equivalent Tuwaiq Mountain Formation in central Saudi Arabia (Lindsay *et al*. 2014; Hakami and İnan 2016; Hakami *et al*. 2016). Furthermore, the Middle Jurassic–Lower Cretaceous black shales of both the Sargelu and Garau formations may be promising resources for oil shale in the High-Folded Zagros area, particularly at sites such as Ghalikuh and Kuh-e-Keyno (Kamali and Rezaee 2012; Rasouli *et al*. 2015; Pirbalouti and Moayeripour 2017).

Recent analyses of unconventional resources reveal significant shale gas potential in the central regions of the Lurestan area (NIOC Exploration Directorate and RIPI 2018; Abdollahi *et al*. 2021, 2022). Specifically, the basal sections of the Garau Formation and the upper portions of the Sargelu Formation are both promising

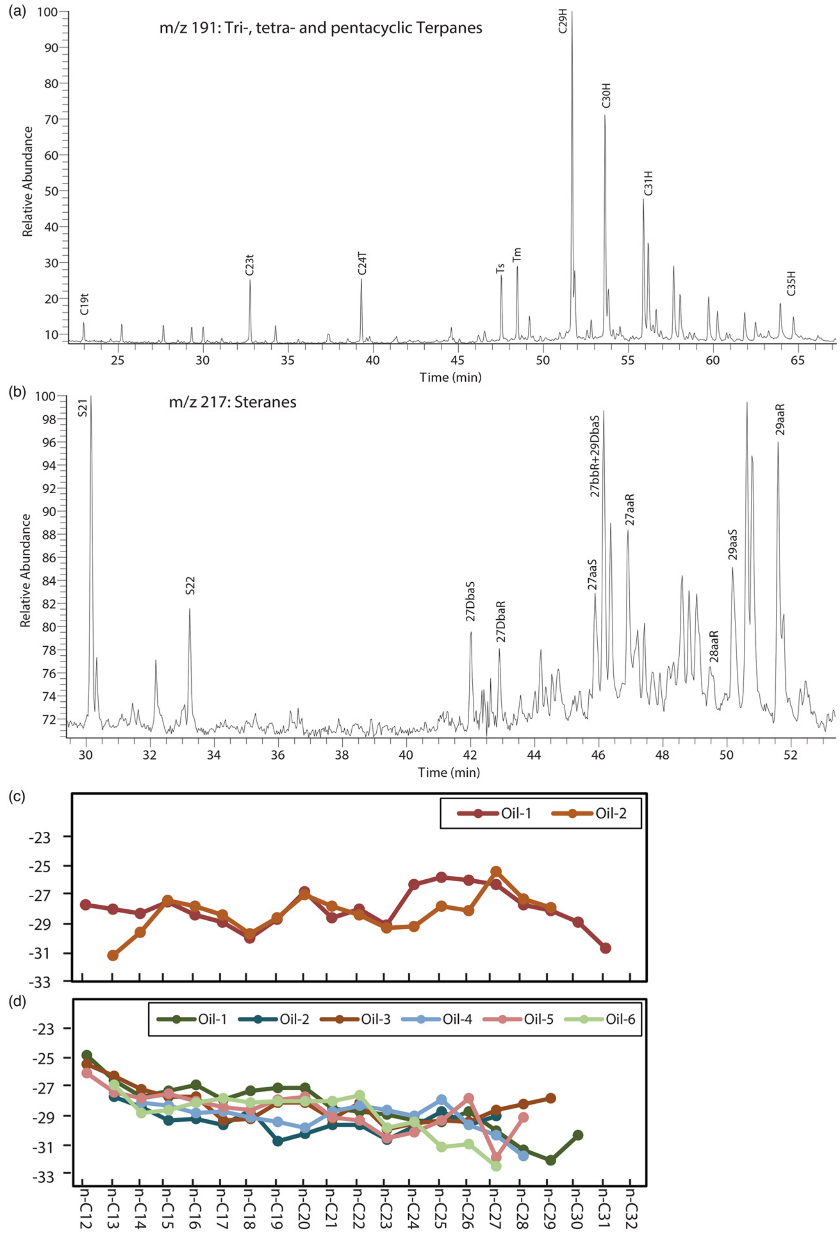

Fig. 13. Biomarker fingerprints of the Jurrasic Sargelu Formation source rock including: (**a**) hopanes (*m*/*z* 191) and (**b**) steranes (*m*/*z* 217). Compound-specific isotope analysis of different oils generated by the Sargelu Formation source rock: (**c**) a zigzag trend and (**d**) the lightening of carbon values in higher molecular weight normal alkanes.

candidates for shale gas exploration (Aqrawi and Badics 2015; Lotfiyar *et al*. 2018; NIOC Exploration Directorate and RIPI 2018).

The Upper Jurassic strata in the Zagros region primarily consist of shallow-water carbonates of the Najmah Formation such as in Lurestan, parts of Khuzestan and the northwestern Persian Gulf, as well as carbonates of the Surmeh Formation in Khuzestan, Fars, and most of the Persian Gulf region. These age-equivalent units exhibit significant hydrocarbon generation potential, notably in Abu Dhabi (Diyab/Dukhan Formation), Qatar (Hanifa Formation), Saudi Arabia (Tuwaiq Mountain Formation) and Iraq (Naokelekan Formation) (e.g. Carrigan *et al*. 1995; Sadooni 1997; Al-Suwaidi *et al*. 2000; Kamali and Rezaee 2003; Alsharhan 2014; Aqrawi and Badics 2015).

The Upper Jurassic (Oxfordian–early Kimmeridgian) Hanifa Formation serves as a critical source rock, deposited in an anoxic intrashelf basin that spans eastern Qatar and western onshore and offshore Abu Dhabi. The organic richness of this formation diminishes towards the ENE, with a TOC content ranging from 2 to 6% (averaging *c*. 4%) (NIOC Exploration Directorate and Repsol 2002). The Hanifa Formation source rock features Type II kerogen and reaches *c*. 250 m in thickness in Qatar, while its thickness can exceed 500 m closer to the Shah Oilfield in Abu Dhabi, where TOC values drop to a minimum of 0.5%. Estimations suggest that the Hanifa Formation source rock may have generated over 150 Bbbl of oil, assuming a source-rock potential (S1 + S2) of 10 kgHC t^{-1} rock, a 75% conversion factor, a density of 2.55 g cm^{-3} and a 50% oil migration efficiency (Hawas and Takezaki 1995; Taher 1997; Ayoub and En Nadi 2000).

The Hanifa and Tuwaiq Mountain formations were deposited in depressions flanking the Qatar Arch during the Callovian–Kimmeridgian period (Bordenave 2014). They were deposited in the depressions situated to the east and west of the Qatar Arch during the Callovian–Kimmeridgian period (Bordenave 2014) (Fig. 4).

Reservoir rocks and seals

The shallow-marine carbonates of the Middle–Upper Jurassic Surmeh Formation are the main reservoir for several major fields throughout the Iranian Zagros and Persian Gulf regions (Motiei 1993; Lasemi and Jalilian 2010). These carbonates extend laterally into the Sargelu basinal succession (James and Wynd 1965) (Fig. 3). To the south, the Arab Formation correlates with the carbonate–anhydrite cycles in the upper part of the Surmeh Formation. The Arab Formation is a prolific hydrocarbon

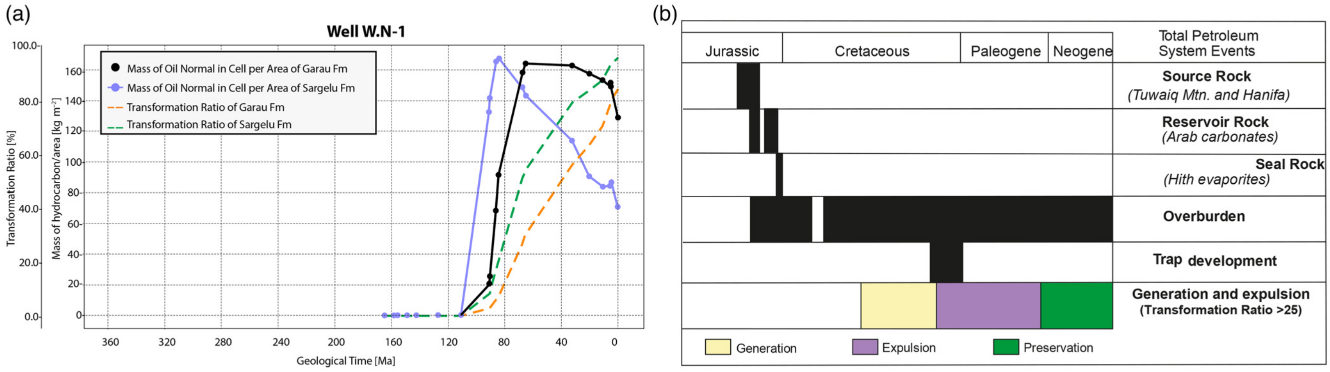

Fig. 14. (**a**) Cross-plot of transformation ratio v. time showing the approximate time of oil generation from Sargelu Formation and Garau Formation source rocks at well W N-1 in Lurestan. (**b**) Petroleum systems event chart obtained from modelling studies in Iraq. Source: (a) from Khani *et al.* (2018); (b) from Fox and Ahlbrandt (2002).

producer across Saudi Arabia, Bahrain, Qatar and Abu Dhabi (Ayres *et al.* 1982; Al-Silwadi *et al.* 1996; Alsharhan and Nairn 1997; Lindsay *et al.* 2006; Ehrenberg *et al.* 2007; Hönig and Cédric 2015).

The Upper Jurassic carbonate–anhydrite cycles (A–D) are recognized as proven reservoirs and effective cap rocks throughout the external Fars area and Persian Gulf (Motiei 1993; Alsharhan and Kendall 1994). In the NE and eastern Zagros regions, evaporites of the Hith Formation, which are thin or are replaced by the brecciated carbonates of the upper Surmeh Formation, reduce the seal efficiency. Consequently, oils might have migrated upwards from Jurassic or even Paleozoic source rocks and mixed with those generated from younger sources (Pitman *et al.* 2004).

The Upper Jurassic Gotnia Formation extends from southern and central Iraq into Khuzestan and Lurestan, with a notable presence in fields such as Emam Hassan and Masjid-e-Suleyman. The Gotnia Formation averages about 170 m in thickness and is primarily composed of anhydrites, with lesser amounts of salt, dolostone and shale (Abeed *et al.* 2013). Notably, in the recently drilled Minoo well located in the Abadan Plain, the Gotnia Formation exceeds 250 m in thickness and includes two significant salt units totalling *c.* 150 m (see Fig. 11).

It is important to highlight that extensive fracture networks can create unique reservoir opportunities, although they may have limited economic viability within the Jurassic succession of the Zagros region. These fracture networks can enhance the reservoir potential of source-rock intervals that lie within the oil window. This unconventional play has already been documented in the Jurassic systems of the northern Arabian Plate, Iraq and western Abu Dhabi (Goff 2005; Aqrawi *et al.* 2010; Taher 2010). Identifying the extent and characteristics of similar fractured source rock–reservoir systems in the Iranian Zagros and Persian Gulf regions will represent a significant opportunity for future exploration in these regions.

Hydrocarbon generation and migration

Modelling studies indicate that hydrocarbon generation from the Sargelu Formation source rocks in the Lurestan area commenced during the Middle Cretaceous, with hydrocarbon expulsion – characterized by a transformation ratio of *c.* 25% – starting in the Late Cretaceous (Khani *et al.* 2018) (Fig. 14a). These processes closely align with trap formation resulting from ophiolite obduction and the closure of the Neo-Tethys Ocean during the Alpine Orogeny (Fig. 14b). Similar modelling conducted on the stratigraphically equivalent Sargelu Formation source rock in the Iraqi Zagros yielded comparable results (Aqrawi *et al.* 2010; Abeed *et al.* 2012; Aqrawi and Badics 2015), as did studies of the Tuwaiq Mountain Formation source rock in Saudi Arabia (Hakami and İnan 2016). The intense uplift and erosion associated with the Alpine Orogeny facilitated the remigration of previously trapped hydrocarbons into new reservoirs. It also led to their dissipation to the surface due to the erosive removal of the overlying seal – the Gachsaran Formation (Goff *et al.* 1995; Goff 2005). In the Lurestan area, where drilling outcomes have often been underwhelming, this model may account for the frequent surface bitumen shows and substantial deposits of gilsonite (Goff *et al.* 1995; Goff 2005; Alipour 2024).

