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ORIGINAL PAPER-EXPLORATION GEOLOGY

# An innovative approach for investigation of overpressure due to hydrocarbon generation: a regional study on Kazhdumi formation, South-western Zagros Basin, Iran

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## Abstract

Overpressure is always considered as a severe problem in the oil industry. Besides creating life risks through serious accidents while drilling, failure to correctly identify high-pressure intervals causes a significant increase in costs and prolongs the drilling process. Kazhdumi Formation in the Abadan Plain is considered as a high-pressure formation in several wells. Various reasons can cause overpressure problem. Hydrocarbon generation is one cause of abnormal pressure in source rocks. Understanding hydrocarbon generation potential can be a helpful approach since the Kazhdumi Formation is considered as a probable source rock in this area. In this paper, in order to better understand the problem of abnormal pressure in Kazhdumi Formation, geochemical concepts and tools have been applied. To that way, 1D petroleum system modeling of five wells was done, and the thermal maturity level of Kazhdumi Formation was determined and then, compared with drilling records. The results indicate that in wells where this formation has sufficient organic matter and has reached an early mature level, there is an abnormal pressure problem. Otherwise, this formation does not show abnormal pressure. Also, geochemical data are not available in all drilled wells, which makes impossible the assessing of hydrocarbon generation role. Therefore, petrophysical well logs (sonic (DT), neutron (NPHI), density (RHOB), spectral gamma ray (SGR), and resistivity (RES)) as well as 137 sets of geochemical data belonging to 13 wells from 7 oilfields in the Abadan Plain were used to predict geochemical indicators. Using artificial neural networks, geochemical data of a well in Abadan Plain were predicted. This selected well has a high-pressure problem in Kazhdumi Formation, but no geochemical data are available in this well. The results of predicted geochemical data show that the high-pressure phenomenon in this well may also be due to hydrocarbon generation. The precise understanding of the abnormal pressure, resulting from hydrocarbons generation, requires comprehensive studies and a full investigation of the studied area. However, the results of this paper help to predict approximately the behavior of the source rocks before drilling. Acquiring this overview will aid in reducing drilling hazards and costs.


**Keywords** Overpressure · Kazhdumi formation · Abadan plain · Petroleum system modeling · Hydrocarbon generation

## Abbreviations

| | |
|---|---|
| DT | Sonic log |
| HC | Hydrocarbon |
| HF | Heat flow |
| NIOC | National Iranian Oil Company |
| NPHI | Neutron log |
| RHOB | Bulk density log |
| PCF | Pound per cubic feet |
| PWD | Paleo-water depth |
| RES | Resistivity log |
| SGR | Sum gamma ray log |
| SWI | Sediment-water interface |
| TOC | Total organic carbon |
| TR | Transformation ratio |

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## Introduction

Abnormal pressure is a crucial drilling engineering concept that refers to pressure that differs from the hydrostatic pressure (lower or higher) at a specific depth (Bradley 1976). Overpressure or positive pressure anomaly describes the situation that formation pressure is above the normal hydrostatic pressure (Mouchet and Mitchell 1989). Using the velocity obtained from seismic data can play an effective role in predicting abnormal pressures before drilling. These seismic-base methods have been used many times in recent studies (Ugwu 2015; Hoskin and O'Connor 2016; El-Werr et al. 2017). The precise prediction of overpressure before drilling operation is a critical task, since the lack of information about over pressured intervals can result in serious problems while drilling. Several factors that are considered as over pressure indicators are fluid flow, lost circulation, pressure kick, pipe stuck and blowout. In addition to be dangerous, these incidents are time-consuming and increase the non-productive time of the rig (Hansom and Lee 2005; Zhang 2011). Different factors cause abnormal pressure. Mainly, overpressure mechanisms are of primary or secondary types. Disequilibrium compaction is considered a primary mechanism, whereas water expansion due to thermal effect, clay diagenesis, osmosis phenomenon, organic matter cracking and clay mineral transformation are secondary mechanism (Bradley 1976; Mouchet and Mitchell 1989; Anissimov 2001; Shi et al. 2005; Nwozor et al. 2013; Zhang et al. 2019; Alabere and Akangbe 2021; Pwavodi et al. 2023). Generally, all these factors can be categorized in three main mechanisms: changes of pore volume, changes of fluid volume, and fluid movement due to changes of pressure or buoyancy (Osborne and Swarbrick 1997; Zhang et al. 2019; Alabere and Akangbe 2021; Pwavodi et al. 2023).

The process of converting organic matter into hydrocarbon, which is associated with producing lighter substances than the initial organic matter, results in volume increment. In the confined situations, this phenomenon can create the abnormal pressure (Mouchet and Mitchell 1989; Xiaorong 2000; Hansom and Lee 2005; Zhang et al. 2019). In other words, source rocks can provide abnormal pressure due to the hydrocarbon generation (Meissner 1976, 1978; Law and Spencer 1981; Spencer 1983, 1987; Hansom and Lee 2005; Guo et al. 2010, 2016; Yang et al. 2016; Zhang et al. 2019). The source rocks with adequate content of organic matter, which are in hydrocarbon generation window, can be a cause of overpressure (Burrus 1998). Also, gas generation can be the reason for local overpressure (Hansom and Lee 2005; Tingay et al. 2013). Besides the quality of organic matter, the quantity is also a controlling parameter (Guo et al. 2010; Zhang et al. 2019). The Kazhdumi Formation in Abadan Plain plays a potential source rock role (Asadi Mehmandosti et al. 2022).

Until now, limited researches have been published regarding the hydrocarbon generation's role in overpressure creation. The magnitude of overpressure in shales of Delaware Basin has been assessed in 2005. The results of this research show that simultaneous production of oil and methane gas can generate an exorbitant amount of overpressure (Hansom and Lee 2005). Tingay et al. (2013) analyzed the overpressure magnitude of the northern Malay Basin. They concluded that gas generation has the most contribution to excess pressure in source rocks of the studied region (Tingay et al. 2013). Han et al. (2019) evaluated the elastic properties of organic shale. They deduced that elastic properties depend on kerogen stress and pore pressure (Han et al. 2019). In the Chezhen Depression, Bohai Bay Basin, China, Zhang et al. (2019) and Li et al. (2021) discovered that overpressure in the third and fourth members of the Shahejie Formation is caused by hydrocarbon generation (Zhang et al. 2019; Li et al. 2021). The assessment of Ordos Basin shale also confirms the impact of hydrocarbon generation on excess overpressure (Liu et al. 2021).

In this paper, the effect of hydrocarbon generation on overpressure creation will be addressed. In the Abadan Plain, there are high-pressure intervals in the Kazhdumi Formation. The challenging issue is that this phenomenon is not observed in all drilled wells. In other words, this is a local problem and only exists in some places. To unravel this quandary, this paper aims to assess the effect of hydrocarbon generation in overpressure creation. Since Kazhdumi is considered as a probable source rock (Asadi Mehmandosti et al. 2022), hydrocarbon generation effect can also be considered as a possible reason for these local difficulties due to the high-pressure intervals of Kazhdumi Formation. In this study, we used the information of seven oil fields in the Abadan Plain to explore a logical relationship between hydrocarbon generation and overpressure problems. Figure 1 shows the studied area and locations of the studied wells.

## Geological setting

Abadan Plain is one of the most significant areas containing considerable amounts of hydrocarbon. This area, which is a sector of Mesopotamian Basin, toward the eastern and northern borders, is limited by Dezful Embayment and is confined to the Persian Gulf in the southern margin (Fig. 1). This area is continued into the Iraq. Although the geology of Abadan Plain has been affected by Zagros orogeny, the structural trends of this area mainly follow the Arabic N-S trend (Alavi 1994; Fard et al. 2006; Atashbari et al. 2018; Tavakolian et al. 2022; Tajmir Riahi et al. 2023). Quaternary deposits cover the surface of this depositional flood plain, and there is no outcrop of deep formations in the Abadan Plain.

