Marine and Petroleum Geology 153 (2023) 106312

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Orbital obliquity evolution during the late Paleozoic ice age across the northeastern gondwana: Implications for regional sea-level change trigger and reservoir quality assessment

Omid Falahatkhah[a], Masoud Serajamani[b], Ali Kadkhodaie[c,*], Tahar Aïfa[d], Shermineh Ebrahimi[e], Ali Asghar Ciabeghodsi[e], Seyed Mohammad Zamanzadeh[f], Ebrahim Sfidari[g], Mohammad Vahidinia[a], Abbas Ghaderi[a]

[a] Department of Geology, Faculty of Science, Ferdowsi University of Mashhad, Mashhad, Iran
[b] Department of Earth Sciences, Institute for Advanced Studies in Basic Sciences (IASBS), Zanjan, 45137-66731, Iran
[c] Earth Sciences Department, Faculty of Natural Sciences, University of Tabriz, Tabriz, Iran
[d] Univ Rennes, CNRS Géosciences Rennes – UMR 6118, Bat.15, Campus Beaulieu, F-35000, Rennes Cedex, France
[e] Department of Geology, Faculty of Sciences, Urmia University, Urmia, Iran
[f] School of Geology, College of Science, University of Tehran, Tehran, Iran
[g] Petroleum Geology Research Group, Research Institute of Applied Sciences, ACECR, Iran

ARTICLE INFO

Keywords:
Amplitude modulation cycles
Lower permian
Depositional noise event
Astrochronology
Middle east

ABSTRACT

Orbitally-induced cycles build stratigraphic sequences on time spans ranging from several thousand to several million years by altering depositional conditions. Previous works have shown that the gas-bearing Faraghan Formation (Cisuralian) has been impacted by orbitally-forced climatic change, resulting in the development of sedimentary sequences on astronomical cycle timescales. Obliquity evolution has been observed in the Faraghan Formation, with ~1.2 Ma and ~173 ka modulation cyclicities recorded. We attribute a strong sedimentary noise observed in the Faraghan Formation, which is distinct from the other noises, to a transregional sea-level rise, most likely correspond to MFS P10. The prolific gas zones (PGZ) in the Faraghan Formation are in consistent relationship with obliquity maxima and depositional noise events, which are associated with high obliquity power. This constant offers the hypothesis that obliquity altered the sedimentary regime in such a way that favorable conditions for reservoir quality development occurred. The ~173 ka obliquity modulation cycle is recorded from the Late Paleozoic. It is postulated that this periodicity was the causal mechanism for the creating of the Faraghan Formation's fifth-order sequences. The reconstructed sea-level patterns from sedimentary noise modeling (DYNOT) confirm the three third-order sequences proposed for the Faraghan Formation by displaying three different sedimentary noises. The detected ~1.2 Ma obliquity modulation cycles match the ~1.2 Ma periodicities filtered from the DYNOT median values, indicating that the ~1.2 Ma orbital cycle is one of the primary drivers of regional sea level. ~1.2 Ma obliquity modulation cycles are correlated with third-order sequences, implying that the aforementioned cycle was one of the key mechanisms causing the creation of these third-order sequences.

1. Introduction

One of the pivotal periods in Earth's history is the Cisuralian. It was characterized by tectonic activity and global phenomena like eustatic sea-level variations, dramatic paleoenvironmental and paleoecological shifts, and icehouse conditions (Henderson et al., 2012). During the Carboniferous-Permian, a lengthy glaciation with a duration of ~67 Ma occurred across Gondwana (Roy and Roser, 2013). In this regard, Carboniferous strata in the studied area are distinguished by a gap, the cause of which has been linked to the late Carboniferous glacial episode. The aftermath of this glaciation included rapid sea-level fall, activation of erosional processes, and erosion of all Lower/Middle Carboniferous rocks in this region (Ruban et al., 2007). A high-resolution cyclostratigraphy of the Cisuralian Faraghan Formation was performed in six

* Corresponding author.
E-mail address: kadkhodaie_ali@tabrizu.ac.ir (A. Kadkhodaie).