Evidence suggests that Jurassic source rocks contributed to the charging of Cretaceous and Cenozoic reservoirs in the Soroosh, Aboozar, Arash and Nowroz fields in the northwestern Persian Gulf (Hassanzadeh and Khaleghi 2014). This is supported by biomarker parameters, including elevated C_{29}/C_{30} hopane and C_{27}/C_{29} sterane ratios, a C_{28}/C_{29} ratio exceeding 0.7, and a high dibenzothiophene/phenanthrene index (Hassanzadeh and Khaleghi 2014). Hydrocarbon migration within the Jurassic–Cretaceous petroleum system of the Zagros is predominantly influenced by variations in the lithofacies and geometry (Aqrawi *et al.* 2010). Generated hydrocarbons may migrate downwards due to intense overpressures resulting from kerogen cracking within the source-rock interval (Goff 2005).

Lateral migration could also occur through porous carrier beds, potentially extending to the edges of evaporitic seal units, followed by upward migration (Goff 2005; Aqrawi *et al.* 2010). This upward movement may be enhanced by fractures and faults at the margins of these evaporitic units (Goff 2005; Aqrawi *et al.* 2010). A similar phenomenon has been observed in the southern Persian Gulf, where mixed Jurassic oils are found within Cretaceous reservoirs (Alsharhan and Kendall 1986; Al-Silwadi *et al.* 1996, Al-Suwaidi *et al.* 2000; Guthrie *et al.* 2005; Pietraszek-Mattner *et al.* 2008). In Qatar and western Abu Dhabi, oil primarily originates from the Jurassic Hanifa/Diyab Formation (Alsharhan and Whittle 1995; Hawas and Takezaki 1995), migrating eastwards through the Arab reservoir with the Hith anhydrite serving as a regional seal. Upon reaching the edge of the Hith anhydrite in the central southern Persian Gulf, where seal is inefficient, the oil migrates vertically into lower Cretaceous reservoirs.

Offshore Persian Gulf, the Jurassic petroleum system is characterized by long-distance hydrocarbon migration from active source rock kitchens located beyond (i.e. to the south of) Iran's territorial borders (Guthrie *et al.* 2005). Recent geochemical studies of oils from the Persian Gulf provide supporting evidence for this phenomenon (NIOC 2016; Alipour *et al.* 2017*a*, *b*; Alizadeh *et al.* 2017; Baniasad *et al.* 2017). The distribution and maturity patterns of these source rocks indicate migration from a depocentre situated to the south, with inferred migration distances reaching up to 250 km (Fathi Mobarakabad *et al.* 2011).

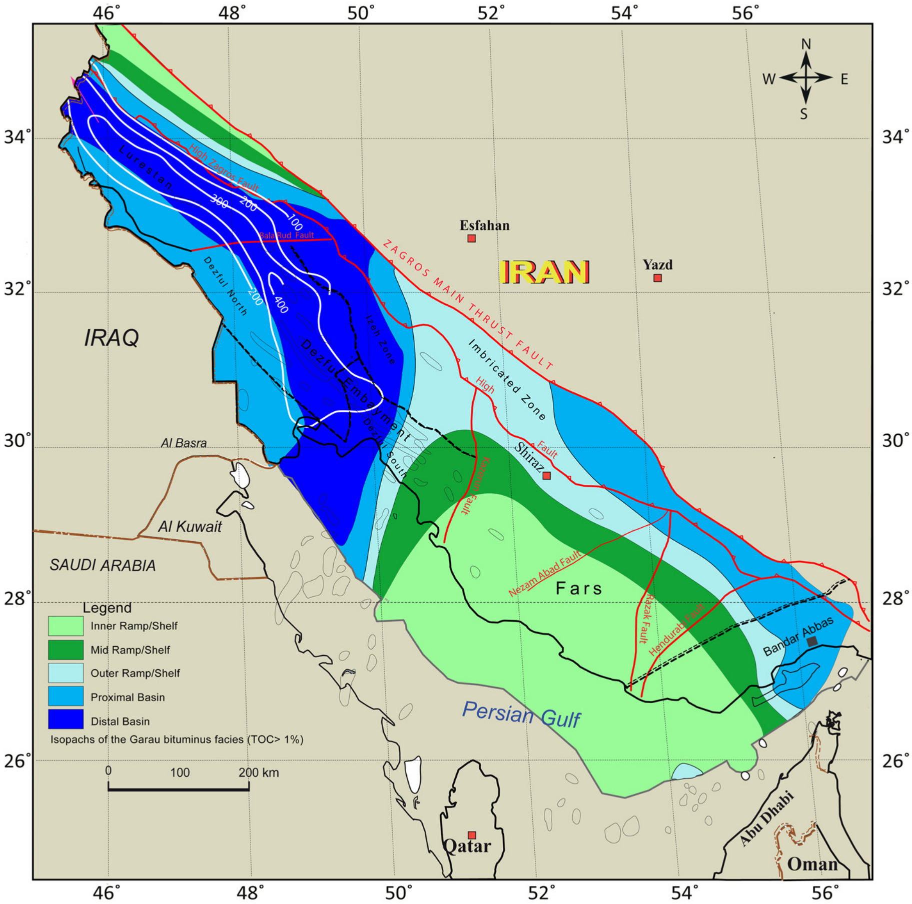

Fig. 15. Palaeogeographical map of the Beriasian–Valanginian maximum flooding surface (MFS) in SW Iran and the contiguous offshore area showing basinal to platformal facies of the Garau and Fahliyan formations, respectively. Areas with TOC values >1 wt% are also shown together with oil- and gas-field locations, and isopachs for the top Asmari to top Bangestan intervals. Source: modified from Piryaei *et al.* (2017) and after Bordenave (2014).

Cretaceous

Source rocks

Significant organic-rich intervals with considerable source rock potential are primarily found in the Lower Cretaceous and, to a lesser extent, in the Upper Cretaceous successions within the Iranian Zagros and Persian Gulf regions.

The Early Cretaceous petroleum system is active throughout the Lurestan and Dezful Embayment, where the basinal organic-rich facies of the Garau Formation are prominent (Fig. 15) (Bordenave and Huc 1995; Bordenave 2014). These high organic shales that are replace by shallow-water carbonates of the Fahliyan Formation eastwards of the Fars Platform (Fig. 15). In the Garau Formation, the TOC values vary between 0.42 and 10.8 wt%, with a mean of 2.2 wt %, indicating a source potential classified as good to very good (Peters and Cassa 1994). The HI values range from 43 to 413 mgHC g TOC^{-1}, averaging at 210 mgHC g^{-1} TOC (Kobraei *et al.* 2017). T_{max} values for the Garau Formation exhibit considerable variability, spanning 433–453°C across the examined wells, with an average of 442°C (Kobraei *et al.* 2017). Palaeogeographical reconstructions showed that the depositional centre of the Garau Formation is in the Dezful Embayment, to the east of the Ahwaz Oilfield, extending into the Lurestan area (Piryaei *et al.* 2017) (Fig. 15). The organic matter present in the Garau Formation is characterized by Type II amorphous kerogen, displaying a wide range of activation energies that range from 39 to 60 kcal mol^{-1}, with a principal activation energy of 55 kcal mol (NIOC Exploration Directorate and RIPI 2005) (Fig. 16).

The Garau Formation source rock is distinguished by a higher abundance of C_{27} steranes and a predominance of C_{29} hopane over C_{30}, as well as a greater abundance of C_{24} tetracyclic terpanes compared with C_{23} tricyclics (NIOC 2021; Shekarifard *et al.* 2025). C_{27} steranes are typically associated with marine phytoplankton,

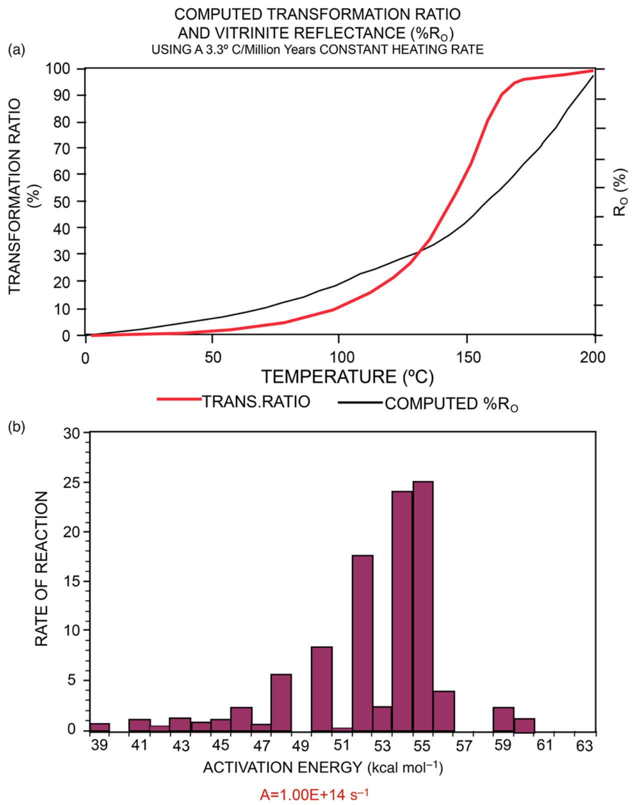

Fig. 16. (**a**) Transformation and vitrinite reflectance evolution of the Garau Formation source rock with increasing temperature. (**b**) The distribution of activation energies defining petroleum generation from the Garau Formation source rock in the Dezful Embayment. The kinetic properties are from hydrocarbon formations in the Garau Formation source rock in the Dezful Embayment.

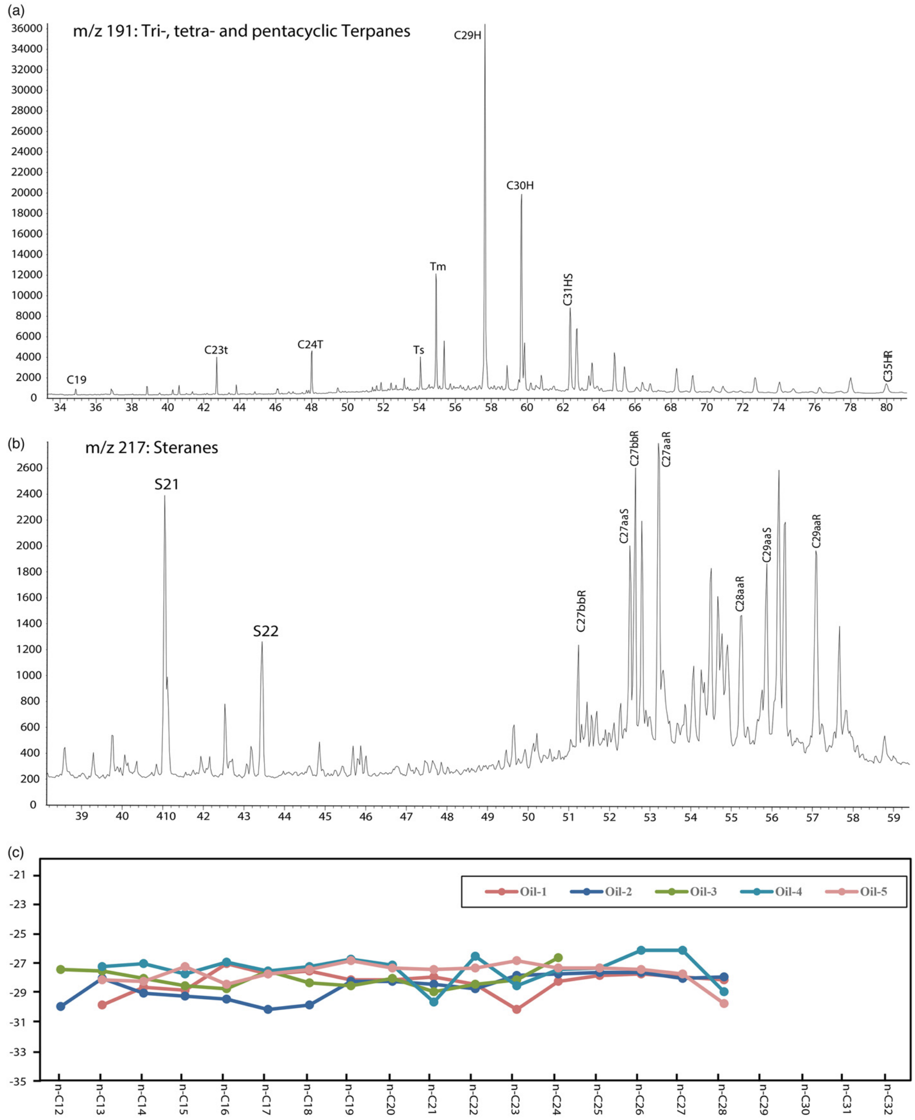

Fig. 17. Biomarker fingerprints of the Cretaceous Garau Formation source rock including: (**a**) steranes (*m/z* 217) and (**b**) hopanes (*m/z* 191). Compound-specific isotope analysis of two different oils generated by the Garau Formation source rock (linear trend).