Even though Dezful Embayment and Abadan Plain are nearby geographically, there are structural differences between them. For instance, the basement tectonic activities are the reason for Abadan Plain's structures (Fard et al. 2006; Soleimany and Sàbat 2010). Also, Abadan Plain has a lower fault frequency than the Dezful Embayment (Motiei 1995; Rajabi et al. 2010). The Kazhdumi Formation from the

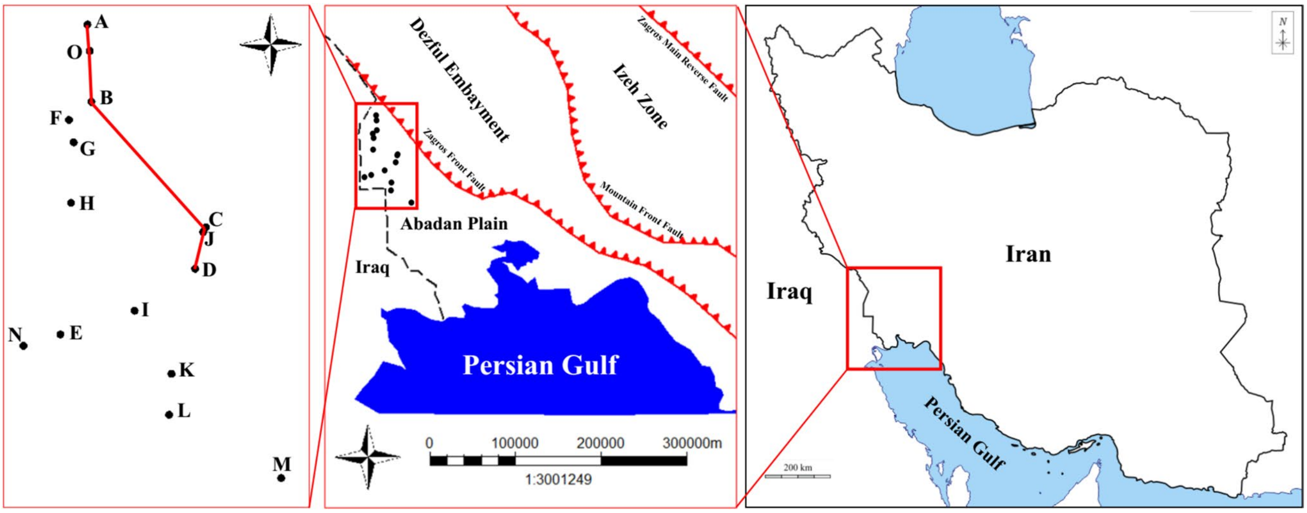



**Fig. 1** Location map of Abadan Plain, Dezful Embayment, and Izeh zone (modified from (Mohsenipour et al. 2022)). Black dots indicate the studied wells. The red line shows the location of section in Fig. 10

Cretaceous Bangestan Group is exposed to Dezful Embayment, Fars and Izeh Zone of Zagros (Motiei 1995). This formation overlies the Dariyan Formation conformably and is underlain by the Sarvak Formation (James and Wynd 1965). A simplified stratigraphic column has been illustrated in Fig. 2. The equivalents of this formation in Iraq and Kuwait are NahrUmr and Burgan formations, respectively (Fig. 3). The type section of Kazhdumi Formation with a thickness of 210 m that was formally described by James and Wynd (1965) is situated in the Tang-e-Gurguda, 10 km north of Gachsaran City (Motiei 2003). It has widely been distributed in the southwest areas of Iran, including Dezful Embayment, Abadan Plain, and northwestern of the Persian Gulf.

Kazhdumi Formation is deposited in the mixed carbonate and clastic environments. It contains calcareous and dark bituminous shale, which is in inter-fingering form with argillaceous limestone and sandstone, particularly in the lower part. In Fars area, Kazhdumi Formation is composed of shallow carbonate rocks, while in Dezful embayment, it mainly has deep shaly facies. A rise in sea level during the Albian time resulted in the deposition of dark organic-rich shales and argillaceous limestones of the Kazhdumi Formation in Iran and its equivalents (e.g., NahrUmr) in adjacent countries (Motiei 1993; Ghazban 2009). The presence of ammonites and a foraminiferal-oligosteginid fauna is attributed to deep marine environments with anoxic conditions and a connection with Neo-Tethys (Ziegler 2001). The sandstone and shale layers at the base of Kazhdumi Formation are known as the "Azadegan Sandstone" Member (Esrafili-Dizaji and Rahimpour-Bonab 2019; Mehrabi et al. 2019). In Iraq and Kuwait, these sandstone intervals are major oil-bearing reservoirs (Ibrahim 1983; van Buchem et al. 2010). In Abadan Plain, the thickness of this formation is approximately 200 m (Sepehr and Cosgrove 2004; Mehmandosti et al. 2015; Kobraei et al. 2017), and Azadegan Sandstone Member is considered as reservoir (Soleimani and Hassani-Giv 2017; Esrafili-Dizaji and Rahimpour-Bonab 2019).

Kazhdumi Formation is known as one of the main source rocks for the Late Cretaceous Ilam and Sarvak and Oligocene–Miocene Asmari formations in SW Iran (Bordenave and Burwood 1990; Rabbani and Kamali 2005; Bordenave and Hegre 2010). This formation is in the peak of oil generation stage in the extent of Dezful Embayment whereas, in Abadan Plain, this formation is immature or is in expulsion phase (Alizadeh et al. 2012; Zeinalzadeh et al. 2015; Kobraei et al. 2017).

## Data availability and methodology

In this study, geochemical data and raw petrophysical logs of 13 wells from 7 oilfields in the Abadan Plain are used. In the first step, data of 5 wells were used for 1D petroleum system modeling (wells A to E, Fig. 1). In the next step, a set of 137 geochemical data (depth, S1, and $T_{max}$) as well as petrophysical logs including sonic, density, resistivity, neutron and spectral gamma ray belonging to 13 wells (wells A to M, Fig. 1) were utilized to predict geochemical data using artificial neural networks. Also, to assess the effectiveness of prediction, another well that was not used in the neural network training process was used (well N, Fig. 1). Then, the neural network results were used to predict the geochemical data in a well without geochemical analysis (well O, Fig. 1). The availability of data is listed in Table 1. The number of datasets belonging to each well has been presented in Table 2. Since there are

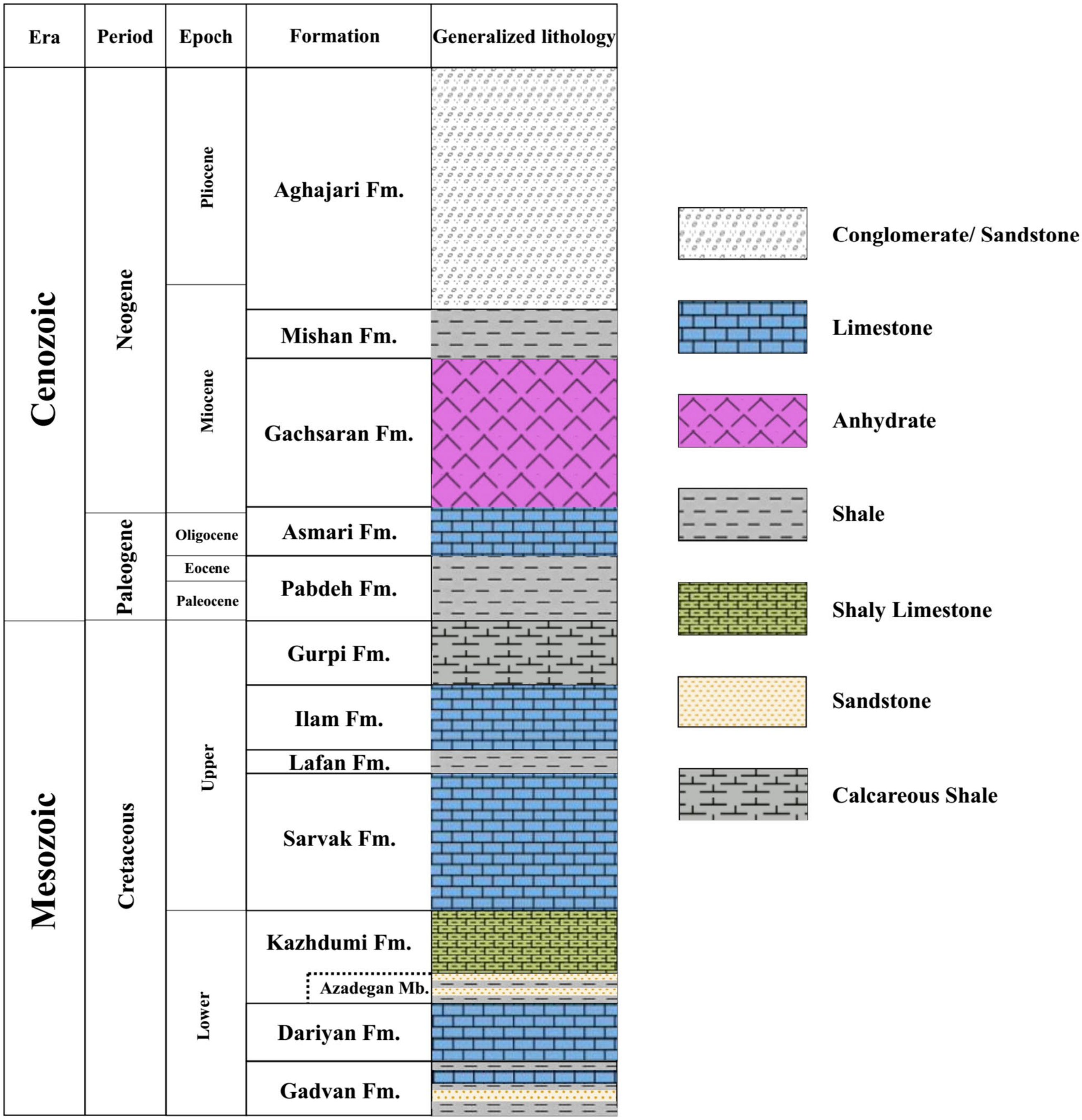



**Fig. 2** Simplified stratigraphic chart of Abadan Plain. Please note that the dominant lithology in each formation is presented, and this column is drawn in a simple and general form

only 71 samples of Kazhdumi Formation, to strengthen the neural network training process, 66 samples from Gadvan Formation have also been used. The contribution of each formation is also specified in Table 2. Also, the statistics of geochemical data belonging to Kazhdumi and Gadvan formations are listed in Table 3. These data are reported from internal NIOC report (Alizadeh 2015). The steps of the study are shown in Fig. 4. The procedures of petroleum system modeling and artificial neural networks were discussed in detail as follows.