https://doi.org/10.1016/j.marpetgeo.2023.106312
Received 23 November 2022; Received in revised form 3 May 2023; Accepted 5 May 2023
Available online 6 May 2023

subsurface sections in the Persian Gulf region for this study. This work analyzes the orbitally-forced paleoclimatic and paleoenvironmental changes, depositional noise events, sedimentary conditions, and astronomical cycle characteristics (the percent of powers and checking their phases). In addition to these cases, it assesses the sediment accumulation rates, the likelihood of astronomical cycles influencing the production of hydrocarbon materials, and the sequence stratigraphic framework of the Faraghan Formation. Although astronomically forced cycles are recognized as a key parameter in controlling sea level variations, depositional conditions, and the formation of stratigraphic sequences, their relevance and significance in the oil industry and hydrocarbon exploration remain unknown. This work proposes hypotheses concerning the possible significance of orbital cycles in favorable sedimentary conditions for the developing of prolific gas zones in the Faraghan Formation. Numerous stratigraphical processes were cyclic in nature and occurred repeatedly during a sedimentary sequence, and their development or disappearance have been interpreted to correspond to the maxima or minima of orbitally-induced cyclicities. Among these are the correspondences of occurrences of sapropels with precession minima (Bosmans et al., 2015) or obliquity maxima (Tuenter et al., 2003), wildfire activity with eccentricity and precession maxima (Hollaar et al., 2021), glacial period termination with obliquity maxima (Drysdale et al., 2009), singular lithologies such as homogeneous marls with precession maxima (Hilgen and Krijgsman, 1999), and etc. In addition to having a strong influence on the paleoclimate system and paleoenvironmental changes, orbitally-induced cycles can also influence the vertical heterogeneity of reservoir deposits, and if these extrinsic parameters are discovered, they can help predict reservoir features (Zhang. et al., 2022a). Fo r example, in the Eocene siliciclastic reservoir deposits of China's Bohai Bay Basin, lime mudstones were deposited during precession maxima, and mudstones were deposited during precession minima, this has caused mudstones to lead to reservoir deposits with higher porosity and oil concentration (Zhang. et al., 2022a). We also follow the idea that the prolific gas zones in the Faraghan Formation are cyclic and may develop with obliquity maxima.

This study's subsurface sections (in northeastern Gondwana) were influenced by the Intertropical Convergence Zone (ITCZ) during the Permian in the equatorial region. Climatic and tectonic evolution provided favorable conditions for the emergence of the megamonsoon event during this period (Kutzbach and Gallimore, 1989). The dominant megamonsoon affected the climate of the equatorial region by causing a seasonal latitudinal shift in the ITCZ, which regulated temperature, rainfall, and wind patterns (Gibbs et al., 2002; Fang et al., 2018 and references therein). Abadi et al. (2021) found a high-amplitude orbitally-forced climate evolution, along with changes in glacial-interglacial periods and the growth and retreat of ice sheets, in the sedimentary record of Iran's Late Paleozoic (Pennsylvanian-Lopingian) Central Persian Terranes along the northeastern Gondwana margin. Typically, glacial-interglacial cycles are a favorable background for developing obliquity-forced climate change (Lee and Poulsen, 2009). Considering the extraction of light oil and gas from equivalent sedimentary sequences of the Faraghan Formation in the surrounding countries of the Persian Gulf, this formation has been the focus of Iranian and overseas geologists as a potential reservoir unit in recent years.