indicating a significant marine organic matter contribution (Grantham 1986). Oils generated from the Garau Formation source rock exhibit C_{28} sterane contents that fall between those of Middle Cretaceous and Sargelu Formation oils, suggesting a closer affinity to a Lower Cretaceous source rock (Fig. 17a, b) (NIOC 2021). Compound-specific isotopic analysis of produced oil samples indicates a linear trend in carbon isotopic values for C_{12}–C_{31} alkanes, ranging from −29 to −27‰ (Fig. 17c) (NIOC 2021).

At the present time, the maturity of the Garau Formation corresponds to the peak stage of oil generation, increasing eastwards toward the Dezful Embayment (Kobraei *et al.* 2017). Thermal maturity levels in the Lurestan area rise northwestwards, with the lowest values observed over the Anaran High (Khani *et al.* 2018).

The Aptian–Albian Kazhdumi Formation represents one of the most significant source rocks in the study area (Bordenave and Burwood 1990, 1995; Bordenave and Huc 1995; Bordenave 2014; Alipour 2022; Sfidari *et al.* 2024). Its organic-rich facies are predominantly developed across the Dezful Embayment and the northwestern Persian Gulf (Fig. 18a) (Bordenave and Hegre 2010; Bordenave 2014; Baniasad *et al.* 2017). The extent of the subsiding Kazhdumi Basin was influenced by the Balarud and Kazerun basement faults (Bordenave 2002; van Buchem *et al.* 2010*b*; Vincent *et al.* 2010).

Eastwards, into the Fars Platform of the Dezful Embayment, organic-rich Kazhdumi shales give way to organic-lean marls deposited under oxic, shallow-water conditions (Bordenave 2014), with limited occurrences of relatively organic-rich layers noted in the Izeh Zone (Sherkati and Letouzey 2004). The TOC in the Kazhdumi Formation ranges from 1 to 11 wt%, with a mean value of 5 wt% observed at the depositional centre that is which located in the Ahwaz Oilfield (Bordenave 2002) (Fig. 19a). The Kazhdumi Formation source rock has been identified as featuring oil-prone Type II kerogen (Alizadeh *et al.* 2012*a*; Sfidari *et al.* 2016; Baniasad *et al.* 2017). In addition, the activation energies show a limited range from 40 to 52 kcal mol^{-1}, with a principal activation energy of 46 kcal mol (Karimi *et al.* 2016) (Fig. 19b).

The regional time-equivalent formations to the Kazhdumi Formation source rock include the Middle Aptian–Early Albian organic-rich Bab shales in Abu Dhabi, considered as basinal facies of the Shu'aiba Formation (van Buchem *et al.* 2010*a*, *b*) (Fig. 18b). These sediments are confined to an intrashelf basin known as the Shu'aiba Basin that formed during Aptian times across the region, and which now represents western UAE and Oman (Murris 1980).

The organic-rich intervals in the Bab shales were deposited under anoxic conditions due to restricted hydrodynamic circulation (Azzam and Taher 1995). These shales contain Type II kerogen, with TOC values ranging from 1 to 5 wt%. Although the depocentre of the Bab Basin lies outside Iranian borders in the Persian Gulf, studies on migration pathways suggest that several fields within Iran may have been charged by this source rock (NIOC Exploration Directorate and Repsol 2002).

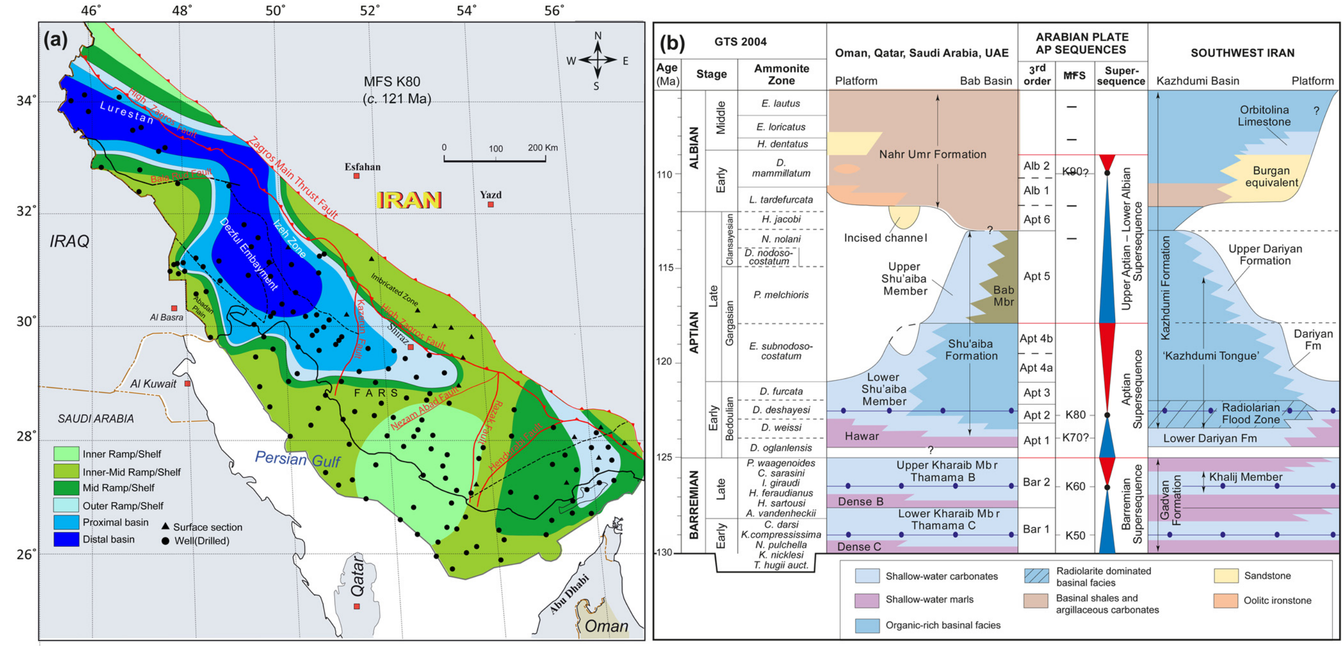

Fig. 18. (**a**) Palaeogeographical map showing the extent of the Kazhdumi Basin in SW Iran at the maximum flooding surface MFS K80. (**b**) Lithostratigraphic reconstructions comparing the architecture of the Kazhdumi and Bab basins. Source: (a) modified from Piryaei *et al.* (2017); and (b) from van Buchem *et al.* (2010*a*, *b*).

During the Cenomanian period, the formation of intrashelf basins in the eastern Arabian Plate facilitated the deposition of organic-rich carbonates within the Middle Sarvak Formation (Azzam and Taher 1993; van Buchem *et al.* 2002; Vahrenkamp *et al.* 2015*a*). These carbonates are laterally equivalent to the Shilaif Formation source rock in the UAE (Azzam and Taher 1993). The basins originated during transgressive phases and later developed in the distal areas of a prograding platform, which was capped by shallow-water Sarvak/Mishrif carbonates (NIOC Exploration Directorate and Repsol 2002). The extent of the organic-rich mid-Cenomanian facies, particularly the Ahmadi Member of the Sarvak Formation, across the Iranian Zagros and Persian Gulf regions has been debated. Recent geochemical studies conducted in the Iranian sector of the southern Persian Gulf have indicated that its TOC values range between 1 and

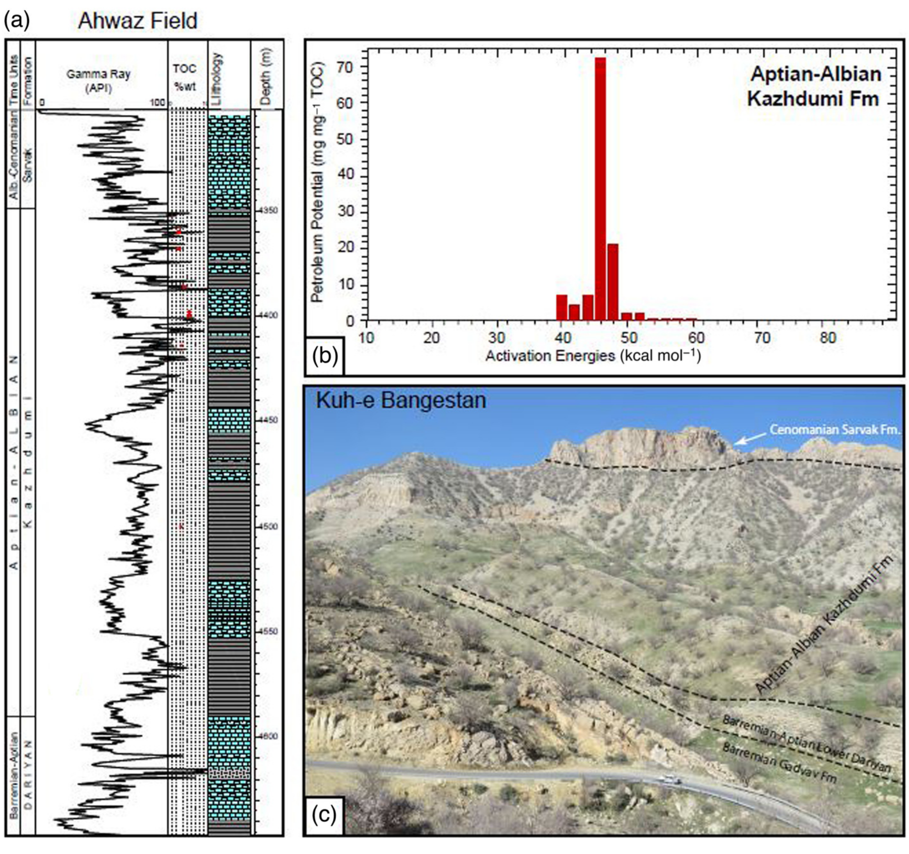

Fig. 19. (**a**) Well section of the Kazhdumi Formation in the Ahwaz Field in the Dezful Embayment showing TOC values and the gamma ray (GR) log. (**b**) Kinetic properties of the hydrocarbon formations from the Kazhdumi Formation in the Dezful Embayment. (**c**) Outcrop photograph showing the maximum temporal extent of the Aptian–Albian Kazhdumi Formation in the Kuh-e Bangestan section, North Dezful Embayment.

6 wt%, predominantly featuring reactive Type II kerogen (Hosseiny *et al*. 2016; Alipour *et al*. 2017*a*; Alizadeh *et al*. 2017).