## 1D petroleum system modeling

A 1D petroleum system was created using data from five wells to assess the hydrocarbon generation of the Kazhdumi Formation using PetroMod 2019 software. Petroleum system

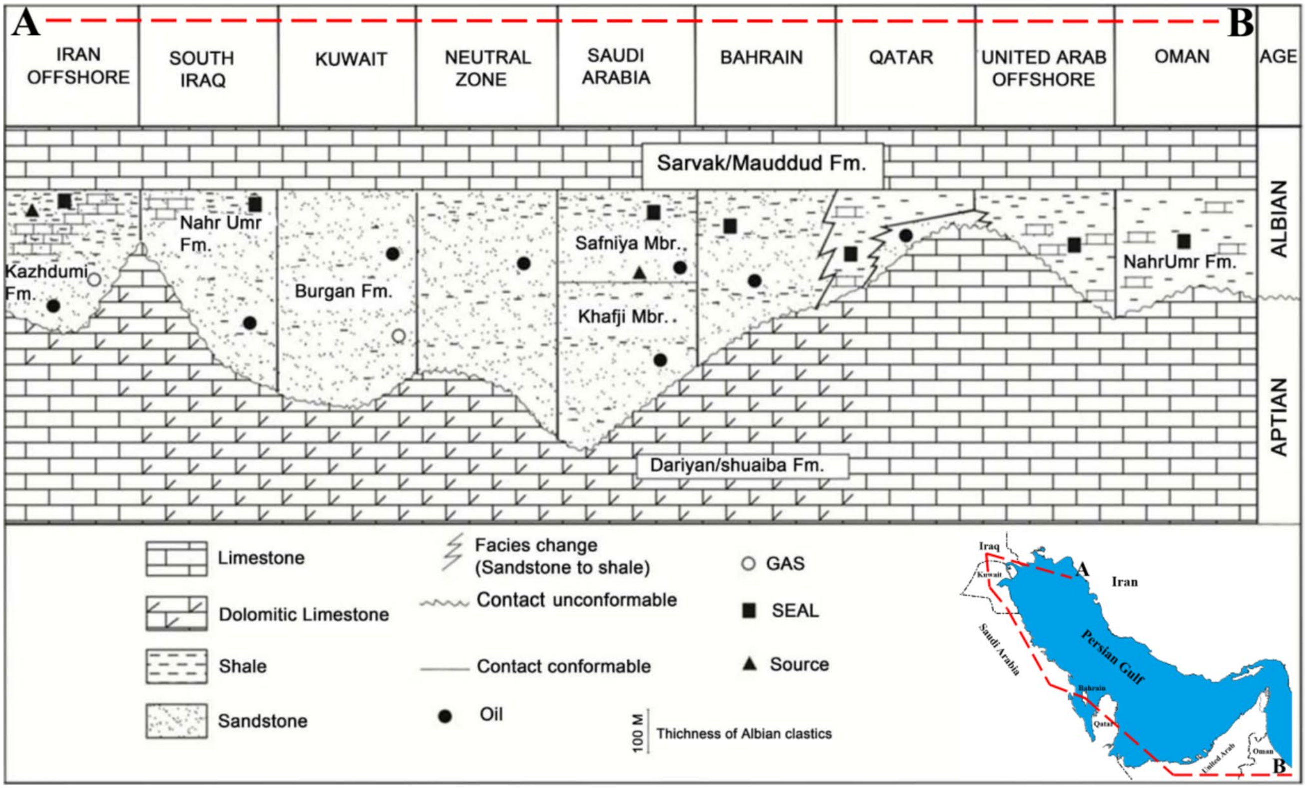



**Fig. 3** Stratigraphic chart of Kazhdumi Formation and its equivalents in the surrounding areas. Modified after (Alsharhan 1994; Noori et al. 2016)

**Table 1** Available data (geochemical data, petrophysical logs, and calibration logs)

| Well name | Geochemical data | | | | Petrophysical logs | | | | | Calibration data | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | S1 | S2 | TOC | *T*max | Sonic | Density | Resistivity | Neutron | Spectral Gamma Ray | Vitrinite Reflectance | Temperature |
| Well A | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Well B | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Well C | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Well D | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Well E | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Well F | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| Well G | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| Well H | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| Well I | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| Well J | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| Well K | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| Well L | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| Well M | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| Well N | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| Well O | × | × | × | × | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |

modeling has many advantages and provides useful information about the maturity of source rocks. In this regard, many researchers have used petroleum system modeling in their studies (Baniasad et al. 2019, 2021; Gawad et al. 2021; Abdelwahhab et al. 2023; Shabani et al. 2023). Until now, researchers have pursued various goals such as discovering

**Table 2** Number of datasets in Kazhdumi and Gadvan formations in each well

| Well name | Number of datasets in Kazhdumi Formation | Number of datasets in Gadvan Formation |
|---|---|---|
| Well A | 7 | – |
| Well B | 4 | 5 |
| Well C | 4 | 3 |
| Well D | 10 | 8 |
| Well E | 10 | 6 |
| Well F | 3 | 7 |
| Well G | 6 | 6 |
| Well H | 4 | 12 |
| Well I | 5 | 4 |
| Well J | 9 | 6 |
| Well K | 2 | – |
| Well L | 3 | 4 |
| Well M | 4 | 5 |
| Total | 71 | 66 |
| | 137 | |

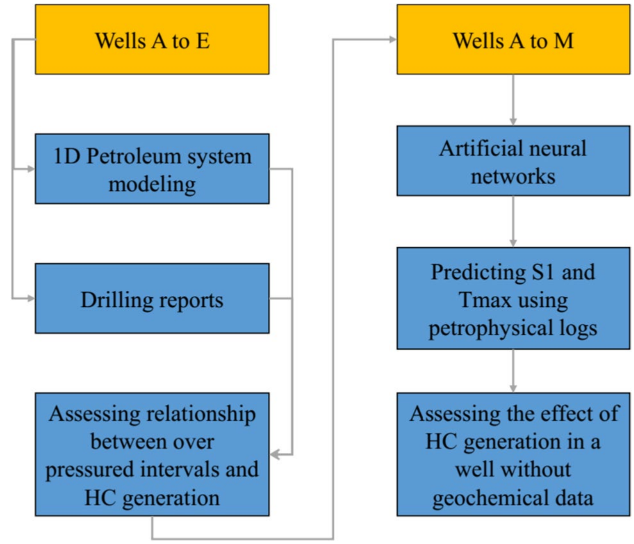



**Fig. 4** A simple flowchart of the steps of the study

new prospects, migration routes and source rock evaluation while using petroleum system modeling. The present paper tries to use petroleum system modeling concepts to evaluate abnormal pressure of Kazhdumi Formation in Abadan Plain.

The geological formations' tops and lithology contents are significant and mandatory input data for 1D petroleum system modeling which were extracted from relevant well reports. Also, the geological events such as deposition, hiatus and erosion as well as their absolute time are other required data which were derived from regional studies (James and Wynd 1965; Soleimany and Sàbat 2010; Soleimany et al. 2011).

Geochemical data are the other prominent obligatory items for 1D petroleum system modeling. Total organic carbon and hydrogen index are two parameters which must be determined in an initial form. The plot of S1 versus TOC was prepared to determine the migration status of the studied samples (Fig. 5a). As depicted, all samples are indigenous. Also, to construct a 1D petroleum system model, kinetic types of source rock should be assigned based on analytical methods or software library. In this study, kinetic types of the Kazhdumi Formation were set based on the kerogen type and the default kinetic models of PetroMod software. As illustrated in Fig. 5b, kerogen types of the Kazhdumi Formation are mainly types II and II/III in the five studied wells. Therefore, the "Abu-Ali et al. (1999), TII (Qusaiba)-cs" kinetic was chosen as the kinetic type of the Kazhdumi Formation. Since samples of well B show the kerogen type III, "Vandenbroucke et al. (1999), TIII (North Sea)-cs" kinetic model was assigned to this well.