2. Geological background

The subsurface sections for this research were located during the

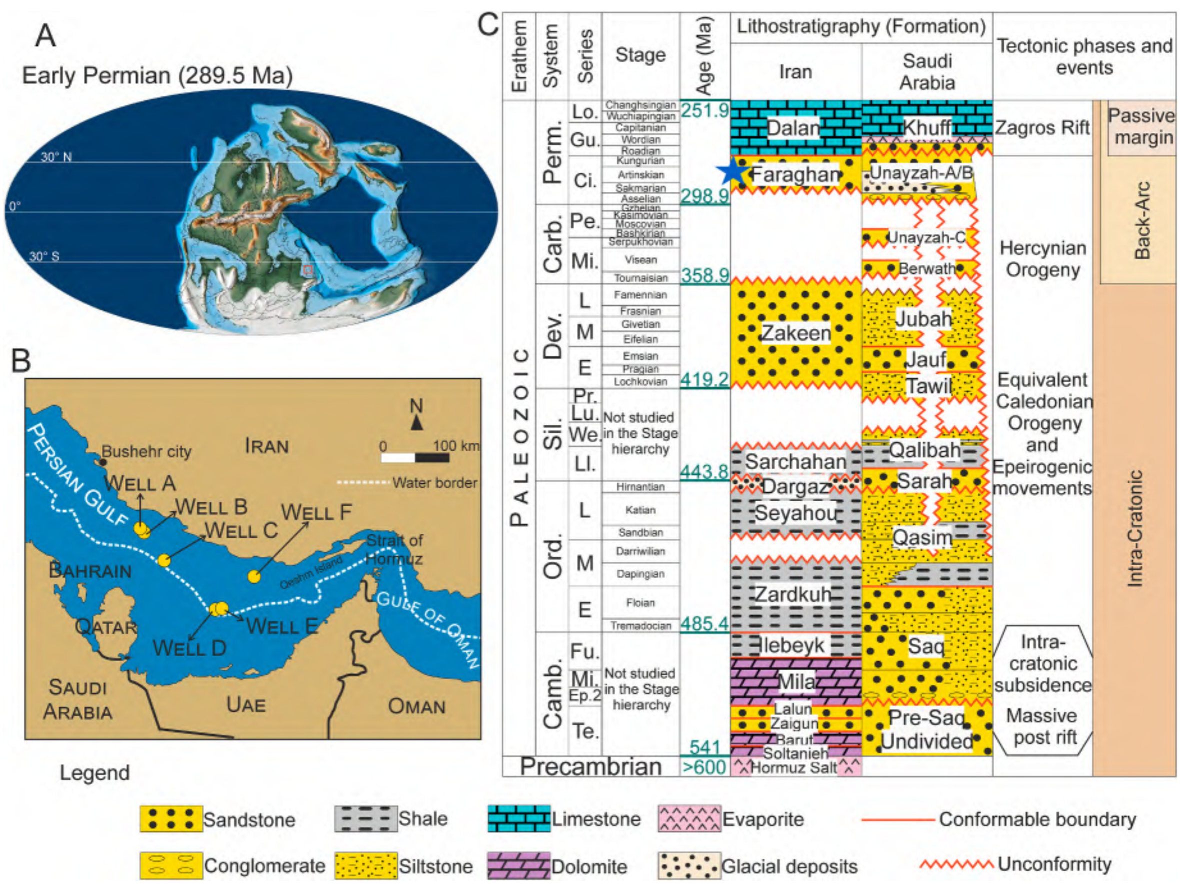

Fig. 1. (a) Global paleogeographic map for the Early Permian after Scotese (2014). The location of the studied sedimentary rocks is shown in the Early Permian paleogeographic map with red box. (b) Location map of the studied wellbores (yellow circles) in the Persian Gulf (modified from Peyravi et al., 2016). (c) Generalized stratigraphic chart and tectonic events of the Paleozoic successions in the Zagros area, SW Iran, the Faraghan Formation is marked with a blue star (compiled and modified from Abu-Ali et al., 1999; Sharland et al., 2001; Ghavidel-Syooki et al., 2011; Asghari, 2014; Vennin et al., 2015).