Reservoir rocks and seals

The principal reservoir rocks overlying the Garau Formation source rock include the Barremian Gadvan (specifically the Khalij Member), the Aptian Dariyan and the Cenomanian–Santonian Sarvak and Ilam formations (Fig. 3) (Bordenave and Hegre 2010; Bordenave 2014). Recently, some proven reservoir potential has been explored for the Maastrichtian Tarbur Formation in the Abadan Plain (e.g. in the Azadegan Field). The spatial and temporal distribution of the Tarbur Formation in the Zagros is strongly related to Late Cretaceous foreland basin evolution, as well is local salt movements (e.g. Piryaei *et al*. 2011; Parham, *et al*. 2019; Abbasi *et al*. 2021). These previously mentioned reservoir formations hold substantial reserves throughout much of the Dezful Embayment oilfields (Bordenave 2014). However, a thick sequence of organic-lean marls separates these carbonates from the Garau Formation source rock, creating a self-contained source rock–reservoir system in the Lurestan area that may hold significant potential for unconventional hydrocarbon resources (Aqrawi *et al*. 2010; Aqrawi and Badics 2015; Rasouli *et al*. 2015; Khani *et al*. 2018).

Potential seals for the Cenomanian–Santonian reservoirs (Sarvak and Ilam formations) are provided by shale-rich intervals of the Santonian–Maastrichtian Gurpi Formation. The Coniacian Laffan Shale serves as an effective intra-reservoir seal, specifically separating the underlying Sarvak Formation from the overlying Ilam Formation in the Iranian Zagros and Persian Gulf regions (Alsharhan and Nairn 2003*a*; Opera *et al*. 2013; Mashhadi *et al*. 2015*a*). In low-relief structures across the Dezful Embayment and Abadan Plain, thick marly units within the upper Gurpi Formation and the Lower Paleocene Pabdeh Formation serve as the primary top seals for both the Sarvak and Ilam formations (Bordenave 2014; Rabbani *et al*. 2014). However, within high-relief anticlines (e.g. Kabir Kuh, Khaviz and Dill anticlines), intense fracturing can compromise the sealing capacity of these marls and shales. This fracturing may lead to hydraulic communication, effectively merging the Sarvak and Ilam limestones with the overlying Miocene Asmari Formation into a single, interconnected reservoir system (Opera *et al*. 2013; Bordenave 2014).

Beyond the Ilam and Sarvak carbonates, upper Aptian–lower Albian siliciclastics – specifically the Azadegan/Burgan sandstones of the Kazhdumi Formation – are also considered as significant reservoir rocks in the Coastal Fars, the Abadan Plain and northern Persian Gulf (van Buchem *et al*. 2010*b*). These siliciclastics may manifest as sand-filled incised valleys at top of the Dariyan Formation or as thin sand veneers at the base of the Kazhdumi Formation (van Buchem *et al*. 2010*a*), often capped by thick Kazhdumi shales (Fig. 18b).

In addition, the Berriasian–Hauterivian Fahliyan and Aptian Dariyan carbonates, along with their time-equivalent the Gadvan and Khalij limestones, are regarded as important reservoir rocks across numerous oilfields in the Zagros and Persian Gulf regions (Abdollahie Fard *et al*. 2006). However, oil within these carbonates is predominantly found in microporous formations, which may lead to low primary recovery rates. Consequently, secondary or tertiary recovery techniques and directional drilling may be necessary to enhance overall recovery (van Buchem *et al*. 2010*a*). Intraformational tight lithofacies associated with transgressive systems tracts may serve as effective seals for reservoirs within the Fahliyan Formation (Motiei 1993). Unpublished studies from NIOC indicate that the Kazhdumi Formation acts as a regional seal for Dariyan reservoirs in numerous offshore fields, including the South Pars Field (Motiei 1993).

Further south, in the southern Persian Gulf, the thin shales of the Laffan Formation are likely to have exerted some influence over the Cretaceous petroleum system (Alipour *et al*. 2016). Meanwhile, the thick shales of the Upper Cretaceous Gurpi Formation are expected to provide a robust cap rock for the stacked Ilam and Sarvak reservoirs across both the Iranian and Arabian sectors of the Persian Gulf (Alsharhan and Nairn 2003*a*; Esrafili-Dizaji and Rahimpour-Bonab 2019).

Hydrocarbon generation and migration

Modelling studies suggest that hydrocarbon generation from the Lower Cretaceous Garau Formation source rock occurred during the Late Cretaceous (*c*. 100–80 Ma) in deeply buried regions of the Lurestan area (Khani *et al*. 2018) (Fig. 14a). Due to limited connectivity between organic-rich shales and potential carrier beds, a significant portion of the hydrocarbons is likely to have remained trapped within the source rock, leading to the cracking of many hydrocarbons into pyrobitumen and gas (Khani *et al*. 2018). Moreover, considerable amounts of migrated hydrocarbons may have been lost due to the unfavourable timing of early hydrocarbon generation relative to the late formation of traps, which resulted in extensive breaching of potential reservoirs such as the Ilam and Sarvak formations (Bordenave 2014). Nevertheless, some hydrocarbon accumulations in the Abadan Plain – such as the Khami Group reservoirs at the Jufair and Darquain fields – and in the NW Persian Gulf (e.g. Dorood Field) rely primarily on short-range lateral migration and the mixing of hydrocarbons sourced from both the Sargelu and Garau formations (Bordenave 2014; Baniasad *et al*. 2017) (Fig. 20a, b).

The Aptian–Albian Kazhdumi Formation source rock reached the oil window during the Middle–Late Miocene in the Dezful Embayment (Bordenave and Burwood 1995; Opera *et al*. 2013). Thermal maturity modelling indicates a significant decline in maturity over the South Pars Palaeohigh, suggesting minimal hydrocarbon generation from this source rock (Sfidari *et al*. 2016) (Fig. 21a). In contrast, thermal maturity appears highest in the Dezful Embayment, where generated hydrocarbons may have migrated vertically and/or laterally based on specific lithofacies architecture and porosity–permeability distribution patterns to final reservoirs (Fig. 21b) (Bordenave and Hegre 2005; Baniasad *et al*. 2021).

Hydrocarbon generation from the Cenomanian Middle Sarvak Formation source rock in the southern Persian Gulf basin is modelled to have begun around 40 Ma (Mashhadi *et al*. 2015*b*; Alipour *et al*. 2017*a*; Alizadeh *et al*. 2017). The expulsion of generated hydrocarbons is anticipated to have benefitted from the proximity of shelfal Mishrif Formation carbonate reservoirs (Al-Zaabi *et al*. 2010; Alizadeh *et al*. 2017; Hosseiny *et al*. 2017). A significant fraction may have become trapped within basinal facies of the Middle Sarvak Formation source rocks, raising the potential for unconventional oil accumulations in local depressions across the southern Persian Gulf (Taher 2010; Alizadeh *et al*. 2017; Alipour *et al*. 2021). Although developing these untapped resources will require advanced drilling technologies, they are promising targets for the future exploration activities in the region (Taher 2010; Alipour *et al*. 2017*a*).

The Cenozoic petroleum system

Approximately 45% of total oil reserves discovered in the Iranian Zagros and Persian Gulf regions are accommodated within the Cenozoic petroleum system (Bordenave and Hegre 2005; Al-Husseini 2007; Esrafili-Dizaji and Rahimpour-Bonab 2019). This system features a world-class example of a siliciclastic and fractured carbonate reservoir, the Oligo-Miocene Asmari Formation, capped by an efficient evaporitic seal provided by the Miocene Gachsaran

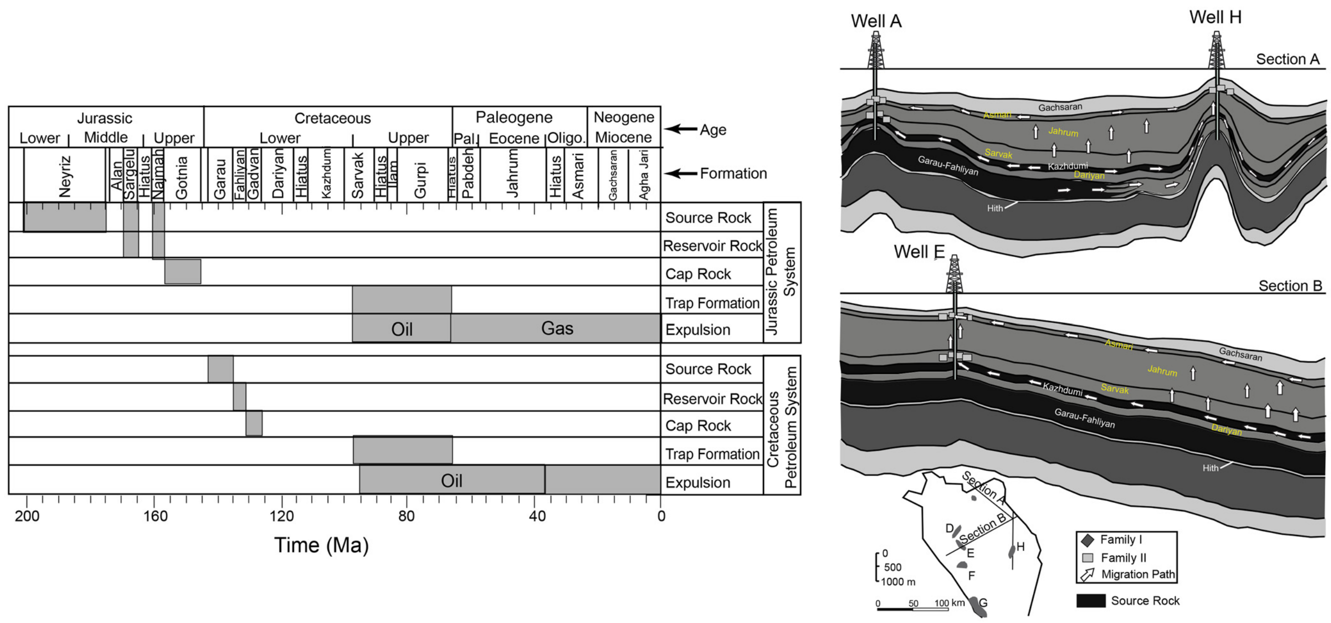

Fig. 20. (**a**) Jurassic–Cretaceous petroleum system event charts for the Abadan Plain. (**b**) Schematic cross-sections showing the dominant migration style in the NW part of the Persian Gulf. Source: (a) from Zeinalzadeh *et al.* (2015); and (b) from Baniasad *et al.* (2017).

Formation (Alsharhan and Nairn 2003*a*). In addition, the Paleocene–Eocene Jahrum Formation, the Miocene Guri Member of the Mishan Formation and pay zones in the Pabdeh Formation could be additional reservoir units, contributing to the hydrocarbon accumulations in fields such as Khesht Field next to the Kazerun Fault, the Sarkhun Field in the Bandar Abbas area and the Saman Field in the North Dezful Embayment (Rastegar Lari 2008; Esrafili-Dizaji and Rahimpour-Bonab 2019; Gholamalian *et al.* 2023). The only Cenozoic source rock for this petroleum system in the Iranian Zagros and Persian Gulf regions is the late Eocene–early Oligocene interval of the Pabdeh Formation (Piryaei and Davies 2024) (Fig. 3). However, this formation is considered to be at an early mature phase for petroleum generation across much of the Dezful Embayment (Karimi *et al.* 2016). In highly fractured anticlines, vertical migration of oil from the underlying petroleum systems might have led to an interconnection of the Mesozoic–Cenozoic source rocks migration into the Asmari reservoirs (Bordenave and Hegre 2010; Bordenave 2014). Such a fracturing might also have enhanced the reservoir potential of the Pabdeh Formation shales, as evidenced by observations from the Zeloi, Karanj and Parsi oilfields (Soleimani and Zamani 2015).