Paleo-water depth (PWD), sediment–water interface (SWI) temperature and heat flow (HF) are considered as boundary conditions which must be specified for petroleum system modeling. PWD is an approximate depth of deposition, which can be estimated based on the environment of sedimentation. SWI temperature can be determined through global mean temperature at sea level based on (Wygrala 1989) method. In this approach, the latitude of the studied area is required for automatic estimation. Finally, the present-day HF is determined based on the existed data, whereas paleo HF will be calculated through calibration procedure. Temperature data and vitrinite reflectance were applied as calibration dataset. The statistics of these data are presented in Table 4. To measure the vitrinite reflectance values, a standard reflected light microscope was used. The kerogen-containing rock chips were placed in epoxy resin

**Table 3** Statistics of the Kazhdumi and Gadvan formations geochemical data belong to the 13 studied wells

| | S1 (mg HC/g rock) | | | S2 (mg HC/g rock) | | | TOC (wt%) | | | $T_{max}$ (°C) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Kazhdumi | Gadvan | Total | Kazhdumi | Gadvan | Total | Kazhdumi | Gadvan | Total | Kazhdumi | Gadvan | Total |
| Minimum | 0.09 | 0.03 | 0.03 | 0.09 | 0.11 | 0.09 | 0.15 | 0.18 | 0.15 | 416 | 291 | 291 |
| Maximum | 2.21 | 13.24 | 13.24 | 26.96 | 6.8 | 26.96 | 4.95 | 2.54 | 4.95 | 442 | 587 | 587 |
| Average | 0.54 | 1.93 | 1.26 | 5.57 | 1.75 | 3.59 | 1.63 | 0.93 | 1.27 | 429 | 418 | 423 |

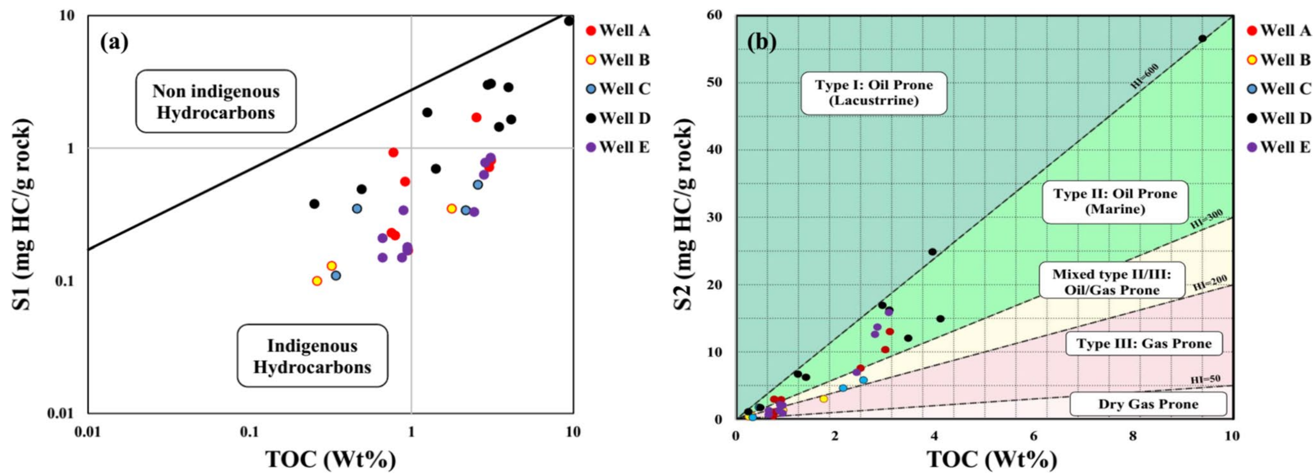



**Fig. 5** **a** S1 versus TOC plot to determine indigenous or non-indigenous hydrocarbon of the five studied wells. All the studied samples are indigenous. **b** Diagram of S2 vs TOC to determine the kerogen types. The kerogen types of the Kazhdumi Formation are mainly types II and II/III in the studied wells. To find the location of wells (A to E), please refer to Fig. 1

**Table 4** Statistics of the vitrinite reflectance and temperature data belong to the A to E wells

| | Vitrinite reflectance (%Ro) | Temperature (°C) |
|---|---|---|
| Minimum | 0.51 | 70 |
| Maximum | 0.78 | 148 |
| Average | 0.61 | 115 |

blocks. In the next step, the samples were polished using abrasive paper and powder. The reflected light by organic matters of the samples was measured using a photometer under oil immersion.

## Prediction of S1 and $T_{max}$ using artificial neural networks

Since geochemical data are not available in all wells, one can predict them through petrophysical well logs, which are always measured. Artificial neural networks are considered as proper and strong tools to learn the complicated patterns and can estimate with high precision. Artificial neural networks, which are constructed based on the human brain, consist of neurons and links. Every network includes three primary layers: (1) the input layer for receiving input data, (2) the hidden layer that can comprise multiple layers for analyzing the input data, and (3) the output layer for providing the desired results (Zeidenberg 1990). As presented in Table 2, there are only 71 samples of Kazhdumi Formation. In order to strengthen the neural network training process, 66 samples from Gadvan Formation have also been used. Therefore, 137 datasets of geochemical data (depth, S1, and $T_{max}$) belonging to 13 oil wells of 7 fields (Kazhdumi and Gadvan formations) in the Abadan Plain were used. The statistics of these data which were derived from internal NIOC report (Alizadeh 2015) are outlines in Table 3. Also, petrophysical well log data of these 13 oil wells (sonic, resistivity, density, neutron, and spectral gamma ray) were available in Kazhdumi and Gadvan intervals.

To predict S1 values using artificial neural networks, petrophysical well logs including sonic, neutron, density, resistivity and spectral gamma ray were used. Other researchers used these well logs to predict TOC values (Bolandi et al. 2015; Gholipour et al. 2016a, 2016b), and they can be considered as proper inputs to predict S1 as an indicator of generated hydrocarbon. Furthermore, petrophysical well logs, specifically sonic, neutron, density, and resistivity, are utilized to predict $T_{max}$ as a measure of thermal maturity. These well logs were previously applied to thermal maturity prediction (Hussein and Abdula 2018; Tariq et al. 2020). Moreover, since the quantity of neurons in the hidden layer greatly impacts the prediction results, several artificial neural networks were developed with differing neuron counts. The correlation coefficients of different cases were depicted in Fig. 6. As shown, 16 and 20 neurons were applied for predicting S1 and $T_{max}$, respectively. The relevant correlation coefficient values for predicting S1 and $T_{max}$ are 0.84 and 0.71, respectively.

## Results

### Assessment of relationship between abnormal pressure and hydrocarbon generation

The results of a 1D petroleum system analysis can provide significant benefits in assessing the Kazhdumi Formation as