Permian in the mid-latitudes, across northeastern Gondwana close to the Paleotethys (Fig. 1a). The studied wellbores were chosen from Iran's significant gas fields in the western (Golshan gas field), central (South Pars gas field), and eastern (Salman and Kish gas fields) parts of the Persian Gulf (Fig. 2). Two wells from the Golshan field (wells A and B), one from the South Pars field (well C), two from the Salman field (wells D and E), and one from the Kish field (well F) were explored in this study. The Faraghan Formation at studied subsurface sections has 112.7 m, 150.7 m, 120.8 m, 83.7 m, 123.1 m, and 75.8 m thicknesses at wells A, B, C, D, E, and F, respectively. Following the Carboniferous-Permian Gondwana glaciation, terrigenous deposits [e.g., Faraghan Formation and A-B members of Unayzah Formation (Fig. 1)] spread as the first sediments on the Arabian Plate. These sediments settled with an angular unconformity on older Paleozoic rocks (Al-Husseini, 1992; Asghari, 2014). In this regard, the siliciclastic deposits of the Cisuralian Faraghan Formation formed in the initial phases of sea-level rise within the Zagros Basin (Heydari, 2008). The Faraghan Formation consists of alternating sandstone, shale, and subordinate limestone (Ghavidel-Syooki, 2003). However, limestone was not present in our studied subsurface sections. This formation in the Arabian Plate nomenclature is equivalent to A and B members of the Unayzah Formation in Saudi Arabia and the Haushi Group in Oman (Szabo and Kheradpir, 1978; Al-Laboun, 1987). The Faraghan Formation was deposited with an explicit discontinuity on the Devonian (Lochkovian to Frasnian) Zakeen Formation (Ghavidel-Syooki, 2003) (Fig. 1c). In this regard, based on palynostratigraphical research, Ghavidel-Syooki (1994) has reported a 70–80 Ma hiatus across the Zakeen and Faraghan Formations. However, other palynological researches have indicated the presence of Lower Carboniferous (Mississippian) strata in the region (Sabouri et al., 2014; Sabbaghiyan and Aria-Nasab, 2019). This hiatus is linked with the Carboniferous-Permian Gondwana glaciation (Ruban et al., 2007). The Faraghan Formation is overlain by the fossiliferous carbonate deposits of the Dalan Formation (Guadalupian-Lopingian) (Fig. 1c) (Zamanzadeh, 2008).

The Faraghan Formation exhibits a retrogradational stacking pattern (deepening upward, compared to the underlying lithostratigraphic unit [Devonian Zakeen Formation with similar lithology]), which resulted from the relative sea-level rise that continued up into the Lopingian in the study area (Zamanzadeh, 2008). Based on sedimentological and petrographic studies in the Zagros region, the depositional environment of the Faraghan Formation is a shallow marine coastal shelf, and more specifically, the sub-environments of the coastal plain, delta, alluvial plain, estuarine, tidal flat, lagoon, and shoreface (Zamanzadeh, 2008a, 2008b; Asghari, 2014; Zoleikhaei et al., 2015).

Based on detailed palynological studies, the age of the Faraghan Formation in the Zagros region has been determined to be Cisuralian (Sakmarian to Kungurian) by Ghavidel-Syooki (1984), 1988. He has established the pollen/spore assemblage zone P1 (Hamiapollenites-Vittana) based on the disappearance of all the Devonian palynomorph taxa and the appearance of the Cisuralian marker species of pollen and spore (Hamiapollenites perisporites, Hamiapollenites saccatus, Corisaccites alutas, Vittatina subsaccata, Mabuitasaccites ovatus, Tiwariasporites flavatus, Caheniasaccites ellipticus, Potonieisporites granulatus, Boutakoffites elongatus, Fusacolpites fusus, Striomonosaccites triangulais; Laevigatosporites vulgarris) and has determined the age of Faraghan Formation as Cisuralian. In this study, we follow him and use the age of assemblage zone P1 (Hamiapollenites-Vittana) for the Faraghan Formation. However, there is still disagreement about the exact age of this formation, and other researchers such as Szabo and Kheradpir (1978), who believed the Carboniferous age for the Faraghan Formation. In contrast, Spina et al. (2018) assessed the lower and middle parts of the Faraghan Formation as Roadian?-Wordian OSPZ5 Biozone and the upper part to the Wordian?-Capitanian OSPZ6 Biozone in a rather extensive analysis based on palynofloras assemblages. Sabbaghiyan and Aria-Nasab (2019) also related the lower part of the Faraghan Formation to the Early Carboniferous by recording spore species of Radiizonates arcuatus, Spelaeotriletes triangulus, Spelaeotriletes balteatus, Spelaeotriletes arenaceus and Aratrisporites saharaensis, and comparing it to the Berwath Formation in Saudi Arabia in another palynological investigation.