Source rocks

The Pabdeh Formation was deposited in a SE–NW-elongated foredeep basin extending from the Strait of Hormuz to the Lurestan area. The most effective source rocks of the Pabdeh Formation are located within the Khuzestan and Lengeh troughs (Piryaei and Davies 2024), which were deposited during the late Eocene and early Oligocene periods (Bordenave 2002; Bordenave and Hegre 2005; Piryaei and Davies 2024) (Fig. 22). Within the Dezful Embayment, the TOC content in the Pabdeh Formation varies

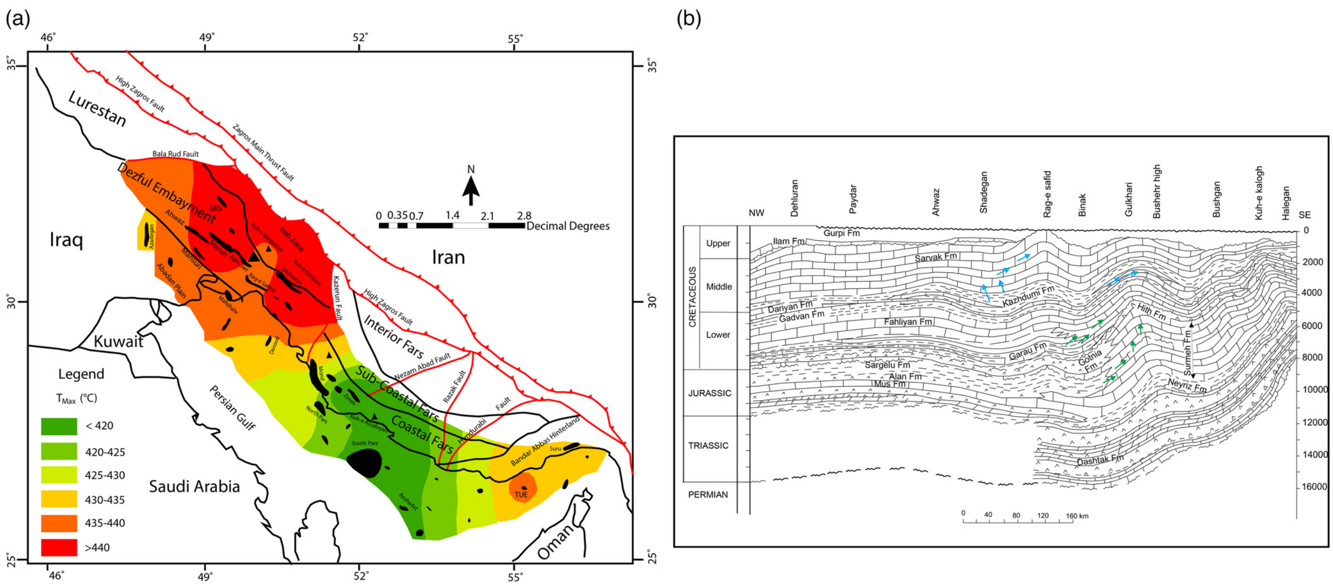

Fig. 21. (**a**) Outline map of SW Iran and the adjacent offshore area showing variations in the maturity (Rock-Eval T_{max} in °C) of the Kazhdumi Formation source rock. (**b**) Schematic cross-section showing the migration patterns of Kazhdumi Formation-derived oil in the Zagros fold belt. Source: (a) from Sfidari *et al.* (2016); and (b) from Baniasad *et al.* (2021).

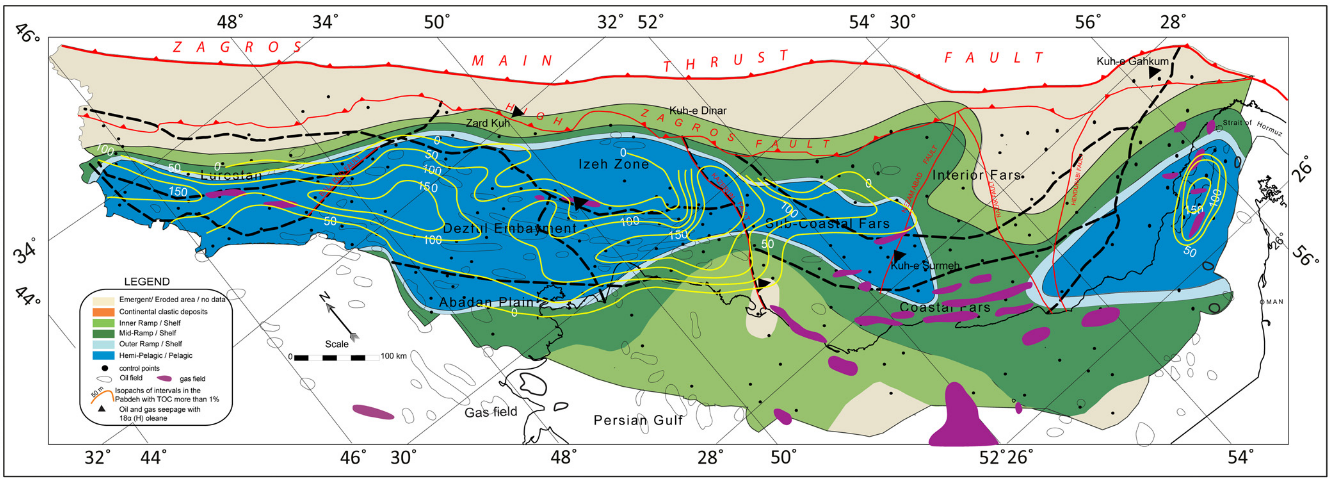

Fig. 22. Map of the Zagros fold belt showing the extent of deep-water, organic-rich intervals in the Eocene Pabdeh Formation, which change laterally to shallow-water carbonates of the Jahrum Formation, with TOC >1 wt% intervals. Source: modified from Piryaei *et al*. 2015); the TOC values are from Bordenave (2014).

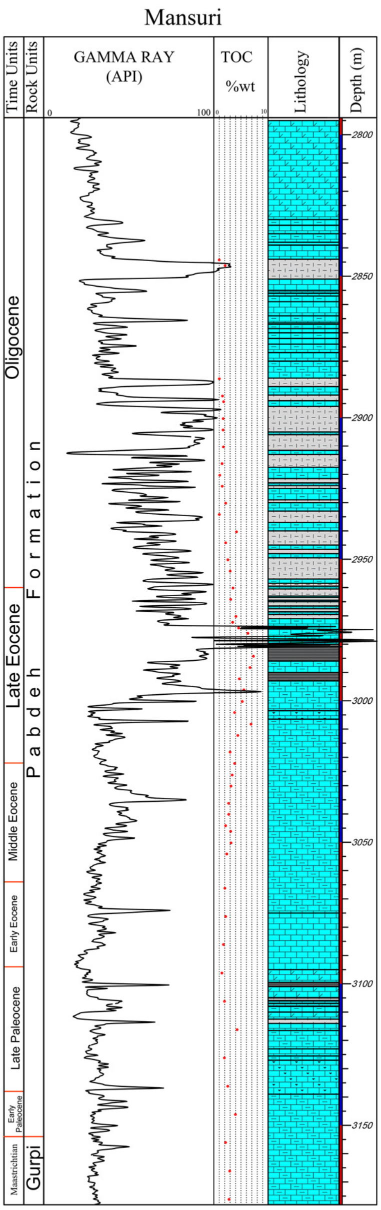

Fig. 23. Well section of the Pabdeh Formation in the Dezful Embayment (Mansuri Field) showing the TOC values in red solid circles and the gamma-ray (GR) log.

between 0.2 and 7.2 wt%, with peak values recorded in the Mansuri Oilfield (Fig. 23). Euxinic conditions in certain areas of the depression facilitated the deposition of organic-rich strata featuring Type II amorphous-algal organic matter, influenced by a terrigenous input (Bordenave 2014; Baniasad *et al*. 2016; Alizadeh *et al*. 2020). This organic matter is characterized by a relatively high sulfur content and a narrow activation energy distribution ranging from 42 to 54 kcal mol^{-1}, with a principal activation energy of 48 kcal mol^{-1} (Bordenave and Burwood 1990; Bordenave and Hegre 2005; Karimi *et al*. 2016) (Fig. 24).

In the eastern Persian Gulf, the thickness of the Pabdeh Formation varies from 613 to 1939 m (NIOC Exploration Directorate and Statoil 2003). Samples from this formation exhibit variable TOC contents (0.17–13.9 wt%) and S2 values (0.13–28.66 mgHC g^{-1} rock) (NIOC Exploration Directorate and Statoil 2003). The highest quality source rocks are found in wells located in the southwestern parts of the eastern Persian Gulf, such as the Ashkan, Qeshm and Tusan fields (NIOC Exploration Directorate and Statoil 2003). Interestingly, source-rock potential tends to increase toward the top of the Pabdeh Formation; however, the richest interval in the Qeshm Field occurs near the base of the formation, representing one of the highest quality source rocks in the entire eastern Persian Gulf (NIOC Exploration Directorate and Statoil 2003). Hydrogen indices from well samples indicate that the Pabdeh Formation predominantly contains gas-prone kerogen, with an average HI value of 198 mgHC g^{-1} TOC (NIOC Exploration Directorate and Statoil 2003).

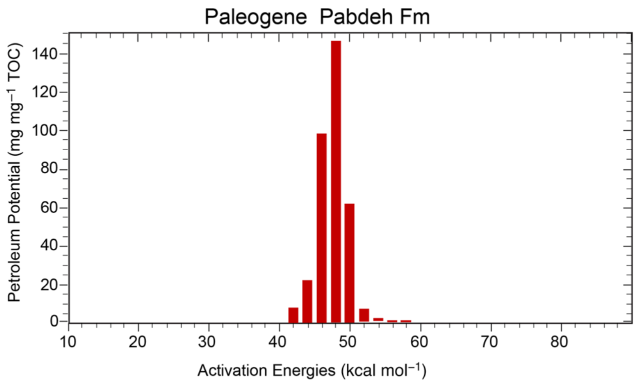

Fig. 24. Kinetic properties of the hydrocarbon formations from the Pabdeh Formation source rock in the Dezful Embayment. Source: from Karimi *et al*. (2016).

Notably, samples exhibiting a higher source-rock potential (i.e. S2 > 6 mgHC g^{-1} rock) have an average HI value of 381 mgHC g^{-1} TOC, suggesting their capacity to generate both oil and gas (NIOC Exploration Directorate and Statoil 2003). Therefore, the Pabdeh Formation exhibits significant variability in TOC content and source-rock quality across the Dezful Embayment and eastern Persian Gulf. This spatial variability reflects the complex depositional environment and organic matter input influencing the hydrocarbon potential in the region.

Reservoir rocks and seals

The Oligo-Miocene Asmari Formation, which consists of *c*. 480 m-thick shallow-marine limestones, is the main reservoir for the Cenozoic petroleum system (McQuillan 1985; Motiei 1993; Sepehr and Cosgrove 2004) in Iran. The hydrocarbon productivity of the Asmari Formation reservoir in the Iranian Zagros region is also enhanced by both fracture density and spacing (McQuillan 1985; Ahmadhadi *et al*. 2008). Van Buchem *et al*. (2010*a*, *b*) have identified four types of reservoirs in the Dezful Embayment, including siliciclastic, mixed siliciclastic–carbonate, mixed carbonate–evaporitic and carbonate, which extend from the Abadan Plain to the SW to the Izeh Zone in the NE of the Zagros region. Structural traps within the Dezful Embayment are primarily large-scale Zagros orogenic anticlines, where the Asmari Formation reservoir is effectively sealed by overlying anhydrites from the Gachsaran Formation (Bahroudi and Koyi 2004). It is worth mentioning that mixed stratigraphic and structural traps have also been discovered for the Asmari Formation, particularly where the Ahwaz Sandstone Member becomes the main reservoir (e.g. at the NW Persian Gulf and Abadan Plain) (Piryaei and Davies 2024).