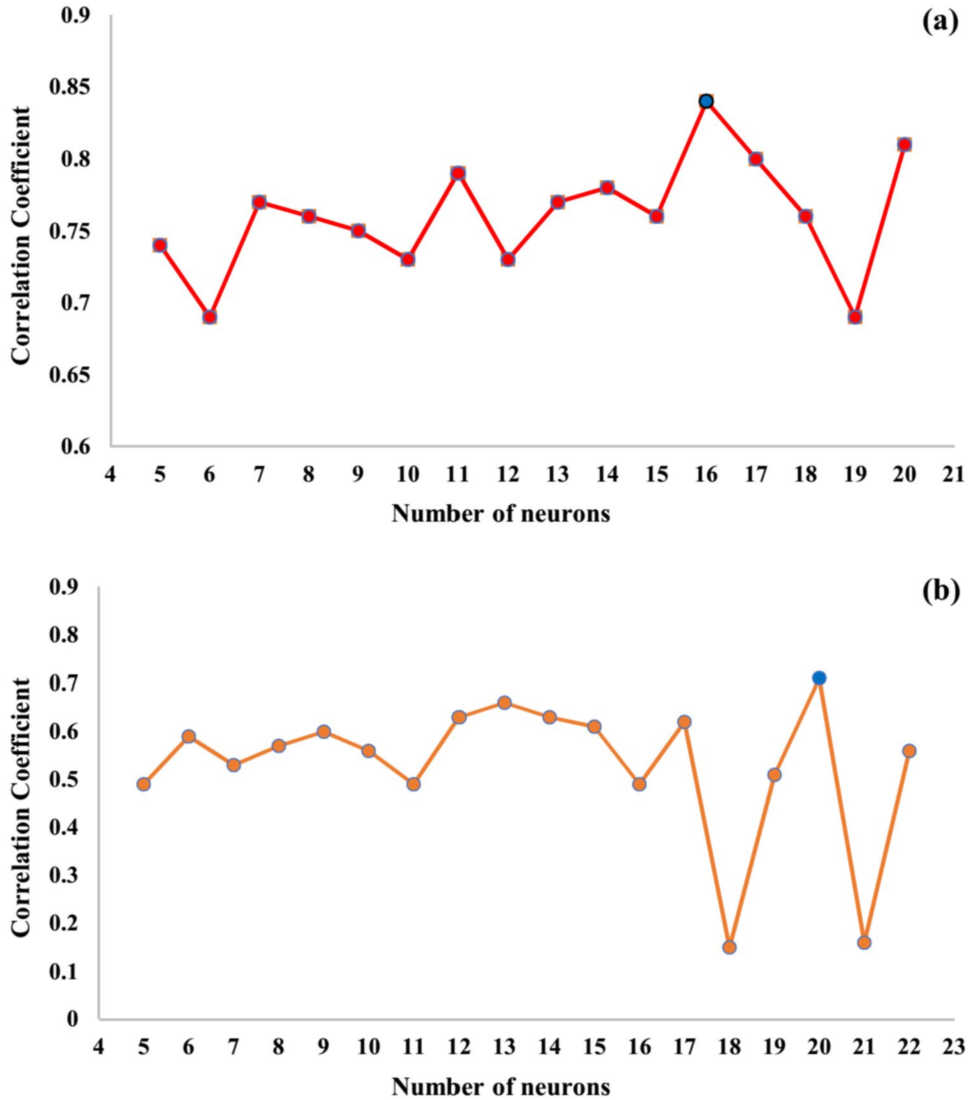
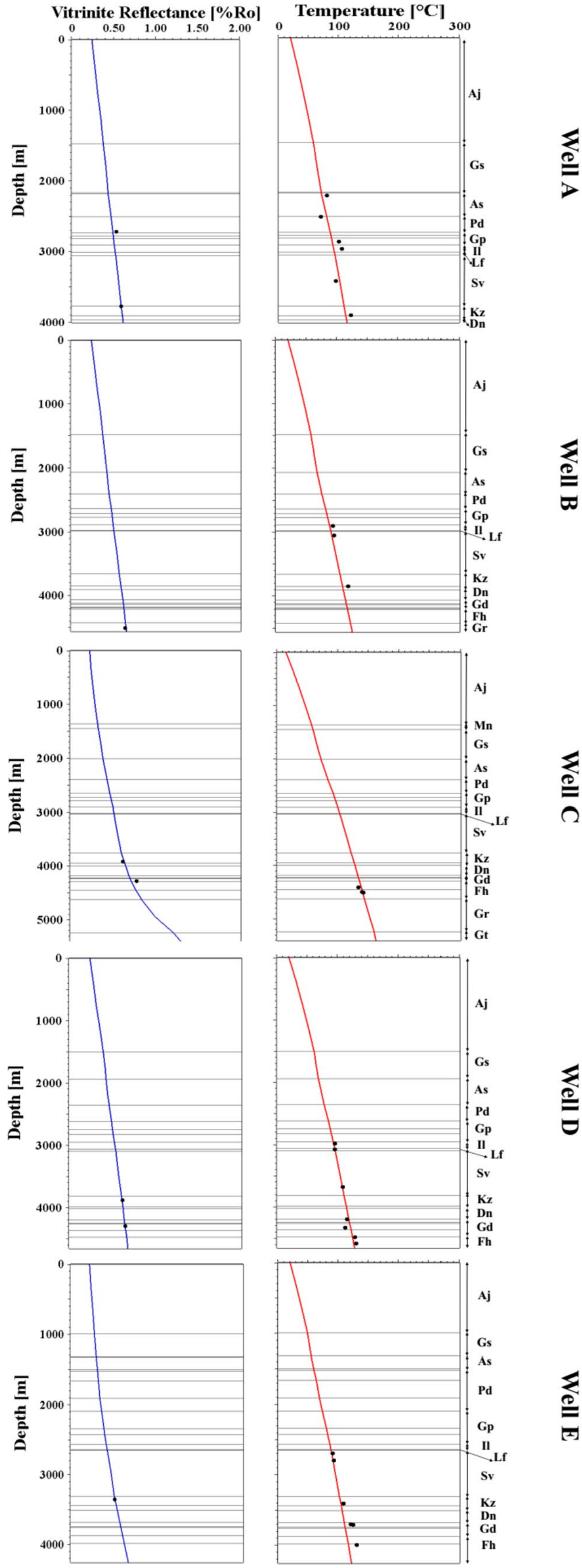



**Fig. 6** Variation of correlation coefficient values versus number of neurons for S1 (**a**) and $T_{max}$ (**b**) prediction. 16 and 20 neurons for hidden layers were selected to predict S1 and $T_{max}$, respectively

a potential source rock. However, these results would not be applicable without validating. As mentioned in the previous section, temperature and vitrinite reflectance data were used for this purpose. Figure 7 illustrates the validation of constructed models of five studied wells. In wells A, B, and D, Basin %Ro algorithm (Nielsen et al. 2017) was used to calculate the thermal variation whereas in wells C and E, Easy %RoDL (Burnham et al. 2017) and IKU %Ro (Ritter et al. 1996) were applied, respectively.

The results of the Kazhdumi Formation indicate the present-day temperature of this formation varies from 100 °C (well E) to 125 °C (well C) (Fig. 8a). Also, the thermal history of the Kazhdumi Formation is depicted in Fig. 8b. The highest maturity level belongs to well C and well D (0.62%Ro). Afterward, well A and well B possess 0.6%Ro and 0.58%Ro, respectively. The lowest amount of calculated vitrinite reflectance is for well E (0.52%Ro). These results demonstrate that the Kazhdumi Formation is immature in well E whereas, this source rock is in the early mature stage in the other wells. The curves of transformation ratio (TR) show that the values of the present day are up to 12% (Fig. 8c).

As mentioned, the lowest level of present-day maturity belongs to well E. For better comprehension, a relative location map of these five wells is shown in Fig. 9. The most burial depth of Kazhdumi Formation is approximately 3700 m in the location of wells C and D. The highest level of vitrinite reflectance values was observed in these two wells. Burial depth values of Kazhdumi Formation in well A and well B are 3680 and 3650 m, respectively, which is in accordance with their calculated vitrinite reflectance values. As mentioned, Kazhdumi Formation in well E with the lowest value of vitrinite reflectance is still immature. As depicted in Fig. 9, the top of Kazhdumi Formation in well E is 3260 m. In other words, toward north and east areas, burial depth and maturity level of Kazhdumi Formation increase.




| | |
|---|---|
| Aj | Aghajari |
| Mn | Mishan |
| Gs | Gachsaran |
| As | Asmari |
| Pd | Pabdeh |
| Gp | Gurpi |
| Il | Ilam |
| Lf | Lafan |
| Sv | Sarvak |
| Kz | Kazhdumi |
| Dn | Dariyan |
| Gd | Gadvan |
| Fh | Fahliyan |
| Gr | Garau |
| Gt | Gotnia |

**Fig. 7** Model validation using temperature and vitrinite reflectance data. The applied algorithms for vitrinite reflectance modeling are Basin %Ro (wells A, B, and D), Easy %RoDL (well C), and IKU %Ro (well E)