3. Materials and methods

3.1. Gamma-ray log analysis

The spectral gamma-ray (SGR) log records the concentrations of radioactive isotopes of uranium (^{238}U), thorium (^{232}Th), and potassium (^{4}K) in stratigraphic successions (Li et al., 2019b). Geologists extensively use the SGR log in subsurface and outcrop sections in stratigraphic correlation, cyclostratigraphic, sequence stratigraphic analysis, facies

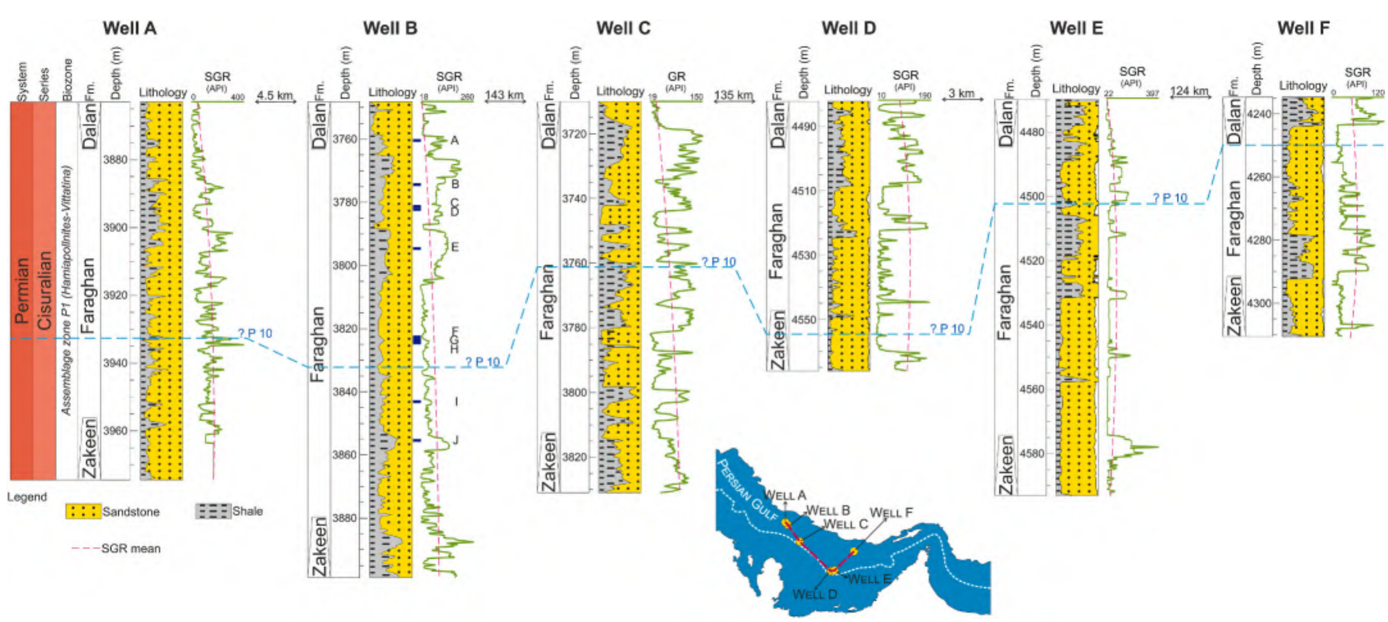

Fig. 2. Stratigraphic columns of the studied subsurface sections. Pollen biozone is from Ghavidel-Syooki (1984, 1988). The position of ? MFS P10 in each well is interpreted through the DYNOT model.

identification, paleoclimate and paleoenvironmental studies (Šimíček et al., 2012; Falahatkhah et al., 2021a and references therein). The SGR log is particularly sensitive to organic matter-rich shales that are highly radioactive (with higher gamma-ray values), so it easily distinguishes organic-rich shales from clean shales. In contrast, dolomites, limestones and clean sandstones with lower radioactivity are characterized by low gamma ray readings (Šimíček et al., 2012; Li et al., 2019b; Falahatkhah et al., 2021a). SGR log data were used for cyclostratigraphic analysis in all wells except C, and a natural gamma-ray (GR) log was used in well C due to a lack of SGR log data. The GR log records the same chemical elements as the SGR, but it cannot separate them and instead shows the total gamma radioactivity produced by the sediments.

3.2. Sedimentary core analysis

In Well B, 88 m of Faraghan Formation were cored. Among the studied core's main factors are the transition in lithological features from sand to shale and vice versa, as well as the sharp change. The sedimentary structures visible in the cores are lamination, stratification (cross, parallel, wavy, and flaser), a rare amount of bioturbation, and pyritization. Some cores photos of the Faraghan Formation are presented in Fig. 3.