Hydrocarbon generation and migration

Hydrocarbon generation from the Pabdeh Formation source rock is a relatively recent phenomenon, with expulsion occurring *c*. 3 Myr ago in the deep synclines of the Dezful Embayment (Bordenave and Hegre 2005; Karimi *et al*. 2016). Hydrocarbon migration from Pabdeh source rock is likely to have occurred through folding-induced fractures that formed during the Zagros Orogeny, facilitating short-distance, subvertical movement into the adjacent Asmari Formation reservoir traps (Bordenave and Hegre 2010). In the eastern Persian Gulf, hydrocarbon generation from the Pabdeh Formation is believed to have commenced in the lower Miocene, particularly in areas where the formation is most deeply buried (NIOC Exploration Directorate and Repsol 2002; Mashhadi *et al*. 2015*a*, *b*). However, it was not until the Pliocene that the Pabdeh Formation reached the oil-generation window in this region (NIOC Exploration Directorate and Repsol 2002). Hydrocarbons within the Cenozoic reservoirs are primarily sourced from the Albian Kazhdumi Formation source rock, with their migration influenced by the degree of structural deformation (Bordenave 2014). The significant fracturing of the Pabdeh Formation has enabled vertical connectivity between the Upper Cretaceous Sarvak Formation reservoir, which contains hydrocarbons derived from the Kazhdumi Formation source rock, and the younger Asmari Formation reservoir, which holds hydrocarbons sourced from the Pabdeh Formation (Bordenave and Hegre 2005). For example, the isotopic analysis of oils from the Marun Field, found in both the Asmari and Sarvak reservoirs, aligns with $\delta^{13}C$ values from the Kazhdumi Formation source rock rather than those from the Pabdeh Formation (Telmadarreie *et al*. 2015). Furthermore, the lack of 18(α)H-oleanane in the oils from Marun Field indicates a relatively minor contribution from the Pabdeh Formation source rock (Bordenave and Hegre 2005).

The oil–source rock correlation in the Iranian Zagros and Persian Gulf regions

Comprehensive studies of the basal Silurian 'hot shale' source rock in Iran are required to establish oil–source rock correlations within the Paleozoic–Triassic petroleum system. Due to its significant depth of burial and inadequate seismic data, both the geographical distribution and geochemical properties of this critical source rock remain largely uncharted. Deep wells that extend to the pre-Permian succession in the Iranian Zagros region, such as those in the South Pars, Golshan, Darang, Kuh-e-Siah and Zirreh fields, have not fully penetrated the entire thickness of the source rock, leaving its characteristics largely speculative (Alipour 2024). Most current interpretations are based on geological, geochemical and modelling studies of surface outcrops of Silurian shales at the Kuh-e-Faraghan location (Szabo and Kheradpir 1978; Ghavidel-syooki *et al*. 2011; Saberi and Rabbani 2015; Ahanjan *et al*. 2017). Consequently, the proposed genetic link between the Silurian 'hot shale' source rocks and gas accumulations in Permian–Triassic reservoir rocks relies on indirect evidence (Aali *et al*. 2006; Bordenave 2008, 2014; Bordenave and Hegre 2010; Memariani *et al*. 2010; Aali and Rahmani 2011; Fathi Mobarakabad *et al*. 2011; Mohsenian *et al*. 2014).

The Jurassic oil–source rock correlations of the southern Persian Gulf have also been established based on the molecular characteristics of associated oils (Alizadeh *et al*. 2017; Hosseiny *et al*. 2017). The oil–source rock correlations in the onshore regions are less defined and primarily rely on indirect evidence from modelling studies (Mehmandosti *et al*. 2015; Zeinalzadeh *et al*. 2015). Nonetheless, recent research suggests that some Jurassic hydrocarbon accumulations in the Iranian Zagros region – such as those in the Azadegan, Darquian and Asmari fields – are genetically linked to the Sargelu Formation source rock (Kobraei *et al*. 2019). Analyses indicate that these Jurassic hydrocarbons are predominantly generated by the Sargelu Formation (Kobraei *et al*. 2019).

The Cenomanian Middle Sarvak Formation source rock is inferred to be a primary contributor to hydrocarbons in the Sarvak and Ilam reservoirs in the southern Persian Gulf (Alizadeh *et al*. 2017; Hosseiny *et al*. 2017). In addition, hydrocarbons generated by the Albian Kazhdumi Formation source rock are likely to be responsible for charging reservoirs within the Burgan sandstones (notably in the NW Persian Gulf in Iran), as well as in the Sarvak and Ilam formations (located in the Dezful Embayment) and the Asmari Formation carbonates (Bordenave and Burwood 1990; Bordenave 2014; Baniasad *et al*. 2016, 2017).

Chemometric analyses were performed on a collection of 21 oil samples from the Dezful Embayment (Table 1) in the current study, focusing on their biomarker parameters. These oils, sourced from Jurassic to Cenozoic reservoirs across various fields, were categorized into three distinct families (A, B and C) based on their thermal maturity, facies and age (Fig. 25). While previous studies have identified five petroleum systems within the Dezful Embayment (Bordenave and Hegre 2010), the oil samples analysed in this study appear to represent only three of those systems. Family A oils are characterized by their unique age-diagnostic biomarker parameters. The oils in Family A are characterized by a high C_{28}/C_{29} regular sterane ratio, suggesting a correlation with Upper Jurassic–Miocene source rocks (Grantham and Wakefield 1988). C_{28} steranes are typically associated with phytoplankton and algae, while C_{29} steranes are linked to higher plants and some algae. A high C_{28}/C_{29} ratio suggests a greater contribution from marine phytoplankton or algae relative to terrestrial organic matter (Peters *et al*. 2005). This family includes oils from fields such as the Haft-Kel, Masjid-e-Suleyman, Par-e-Siah, Parsi, Bibi-Hakime and Gachsaran (Table 1). In contrast, Family B oils are classified as high-maturity oils, exhibiting elevated Ts/Tm, C_{29} sterane ββ/ββ + αα and Dia/Dia +

Table 1. Summary of biomarker ratios used for chemometric classification of oil samples from the Dezful Embayment

Wells	Fields	Ts/Tm	C_{29}/C_{30}	C_{35}/C_{34}	OI	C_{26} NDR	C^{26} NCR	20S/(S + R)	ββ/(ββ + αα)	Dia/Reg	22S/(S + R)	$C_{31}R/C_{30}H$	$\%C_{27}$	$\%C_{28}$	$\%C_{29}$	C_{28}/C_{29}	Family
AZ-A	Ahwaz	0.64	1.07	1.31	0	0	0	0.51	0.57	0.35	0.54	0.57	32.1	29.9	38.0	0.79	C
AZ-I		0.26	1.75	1.52	0	0	0	0.54	0.58	0.17	0.54	0.49	35.4	26.7	37.9	0.71	C
AZ-S		0.44	1.30	1.35	0	0	0	0.54	0.59	0.29	0.55	0.48	35.0	29.3	35.7	0.82	C
MN-I	Marun	0.99	1.05	1.39	0	0	0	0.52	0.60	0.45	0.56	0.50	35.5	29.4	35.1	0.84	C
MN-S		0.56	1.22	1.41	0	0	0	0.55	0.59	0.34	0.55	0.53	37.4	29.0	33.6	0.86	C
KP-A	Kupal	0.47	1.35	1.47	0	0	0	0.49	0.57	0.26	0.11	0.52	30.5	28.4	41.1	0.69	C
KP-S		0.55	1.55	1.55	0	0	0	0.53	0.60	0.28	0.53	0.54	34.7	27.4	38.0	0.72	C
HK-A	Haft-kel	0.73	1.18	1.38	0.17	0.33	0.45	0.51	0.57	0.44	0.56	0.43	35.1	31.2	33.7	0.93	A
MIS-A	Masjid-e-Suleiman	0.81	0.77	1.31	0.22	0.40	0.52	0.49	0.54	0.47	0.57	0.41	35.5	31.8	32.7	0.97	A
PS-A	Par-e-Siah	1.40	0.59	1.13	0.32	0.38	0.53	0.54	0.59	0.50	0.57	0.40	37.8	32.9	29.3	1.12	A
PA-A	Parsi	0.72	0.78	1.34	0.16	0.33	0	0.50	0.57	0.29	0.56	0.50	32.5	31.7	35.8	0.88	A
RM-A	Ramshir	0.51	1.17	1.31	0	0	0	0.51	0.58	0.32	0.92	0.51	33.4	29.3	37.3	0.79	C
RM-S		1.51	0.65	1.13	0	0	0	0.55	0.59	0.50	0.55	0.52	32.5	31.6	35.9	0.88	C
BK-A	Binak	0.47	1.33	1.69	0.09	0	0	0.55	0.59	0.44	0.56	0.43	36.1	28.5	35.4	0.80	C
BK-S	Binak	1.19	0.53	1.12	0	0.19	0	0.52	0.62	1.41	0.61	0.37	38.1	32.7	29.3	1.12	B
BH-A	Bibi-Hakimeh	0.70	0.77	1.20	0.15	0.28	0.45	0.54	0.58	0.54	0.58	0.44	36.1	31.9	32.0	1.00	A
BH-S		0.76	0.78	1.17	0.16	0.31	0.44	0.53	0.57	0.55	0.58	0.41	35.8	32.0	32.2	0.99	A
GG-F	Garangan	3.35	0.71	0.85	0	0	0	0.56	0.60	1.14	0.58	0.35	30.9	31.3	37.9	0.83	B
GG-S		2.69	0.67	0.85	0	0	0	0.53	0.61	1.20	0.61	0.32	31.6	30.8	37.6	0.82	B
GS-A	Gachsaran	0.77	0.81	1.11	0.15	0.32	0.48	0.55	0.59	0.54	0.58	0.41	36.1	31.9	32.0	1.00	A
GS-S		0.72	0.67	1.17	0.13	0.36	0.52	0.54	0.57	0.56	0.59	0.41	35.7	33.0	31.3	1.05	A

Note: $C_{29}/C_{30} = C_{29}$ hopane/C_{30} hopane; $C_{35}/C_{34} = C_{35}$ homohopane/C_{34} homohoapne; C_{26} NDR = C_{26} nor-diacholestane ratio; C_{26}NCR = C_{26} nor-cholestane ratio; 20S/(S + R) = C_{29} ααα20S/(ααα20S + 20R) regular sterane; ββ/(ββ + αα) = C_{29}ββ20R/(C_{29}ββ20R + C_{29}αα20R); Dia/Reg = C_{27} Dia/(Dia + Reg) sterane; 22S/(22S + R) = C_{32}αββ 22S/(22S + 22R) hopane.