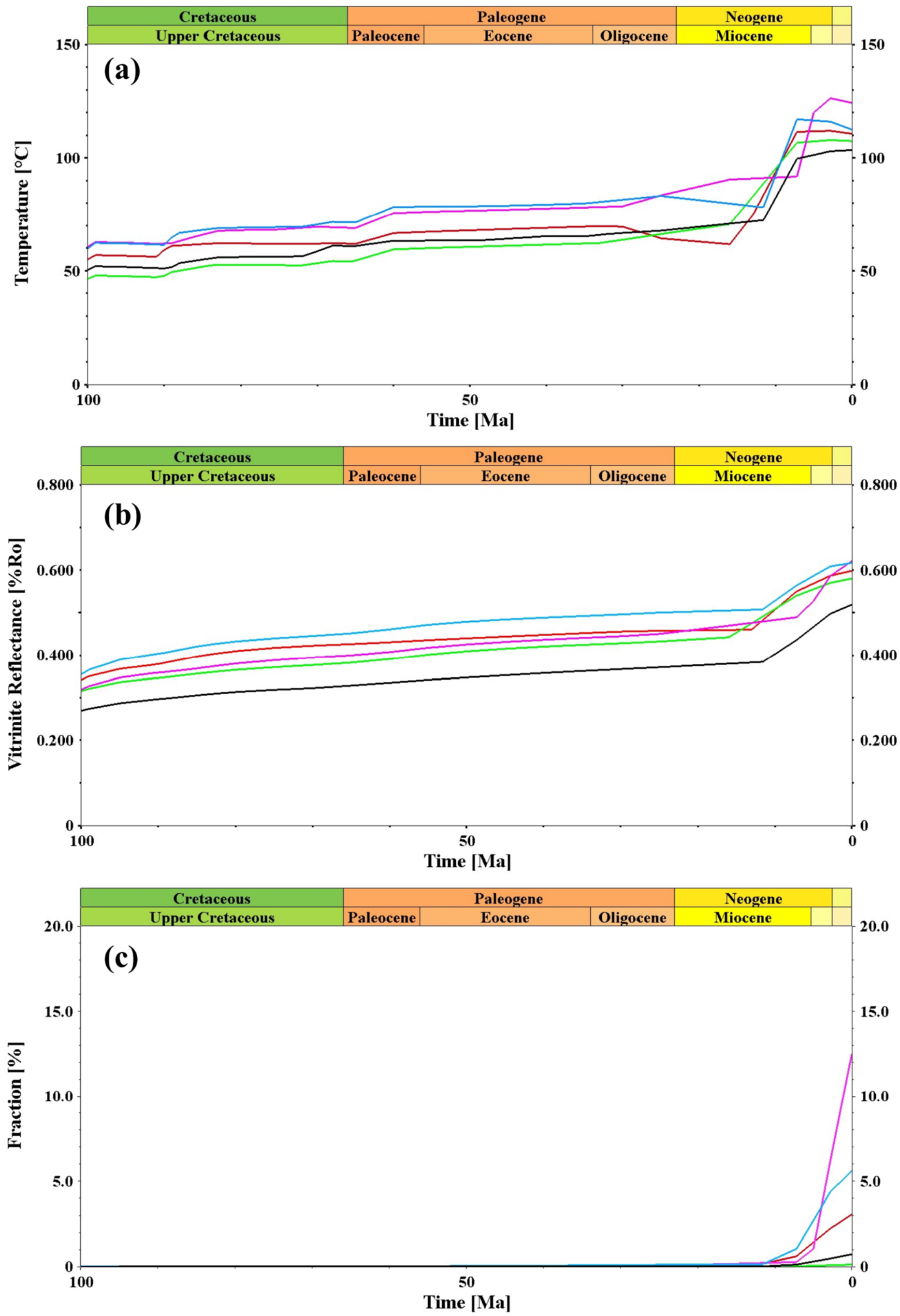



Fig. 8 Variation of temperature (**a**), vitrinite reflectance (**b**), and Transformation Ratio (TR) (**c**) during time for Kazhdumi Formation. In all three figures, the red line is Well A, the green line is Well B, the pink line is Well C, the blue line is Well D, and the black line is Well E

To achieve a great perception of the relationship between abnormal pressure and hydrocarbon generation, drilling reports of these five fields were assessed carefully. In well A, while drilling the base of the Sarvak Formation, a great amount of drilling mud gain was observed. Moreover, in the base of Sarvak Formation and top of Kazhdumi Formation, the mud weight was increased from 89 to 118 PCF, indicating an abnormal pressure in this well. Drilling mud characteristics remain constant while drilling Sarvak and Kazhdumi formations in well B. In other words, there is no evidence for abnormal pressure in this well. In well C, from the base of Sarvak Formation to top of Kazhdumi Formation, the mud weight has been increased two times. Abnormal pressure causes to increase mud weight from 85 to 100 PCF and once again from 100 to 110 PCF. In well D, Kazhdumi Formation shows the high-pressure behavior, and there was mud weight increment two times: one from 82 to 100 PCF, and the other from 100 to 105 PCF. Finally, well E does not show any abnormal pressure situation. The

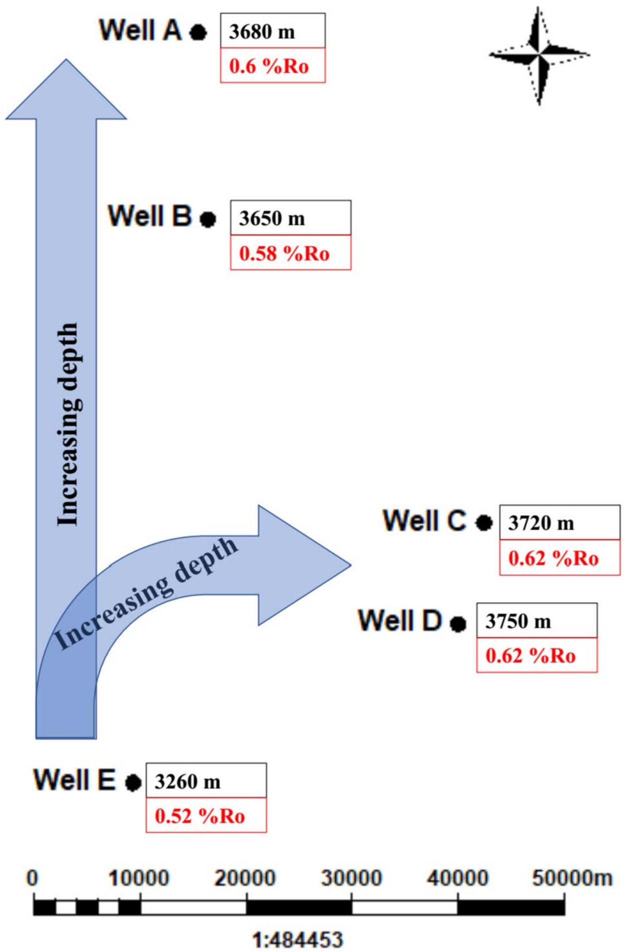



**Fig. 9** A location map of the five studied wells. Black numbers show the top of Kazhdumi Formation and red numbers show the present day calculated vitrinite reflectance. Toward north and east, the level of thermal maturity and burial depth of Kazhdumi Formation increase

mud weight value was 80 PCF from the base of Sarvak to Gadvan.

Drilling history of these five wells indicates that the Kazhdumi Formation is a high-pressure interval in wells A, C, and D, whereas the pressure of this formation is in the normal form in wells B and E. As mentioned earlier, the present-day value of the Kazhdumi Formation vitrinite reflectance in well E is 0.52%Ro indicating immature source rock. Also, there is no pressure problem based on drilling information. In wells A, C and D, the Kazhdumi Formation is early mature and these wells face pressure problem. It can be deduced that wherever the Kazhdumi Formation has reached the early mature stage, there is also the problem of abnormal pressure. Another significant point is that, in well B, Kazhdumi Formation is in the early mature stage (0.58%Ro) but has no abnormal pressure problem. This issue may seem a bit contradictory at first glance. It must be emphasized that maturity level alone is not the determining factor, and the quantity of organic matter plays a prominent role. Generally, quantity of organic matter is determined using TOC values, but since in this study, the aspect of hydrocarbon generation history is significant, the initial values of TOC are helpful. Regarding to challenges and difficulties in defining precise values of initial TOC, the S1 value as an indicator of formerly generated hydrocarbon was used. Also, previous research indicates that S1 has a positive correlation with pore pressure (Zhang et al. 2019). In the case of well B, the S1 content as an indicator of free hydrocarbon, has a scant amount (Fig. 5a). The average value of measured S1 in Kazhdumi Formation of well B is 0.18 mg HC/g rock, which shows insufficient value. Also, in well B, the average values of TOC and S2 parameters are 0.82 wt% and 1.41 mg HC/g rock, respectively. It can be deduced that the Kazhdumi Formation in well B is not a suitable source rock due to insufficient organic matter. Therefore, despite sufficient depth and temperature to enter the oil window, it did not generate hydrocarbon (due to the lack of organic matter) and did not cause abnormal pressure. This issue shows the importance of evaluating the richness of source rock along with the level of maturity. Toward the northern area, burial depth and quantity of organic matter of Kazhdumi Formation increases (Bolandi et al. 2015). Therefore, as an overall consequence, in the eastern parts, which generally have more depth and organic matter, the risk of abnormal pressure is also higher. Although various factors contribute to the presence of abnormal pressure in source rocks, our study findings demonstrate that evaluating the hydrocarbon generation can yield valuable insights in gauging the risk of abnormal pressure.