3.3. The evolutionary correlation coefficient (eCOCO) map for an estimate the sediment accumulation rate (SAR)

The eCOCO maps, which track changes in SAR along the strata, calculate the correlation coefficient between the power spectrum of proxy time series and orbitally related series using a sliding window (Li et al., 2019a). Using the eCOCO map implemented in the Acycle, the null hypothesis of no astronomical forcing is examined using a Monte Carlo simulation method, and the number of joint astronomical parameters in the estimated SAR is taken into consideration. In this method the proxy series are used to measure the astronomical nature of the sedimentary cycles, and accordingly, it is possible to predict how SAR has evolved along the stratigraphic sequence (Li et al., 2019a). The eCOCO maps were used to track the average sediment accumulation rates (Li et al., 2019a).

3.4. Time series analysis

We used the Acycle software package (Li et al., 2019a) to carry out signal processing techniques and time series analysis. The well logs were detrended by applying a 30–40 m rLOESS filter (Li et al., 2019a). The multitaper method (MTM) and harmonic F-test analysis (Thomson, 1982) were performed in conjunction with robust noise modeling (Mann and Lees, 1996) for power spectral analysis in-depth and time domain. To recognize cyclic frequency fluctuations in the stratigraphic domain and to distinguish the changes in sedimentation rate, the Evolutionary Fast Fourier transform (eFFT) spectrograms (Kodama and Hinnov, 2015) have been implemented. To recognize the frequency of astronomical cycles in the time domain, the wavelet transform (WT) scalogram for the 405 ka tuned SGR series was utilized (Torrence and Compo, 1998). Th e Hilbert transform technique (Kodama and Hinnov, 2015) was used to separate the interpreted orbital cycles. The spectral moments (SM) method in the "Polynomial" model was also used to trace the SARs (Sinnesael et al., 2018). The SM analysis was developed by Sinnesael et al. (2018) and used to reconstruct the first-order variations in sedimentation rates. The power decomposition analysis (PDA) method was performed to test the sensitivity of petrophysical well logs to astronomical forcing variations (Li et al., 2019a). Coherence and cross-phase spectrum analysis were used to find phase relationships in the orbital band and our data (Huybers and Denton, 2008). The dynamic noise after orbital tuning (DYNOT) and lag-1 autocorrelation coefficient (ρ_1) sea-level models were used to analyze hidden sedimentary noise in the 405 ka tuned SGR series at studied wells (Li et al., 2018).

The stable eccentricity with periods of 405 ka and ~100 ka remains intact during the stratigraphic record due to Jupiter's enormous mass and other planets (Laskar et al., 2004). Likewise, we used the long-eccentricity (405 ka) and short-eccentricity (~100 ka) along with periodicities of the estimated obliquity (35.5 ka) and precession (21.7 ka and 17.66 ka) by Waltham (2015) for astronomical target periods of the Early Permian.