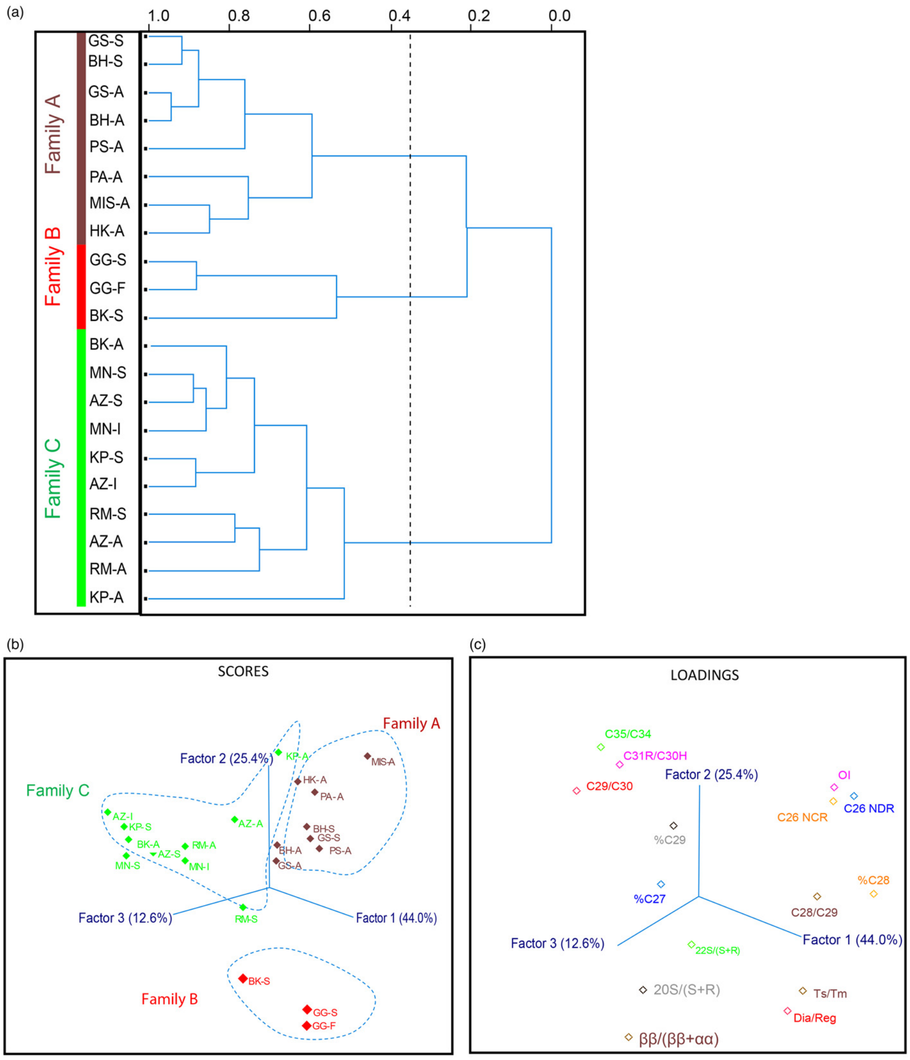

Fig. 25. Results of the chemometric classification (this study) of 21 crude oil samples from the Dezful Embayment. (**a**) Three geochemically distinct clusters of oil families could be identified based on the resulting dendrogram, as well as from (**b**) the score plot and (**c**) the loading plot.

Reg sterane ratios. These oils are likely to have been sourced from Jurassic or older formations and include samples from the Binak and Garangan fields (Table 1). Family C oils display biomarker parameters indicative of anoxic marine conditions in their source rock from the Albian Kazhdumi Formation. This category includes oils from the Ramshir, Binak, Kupal, Marun and Ahwaz fields (Table 1).

Rabbani *et al.* (2014) identified four primary oil groups in the Persian Gulf region through statistical analyses, correlating them with distinct source rocks using age-specific biomarkers and isotope data (Fig. 26). Group I and Group II oils, associated with Jurassic–Early Cretaceous reservoirs, are believed to have originated from Jurassic or older source rocks. Conversely, Group III and Group IV oils, linked to Late Cretaceous–Cenozoic reservoirs, are thought to be derived from Cretaceous or younger sources. The Hanifa-Tuwaiq Formation, Garau Formation and the Diyab Member of the Surmeh Formation are the most likely sources for the Group I and Group II oils. For Group III and Group IV oils, potential sources include the Kazhdumi and Sarvak formations, along with the Khatiyah and Ahmadi members (Fig. 26) (Rabbani *et al.* 2014).

Baniasad *et al.* (2023) investigated the geochemical characteristics of oils and the active petroleum systems in the Eastern Arabian Plate through bulk, molecular and stable carbon isotope data from more than 500 oil samples across 112 oilfields and 11 reservoir levels. Three primary petroleum systems were recognized in the area: Paleozoic, Middle Jurassic–Lower Cretaceous, and Middle Cretaceous–Cenozoic. Clear distinctions in geochemical and isotopic data were found between oils derived from Paleozoic source rocks and those from the overlying petroleum systems. In the Eastern Arabian Plate, oils from the Middle Jurassic–Lower Cretaceous and Middle Cretaceous–Cenozoic systems were classified into 12 families and subfamilies, originating from six significant source rocks: the Middle Jurassic Sargelu Formation, the Lower Cretaceous Garau Formation, the Albian Kazhdumi Formation and the Eocene Pabdeh Formation are the most important source rocks in the Iranian part of the Eastern Arabian Plate. Most oils in the region originated from Middle Jurassic–Lower Cretaceous source rocks, while oils derived from Middle Cretaceous–Cenozoic source rocks are mostly limited to the Dezful Embayment in southwestern Iran and the Sirri District in the southern Persian Gulf (Rabbani 2008).

Further analyses of oil and source-rock samples are required, particularly focusing on stable carbon isotope ratios, to refine these oil families and clarify potential oil–source rock relationships.

Correlation studies in the Iranian Zagros region have faced challenges due to various factors, such as the absence of representative samples from the basal Silurian Sarchahan ‘hot shale’ source rock. In addition, some source kitchens extend beyond Iran’s territorial borders (e.g. the Cenomanian Middle Sarvak Formation and Oxfordian Middle Surmeh Formation source rocks). Furthermore, individual hydrocarbon accumulations may be influenced by secondary alteration processes or mixing from multiple charges’ sources (Alizadeh *et al.* 2017).

Combining findings from various studies on oil families in the Dezful Embayment and Persian Gulf have suggested that Family B

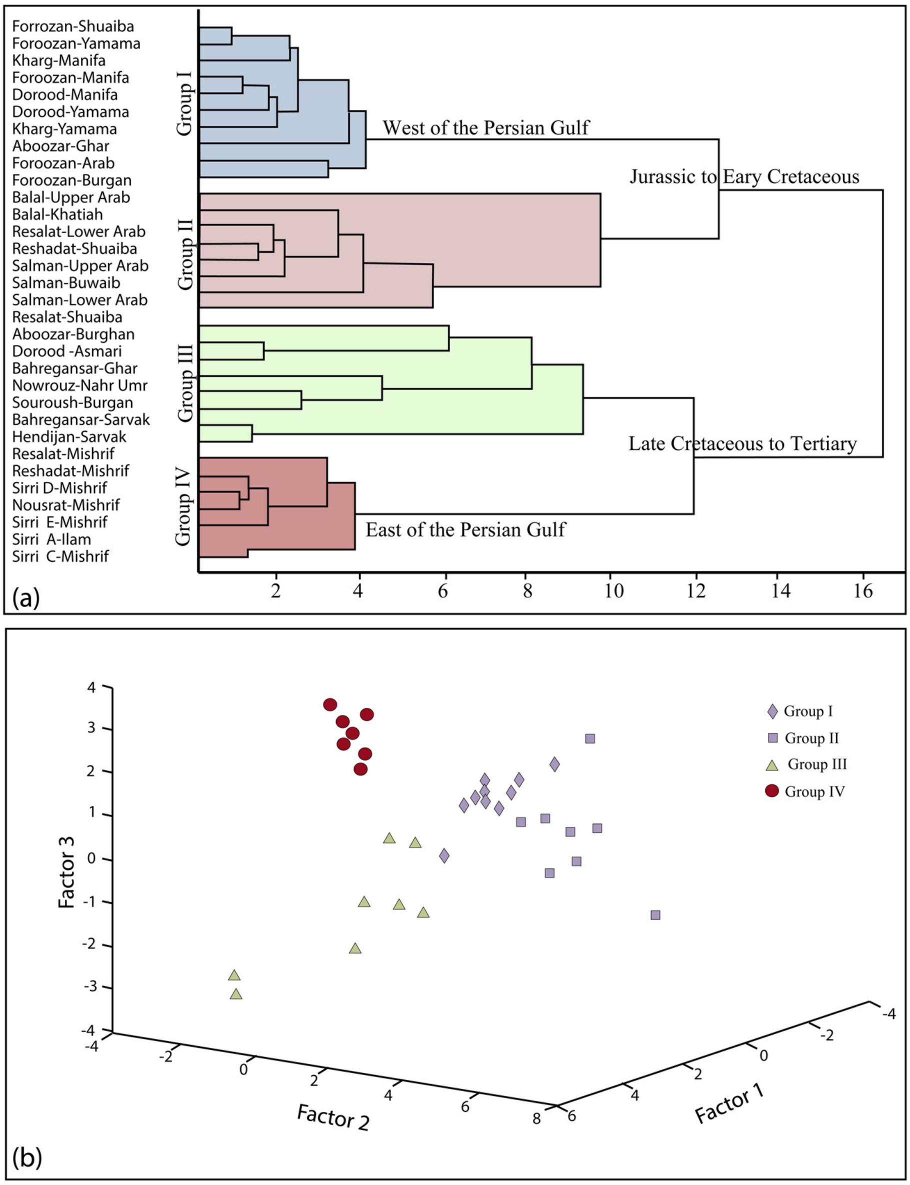

Fig. 26. Results of the chemometric classification of 32 crude oil samples from the Persian Gulf region by Rabbani *et al.* (2014), which identified four geochemically distinct clusters of oil families based on (**a**) the resulting dendrograms, as well as (**b**) four groups from the score plot.

oils of the study from the Dezful Embayment align with the Group I and Group II oils of the Rabbani *et al.* (2014) study in the Persian Gulf, both generated from Jurassic or older source rocks. Group III and Group IV oils in the Persian Gulf region may correlate with either Family A or C of the study from the Dezful Embayment. However, more detailed biomarker studies are needed to distinguish between these two families.

Based on this study, the Kazhdumi and Pabdeh formations exhibit distinct biomarker signatures (Figs 27 and 28). Bitumen from the Kazhdumi Formation contains a higher proportion of diasteranes relative to steranes, elevated levels of C_{27} steranes, and notable C_{29}/C_{30} and $C_{30}/C_{32}+C_{33}$ hopane ratios based on this study. Steranes are relatively stable, but diasteranes, which are rearranged isomers of steranes formed typically during early diagenesis and catagenesis, tend to increase relative to steranes with higher thermal maturity or biodegradation (e.g. Peters *et al.* 2005). Therefore, a higher diasterane/sterane (Dia/Dia + Reg sterane) ratio is often interpreted as an indication of increased thermal maturity or biodegradation of the organic matter. Moreover, a dominance or elevation of C_{27} steranes in a sample suggests a greater contribution of marine-derived organic matter such as algae or zooplankton, reflecting a marine depositional environment (Killops and Killops 2013). Ratios such as C_{29}/C_{30} hopanes and $C_{30}/(C_{32}+C_{33})$ ratios can indicate different bacterial populations or varying redox and depositional environments (Connan and Dessort 1987; Peters *et al.* 2005). For example, elevated C_{29}/C_{30} hopane ratios have been linked to more reducing conditions or sulfate-reducing bacterial activity (Peters *et al.* 2005). Distinctive hopane distributions help in the reconstruction of palaeoenvironments and in assessing microbial contributions to the organic matter (Tissot and Welte 1984).