## Assessment of abnormal pressure due to hydrocarbon generation in a well without geochemical data.

As mentioned earlier, geochemical data are not available in all drilled wells. Since these types of data are vital and necessary to determine whether the abnormal pressure was due to hydrocarbon generation or not, lack of them makes it impossible to investigate this issue. However, almost all wells have petrophysical log data. In the previous section, thermal maturity and S1 values were applied to assess the abnormal pressure due to hydrocarbon generation. Here, a drilled well (well O, Fig. 1) located in Abadan Plain was investigated which, according to the drilling reports, had an unusually abnormal pressure in Kazhdumi Formation. No geochemical analysis was done in this well. To better understand, mud weight values of wells A to E, as well as well O are converted to the pressure gradient. A correlation section from these wells is shown in Fig. 10. The desired interval is shown on the figure in each well between Kazhdumi and Azadegan. The previous research in Abadan Plain shows that if the pressure gradient obtained from the mud weight is more than 13 Mpa/Km, there is an abnormal pressure interval (Atashbari 2016). In well A, the pressure gradient changes from 14.9 to 18.2 Mpa/Km. Also, in well O, this parameter increases from 14.9 to 19.6 Mpa/Km. These values show that well A and O are over pressured in Kazhdumi interval. In wells B and E, pressure gradient is 13 and 12.5 Mpa/Km, respectively. These two wells are not abnormal in Kazhdumi Formation as mentioned earlier. In wells C and D, pressure gradient of Kazhdumi Formation increases from 16 to 17.3 Mpa/Km, and 15.7 to 16.5 Mpa/Km, respectively.

Before predicting $T_{max}$ (as an indicator of thermal maturity) and S1 parameters in this well using artificial neural networks (detail procedure was explained in material and method section), the effectiveness of this method was checked using the other well. In other words, at this stage, the well information was used, which was not involved in the training process of the artificial neural network (well N, Fig. 1). With using petrophysical log data and artificial neural networks, S1 and $T_{max}$ values were predicted in this well. Then, the estimated data were compared with the measured data. The result of this comparison shows that the values of the correlation coefficient for S1 and $T_{max}$ prediction are 0.75 and 0.86, respectively (Fig. 11). Therefore, it can be concluded that the results obtained from the prediction of S1 and $T_{max}$ by artificial neural networks are reliable. In the next step, $T_{max}$ and S1 parameters were predicted in well O. Based on the drilling reports, well O faced an abnormal pressure problem during drilling of Kazhdumi Formation. Mud weight was 95 PCF at the beginning of Kazhdumi Formation drilling. Then, it was raised to 115 PCF and in the next step, to 123 PCF to overcome abnormal pressure (Fig. 12).

Predicted S1 and $T_{max}$ logs as well as SGR, DT, RHOB, NPHI, and RES were illustrated in Fig. 12. Several researchers proposed different ranges for early mature stage which can be different based on the type of Kerogen. Generally, $T_{max}$ ranges of 430–460 °C (Espitalié et al. 1986), 430–435 °C (Baskin 1997), and 430–445 °C (Killops and Killops 2013) have been reported for early mature stage. As shown in Fig. 12, predicted $T_{max}$ values of the studied well generally show the early mature stage. Also, S1 log shows high values which are indicated by transparent shapes in Fig. 12. Approximately 40% of data possess $T_{max}$ values of over 430 °C, in this well. Eventually, it can be deduced that it is possible that the abnormal pressure created in the Kazhdumi Formation in this well is also because of the generation of hydrocarbons.

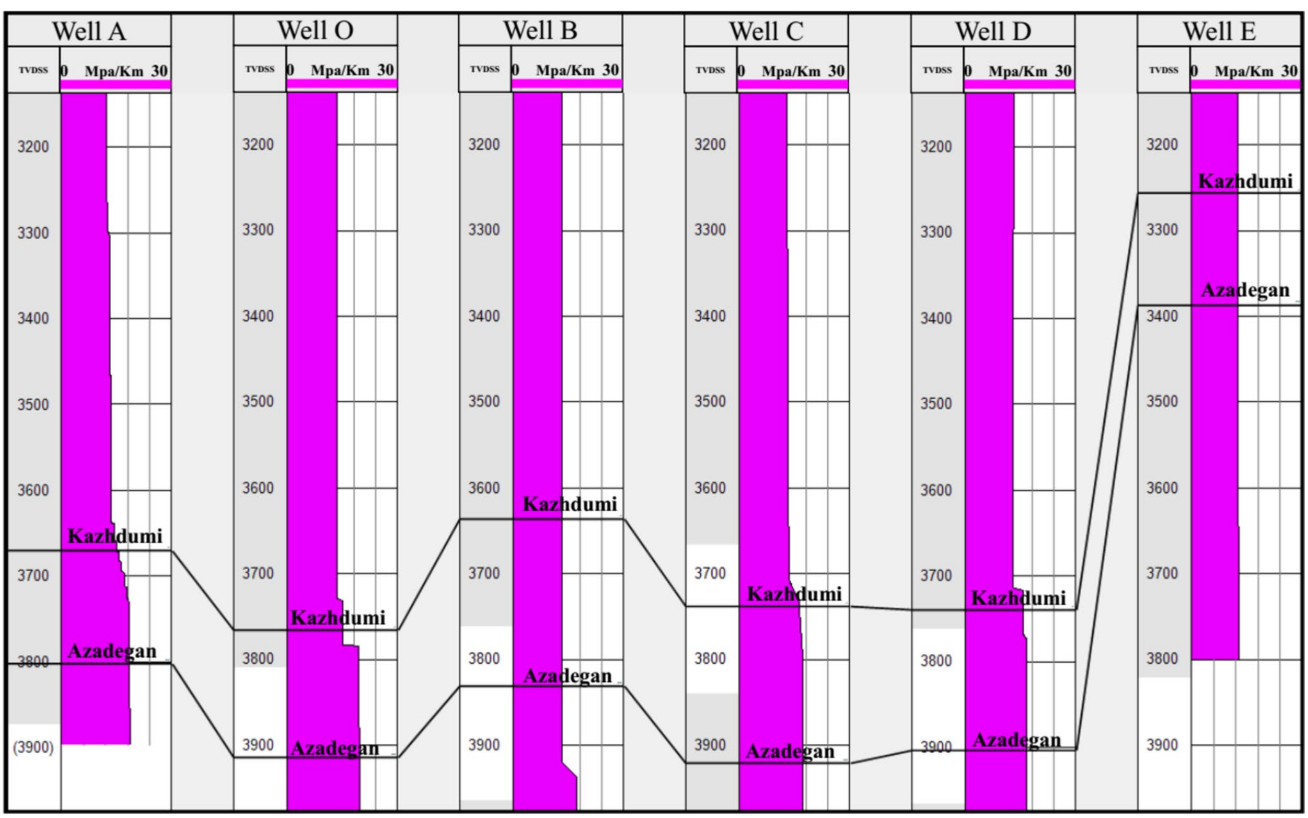



**Fig. 10** Pressure gradient variations in wells A to E, as well as well O. For the location of the section, please see Fig. 1

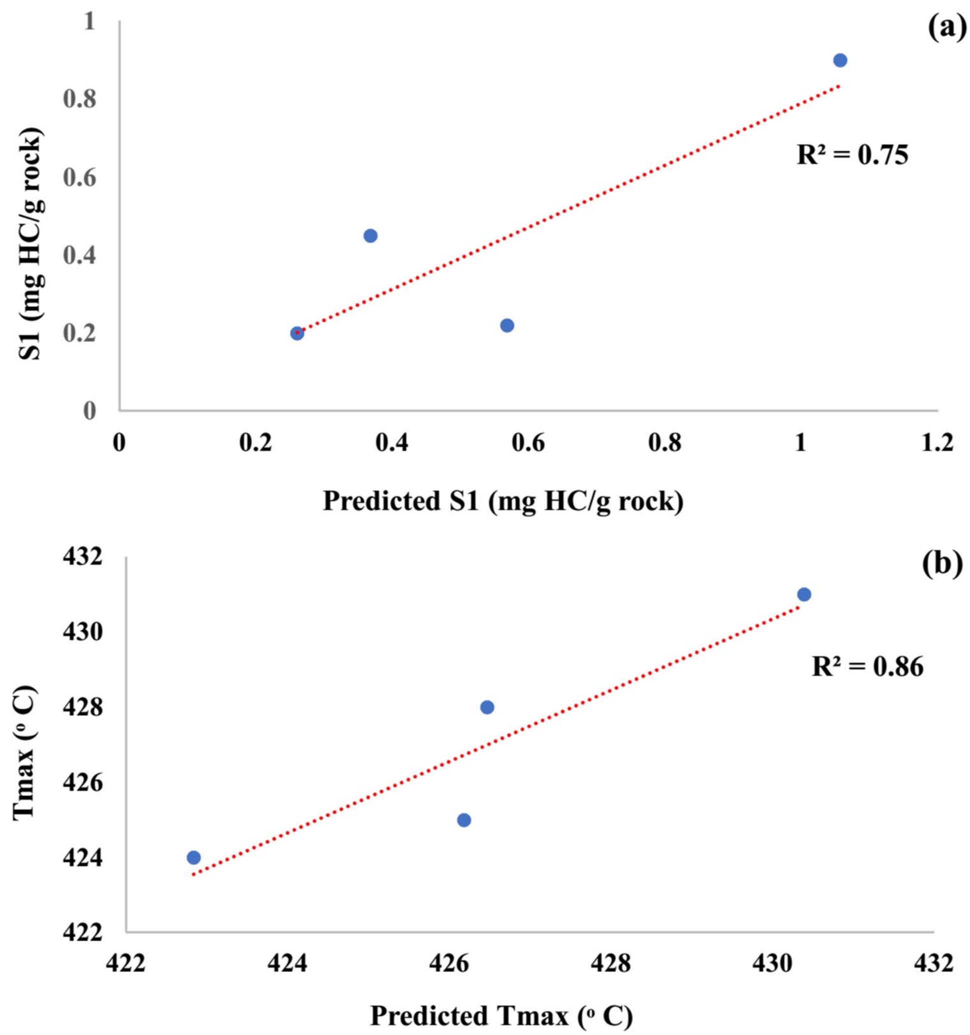



**Fig. 11** The predicted values of S1 (**a**) and $T_{max}$ (**b**) versus measured values in well N (Fig. 1), which was not involved in the training process of the artificial neural network