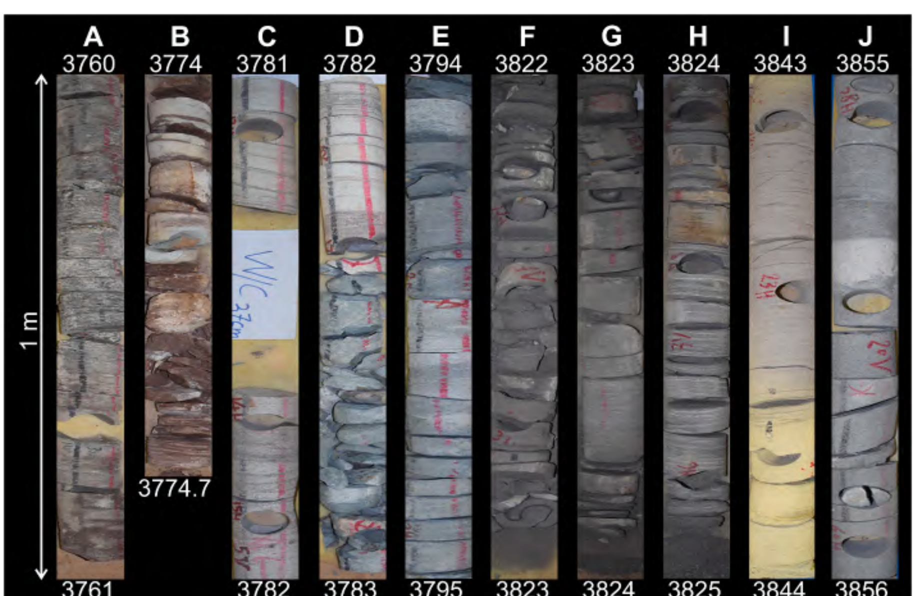

Fig. 3. Some core slab photographs of the Faraghan Formation at Well B. The successive alternations of shale and sand and existing laminations are the main features that can be seen in the photos. The exact location of each core slab in Fig. 2 on Well B is marked with small dark blue boxes.

4. Results

4.1. Estimated SARs of the Faraghan Formation through eCOCO maps and SM methods

The eCOCO maps were applied in tested SARs ranging from 0 to 20 cm/ka (with a step of 0.13 cm/ka) to raw SGR data to estimate the SARs of the Faraghan Formation in the studied wells. At a glance, the eCOCO and evolutionary H_0-SL maps appear to express nearly identical sedimentation rates, but the strong spectral powers that reveal the trend of SAR suggest that the SAR in three wells A, E, and F (Fig. 4 a, e, and f) was relatively higher than the other three wells (Fig. 4b, c, d). Based on this, the sedimentation rates of the Faraghan Formation have been estimated to range between ~3 cm/ka and ~18 cm/ka. The number of orbital parameter maps (in eCOCO analysis) of the investigated wells show a remarkably similar pattern, and their number is probably greater than the four parameters (Fig. 4). The SM analysis can complement the COCO method for estimating average sedimentation rates (Wang et al., 2020). For SM analyses, we used an absolute sedimentation rate of 10.4 cm/ka. This sedimentation rate is obtained from the result of the average rates of the COCO method. The SM method was applied for the SGR data in the wells D and E (Fig. 9).

4.2. Time series analysis in-depth and time domain for the Faraghan Formation

The spectral analysis of the untuned SGR series at Well B exhibits significant sedimentary cycles at 44.9 m, 17.5 m, 10.4 m, 3.9 m, 2.0 m, 1.6 m, and 1.4 m (Fig. 5B). The harmonic F-test analysis results provide strong support for all of these cycles; also, they have 95% confidence levels. Falahatkhah et al. (2021b) from the Guadalupian-Lopingian Dalan Formation (the upper stratigraphic unit of the Faraghan Formation) discovered the 405 ka long-eccentricity cycles in the Persian Gulf's central part with a domain of 48 m–51 m. According to this point, the cyclicity of 44.9 m can be interpreted as a long-eccentricity cycle. The 17.5 m cycle is an exceptional modulation of the obliquity cycle, observed only once in Paleozoic rocks (Wei et al., 2023). This cycle can be identified with domains between 17.5 and 19.4 m in all six studied wells (Fig. 5). According to the amplitude ratio of a long-eccentricity cycle, 10.4 m and 3.9 m periodicities are considered as 100 ka short eccentricity and obliquity cycles, respectively. The 2.0 m, 1.6 m, and 1.4 m cycles with lower amplitudes are attributed to precession. Other results obtained from spectral analysis in the depth domain at wells A, C and E are explained similarly to these results. In addition, the spectral analysis results in the depth domain for wells A, C and E wells are clearly presented in Fig. 5A, C, and D.

Spectral analysis of 405 ka tuned SGR series at Well B indicates the traditional orbital cycles (long-eccentricity, short-eccentricity, obliquity and precession) along with the rare ~173ka modulation of the obliquity cycle, which have confidence levels above 95% (except short-eccentricity cycle) and are supported by the background of high F-test values (Fig. 5F). Similar cycles are known in other wells with 405 ka tuned SGR series, and the spectrum analysis results in the time domain for wells A, C, and E are shown in Fig. 4 E, G, and H, respectively.

The Taner-Hilbert transform was used to extract long-eccentricity, short-eccentricity, and obliquity orbital cycles from the 405 ka tuned SGR series (Fig. 6). The frequencies of the orbital cycles discovered by spectral analysis in all six wells can be traced in the WT scalograms of the 405 ka tuned SGR series, as shown in Fig. 6. Interestingly, the 173 ka obliquity amplitude modulation cycle with significant spectral strengths can be distinguished.