In contrast, the Pabdeh Formation bitumen features a lower diasterane proportion, higher levels of C_{29} steranes, and lower C_{29}/C_{30} and $C_{30}/C_{32}+C_{33}$ hopane ratios (Mehmandosti *et al.* 2015). Significantly, the presence of substantial amounts of 18α(H)-oleanane in NE Dezful Embayment oils sourced from the Pabdeh Formation indicates a contribution from terrigenous angiosperm plants, inferring a Late Cretaceous or younger age (Ekweozor *et al.* 1979). Angiosperm flora first appeared in the Cretaceous (Peters and Moldowan 1993) but proliferated rapidly from the Early Cenozoic onwards. Notably, 18α(H)-oleanane is absent in the Kazhdumi Formation-sourced oils based on this study (Fig. 28). The preference for norhopane over hopane and a high content of C_{35} hopane further differentiate northeastern Dezful oils. In addition, the sterane composition reveals αα20SR ethylcholestane, indicating that these oils are fully mature. The relative abundance of C_{28} compounds in the northeastern Dezful oils suggests a younger

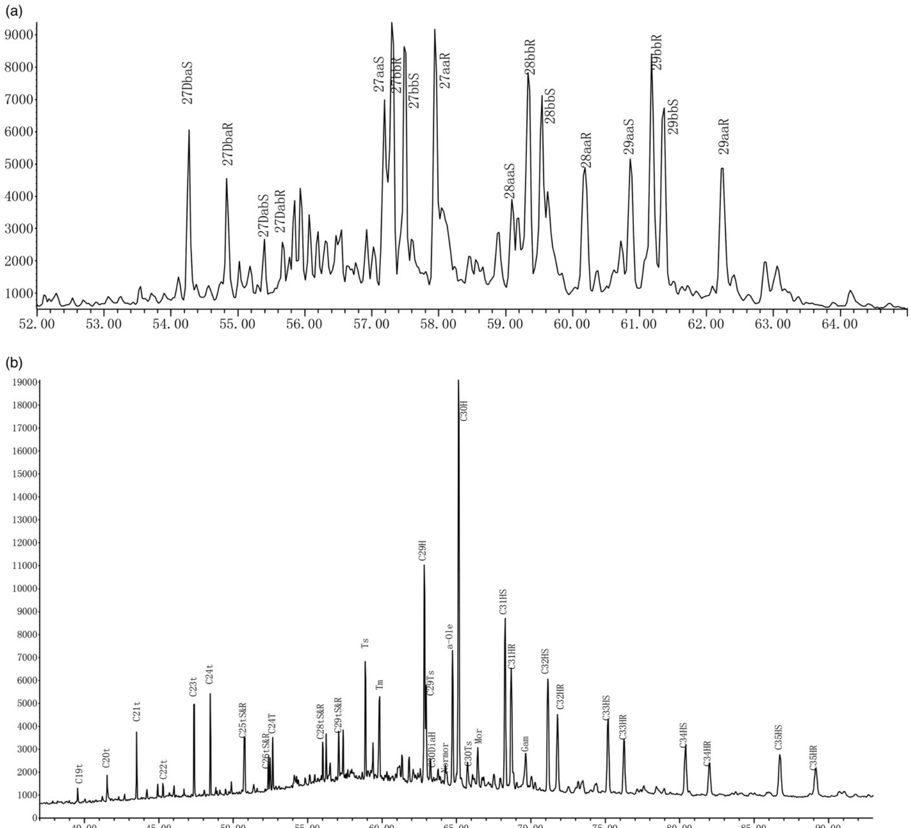

Fig. 27. The specific biomarkers for the Pabdeh Formation source rock identified in this study including both steranes (*m*/*z* 217) and hopanes (*m*/*z* 191).

source compared with those derived from the Kazhdumi Formation (Grantham and Wakefield 1988). This trend has also been noted in Iraq (Connan 1988) and the Aquitaine Basin (Connan and Lacrampe-Couloume 1993), potentially indicating contributions from evaporitic sources that were prevailing during the deposition of the Pabdeh Formation.

Summary

The Paleozoic–Cenozoic stratigraphic successions of the Iranian Zagros region host various source rocks with vertical communication, based on the results from stratigraphic and structural analyses. The source and reservoir rocks of the Paleozoic–Triassic petroleum

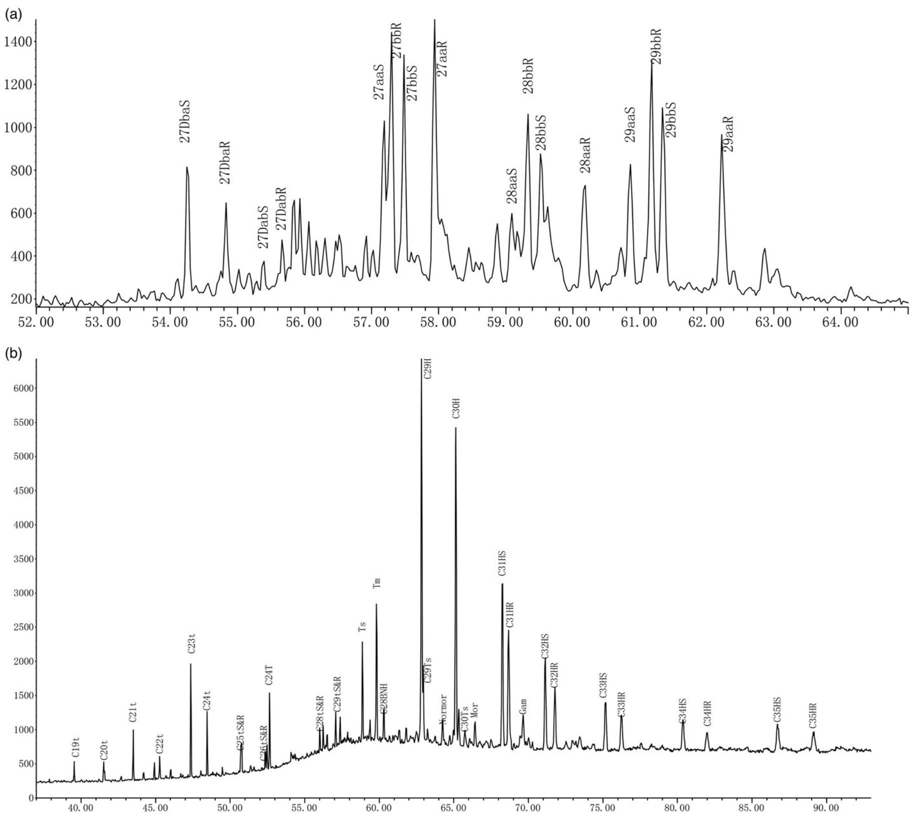

Fig. 28. The specific biomarkers for the Kazhdumi Formation source rock recognized in this study including both sterane (*m*/*z* 217) and hopanes (*m*/*z* 191).

system are usually buried under considerable depths across much of the Iranian Zagros region, which caused this system to be poorly understood. Accessible portions of the upper Paleozoic interval are primarily found in the margins of the Iranian Zagros and the Persian Gulf regions, particularly around palaeohighs. This system has generated substantial volumes of natural gas, notably in the upper Permian Dalan and lower Triassic Kangan Formation reservoirs. Key risk factors include the geographical distribution of the basal Silurian 'hot shale' source rock, the extent and integrity of the Dashtak evaporite seal, and the elevated nitrogen gas concentrations in certain Permian–Triassic reservoirs, such as those in the Lurestan area. The discovery of new oilfields involving the Kangan and Dalan reservoirs in the Fars and Persian Gulf regions will encourage further exploration of the Paleozoic in other regions too. Although the lower Paleozoic petroleum succession remains undiscovered due to its thick sedimentary overburden (>6 km), it should be accessible in elevated sedimentary successions as a result of basement faults and salt diapirs tectonics (Faridi *et al*. 2021).

The Jurassic–Cretaceous petroleum system exhibits considerable potential in the Iranian Zagros region, driven by the presence of organic-rich Jurassic and Cretaceous shaly source rocks, alongside favourable conditions for hydrocarbon generation and migration. The lateral continuity of organic-rich facies and the extent of evaporite cap rocks are critical elements for this system. They can also be considered promising for unconventional oil and gas resources, by applying advanced drilling and extraction technologies. In addition, stratigraphic traps within the Cretaceous petroleum system offer further exploration opportunities, which can be recognized through detailed sequence-stratigraphic modelling.

The Cenozoic petroleum system is active only in specific areas of the Dezful Embayment, where reservoir units may contain hydrocarbons also sourced from underlying systems. The thermal maturity of the Pabdeh Formation source rock, along with the structural deformation required for fracturing within the Asmari Formation reservoirs, plays a crucial role in this system. There may still be remaining potential in the form of early mature oil trapped within the fractured shales of this system.

Geochemical analyses of two sets of oils and source rocks were carried out to understand the existing oil families and to clarify their genetic relationships to the source rocks. These findings will also help in better understanding the migration pathways within the study area and will contribute to the establishment of some accurate petroleum system models in the future.

Concluding remarks

This study provides a comprehensive evaluation of petroleum systems in the Iranian Zagros and Persian Gulf regions, integrating geochemical, geological and modelling approaches to clarify hydrocarbon generation, migration and accumulation.

The key findings include:

(1) Source-rock potential: the Pabdeh, Kazhdumi, Garau, Sargelu and Sarchahan formations exhibit strong hydrocarbon-generating capabilities, supported by biomarker and isotopic evidence (e.g. $\delta^{13}C$ and the presence of oleanane). Kinetic studies further constrain their thermal maturation windows.
   - Late Eocene–early Oligocene (lowstand systems tracts (LSTs) of sequences Pg25 and Pg30) as the richest interval of the Pabdeh Formation, considered an early mature phase for petroleum generation, exhibits hydrocarbon potential, particularly in the Dezful Embayment and Lengeh troughs. Deposited in a NW–SE-elongated foredeep basin under euxinic conditions, it contains organic-rich marine shales and marginal carbonates with maximum TOC values. The formation features Type II amorphous-algal kerogen and a narrow activation energy.
   - The Aptian–Albian Kazhdumi Formation is recognized as one of the most significant source rocks in the study area. Deposited in a subsiding intrashelf basin influenced by the Balarud and Kazerun basement faults, it features organic-rich shales with the highest TOC values that contain mainly oil-prone Type II kerogen. The formation exhibits a narrow activation energy range, indicating efficient hydrocarbon generation. Its biomarker signature, characterized by a high diasterane and C_{27} sterane content, alongside with $C_{29}/C_{30}H < 1$, distinguishes it from other source rocks.
   - The Early Cretaceous Garau Formation is prominent in the Dezful Embayment, Abadan Plain and NE Persian Gulf, with the potential for unconventional resources in the Lurestan area due to its organic richness and fracturing. Deposited in a deep, anoxic intrashelf basin, it contains organic-rich shales with good to very good source-rock potential based on TOC values. The formation features Type II amorphous kerogen with HI, TOC and T_{max} values reflecting peak oil generation maturity in the Lurestan area. Its activation energies range from 39 to 60 kcal mol^{-1} (principal energy 55 kcal mol^{-1}).
   - The Sargelu Formation, a Middle Jurassic source rock, is a major hydrocarbon contributor, particularly in Lurestan, the Abadan Plain and the NW Persian Gulf, associated with a significant shale gas potential in Lurestan. Deposited in a NW–SE-trending deep, anoxic intrashelf basin, it contains organic-rich facies with oil-prone Type IIS kerogen. The formation exhibits thermal maturity, increasing from the main oil window in the NW Persian Gulf to the late oil window towards the Abadan Plain, reaching wet- to dry-gas windows in the Dezful Embayment and Lurestan. Its activation energies span 39–60 kcal mol^{-1} (principal energy 54 kcal mol^{-1}).
   - The Sarchahan Formation is the primary source rock for the Paleozoic–Triassic petroleum system, contributing more than 90% of its hydrocarbons. It is characterized by high organic richness and Type II/III kerogen, as observed in SE Zagros outcrops. The source-rock potential indicates late mature to gas-window maturity. Despite its significant potential, deep burial (>6000 m) limits subsurface sampling, and uncertainties in its geographical extent and migration dynamics suggest untapped potential for unconventional resources like shale gas, particularly in the southern Persian Gulf.

(2) Oil-source rock correlations: chemometric analysis of 21 oil samples identified three distinct oil families, with clear genetic links to specific source rocks. Family A oils are characterized by a high C_{28}/C_{29} regular sterane ratio, suggesting a correlation with Upper Jurassic–Miocene source rocks. Family B oils are classified as high-maturity oils, which are likely to have been sourced from Jurassic or older formations. Family C oils display biomarker parameters indicative of anoxic marine conditions in their source rocks from the Aptian–Albian Kazhdumi Formation.

(3) Regional implications: the integration of unpublished NIOC data with published studies confirms the significant reserves of the Paleozoic petroleum system and highlights analogous petroleum systems across the Arabian Plate.

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Author contributions

PH: conceptualization (equal), data curation (equal), formal analysis (equal), investigation (equal), methodology (equal), resources (equal), software (equal), supervision (equal), validation (equal), visualization (equal), writing – original draft (equal), writing – review & editing (equal); **AP**: conceptualization (equal), data curation (equal), formal analysis (equal), investigation (equal), methodology (equal), resources (equal), software (equal), supervision (equal), visualization (equal), writing – original draft (equal), writing – review & editing (equal).

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Competing interests

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 data that support the findings of this study are available from the corresponding author upon reasonable request.

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