## Discussion

The results of this paper indicate that it can be stated in Abadan Plain, wherever the Kazhdumi Formation is mature and has enough organic matter; the risk of abnormal pressure is high. Therefore, it is better to consider this point in the future drilling operation in this area. However, it must be emphasized that the definitive determination of whether the abnormal pressure in the source rocks was due to hydrocarbon generation or not, requires comprehensive studies and detailed investigation of geology, characteristics such as porosity and permeability, three-dimensional basin modeling. However, the methods presented in this paper can be useful for achieving a general view of the source rock situation in the area and preventing their problems while drilling or reducing their probable risk in the future.

It must be emphasized that the tectonics of the adjacent region and the orogeny of Zagros may also have an effect in creating abnormal pore pressure in this area. Atashbari et al. (2018) stated that in Abadan Plain, the abnormal pressure in some formations such as Gachsaran Formation is related to the proximity to the Zagros Front Fault (to find the location of Zagros Front Fault, please see Fig. 1). In other words, moving away from Zagros is associated with normal pressures in Gachsaran Formation. Also, they concluded that being close to Zagros Front Fault does not have a special effect on the abnormal pressure changes of other formations such as Gadvan and Fahliyan formations in this area, since these two formations have abnormal pressure in the entire region. However, tectonic activity may amplify the pore pressure in this area (Atashbari 2016).

Atashbari (2016) concluded that the primary mechanism of overpressure especially in Gachsaran Formation is disequilibrium compaction which is affected by Zagros orogeny and tectonic activity. Also, it is possible that the kerogen maturation has an effect in creating the abnormal pressure of the Gadvan Formation, which plays a source rock role in this area. Atashbari's studies provide valuable information about abnormal pressure in Abadan Plain area. However, no study has been conducted in Abadan Plain regarding the

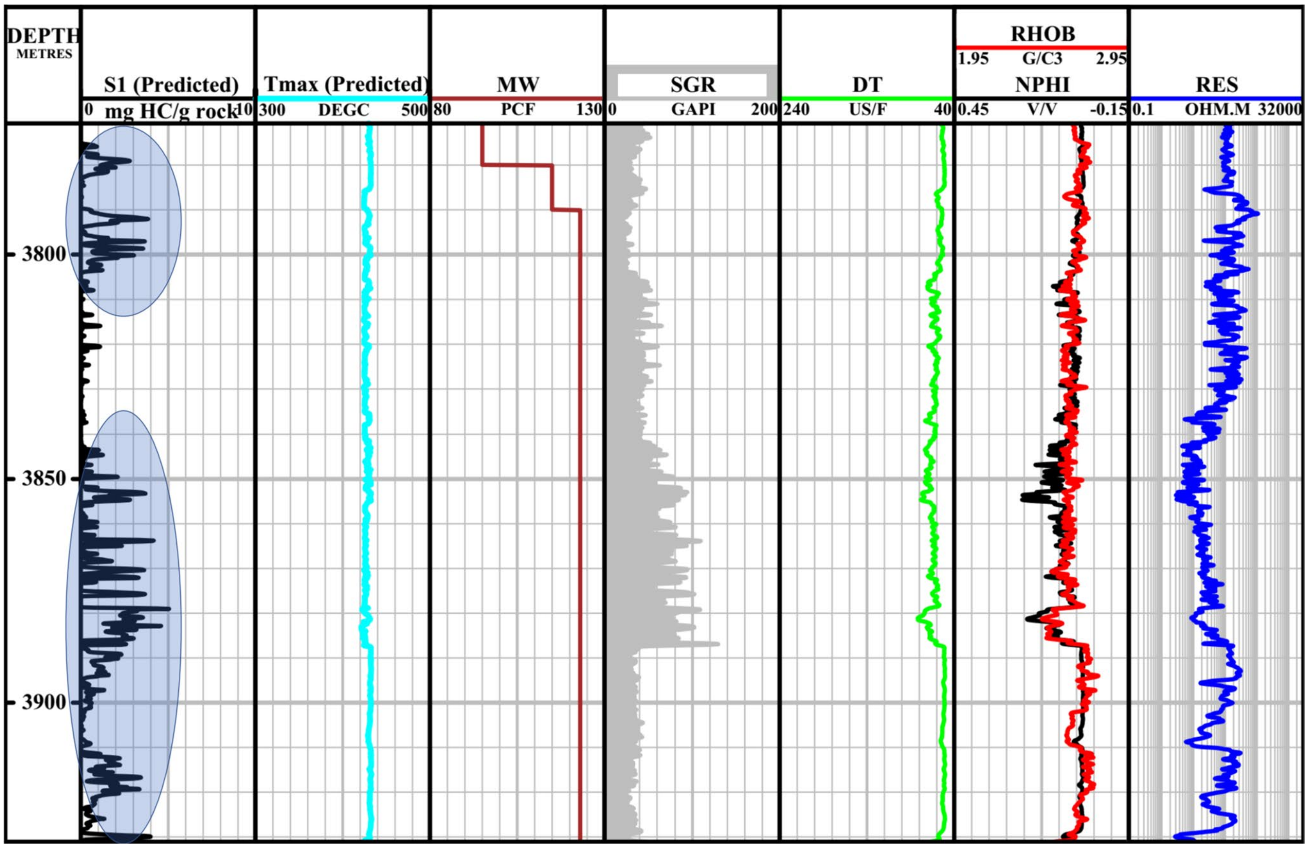



**Fig. 12** Predicted S1 and $T_{max}$ logs as well as MW (mud weight), SGR (spectral gamma ray), DT (sonic), RHOB (density), NPHI (neutron), and RES (resistivity) in well O. To find the location of this well please refer to Fig. 1. The transparent shapes indicate high values of S1

abnormal pressure of Kazhdumi Formation. Summarizing the results of this paper and other studies that have been done in this area show that hydrocarbon generation may be considered as a factor of creating abnormal pressure in Kazhdumi Formation.

## Conclusions

The current study made a qualitative and quantitative formulation between hydrocarbon generation and overpressure in the Kazhdumi Formation. In this regard, geochemical concepts have been used to investigate the role of the source rock in creating abnormal pressures. In this paper, an attempt has been made to find a logical relation between hydrocarbon generation and abnormal pressure using tools such as 1D petroleum system modeling. The followings are concluded:

- The results of 1D petroleum system modeling of the five studied wells in Abadan Plain show that the Kazhdumi Formation is in an early mature stage in four wells (located in the northern and eastern sections) and is immature in one well (located in western section).
- Assessing geochemical data represents that the Kazhdumi Formation is not a source rock with sufficient organic matter in the entire studied area (e.g., in well B).
- Kazhdumi Formation has a greater burial depth toward the northern and eastern parts.
- No abnormal pressure was recorded in the Kazhdumi Formation in wells E and B. The former is due to the immaturity of the Kazhdumi Formation, and the latter is due to the lack of organic matter.
- In Abadan Plain, in wells in which Kazhdumi Formation possesses enough organic matter and enters to early mature stage, the risk of abnormal pressure should strongly be considered. The risk of abnormal pressure (due to hydrocarbon generation) can be assessed using petrophysical well logs in the absence of geochemical data (using artificial neural networks).
- In drilling subsequent wells in this area, abnormal pressures must be considered while drilling the source rock formations.

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## Declarations

**Conflict of 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.

**Ethical statements** This material is the authors' own original work, which has not been previously published elsewhere. The paper is not currently being considered for publication elsewhere. The paper reflects the authors' own research and analysis in a truthful and complete manner. The publication of this manuscript does not engage in or participate in any form of malicious harm to another person or animal.



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