4.3. Revealing the orbital forcing sensitivity of well log records by the PDA method

The PDA method, developed by Li et al. (2019a), tests sensitivity to astronomical forcing variations by evaluating orbital forcing versus the total power ratio of multiple paleoclimate proxies. The PDA approach was applied to 405 ka tuned SGR series in all six wells, revealing the varied power ratios of orbital cycles (Fig. 7). In PDA analysis, the amplitudes of precession, obliquity, short-eccentricity, and long eccentricity can be detected in the power ratio of the well log records, which can be a crucial clue to an astronomical forcing indicator. The spectral powers of the 405 ka tuned SGR series eFFT spectrograms demonstrate the frequency of astronomical cycles in all subsurface sections (Fig. 7). The Faraghan Formation's varying sedimentation rates can be inferred

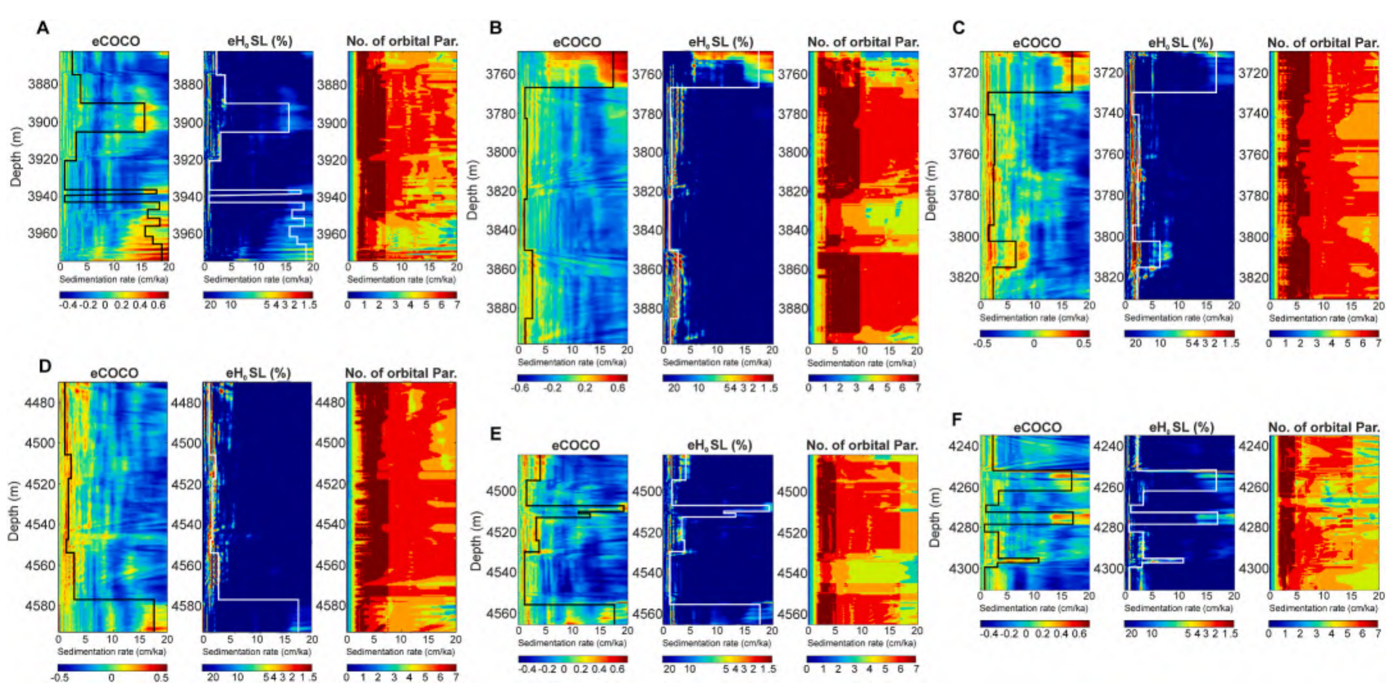

Fig. 4. The results of eCOCO maps for the Faraghan Formation in the studied wells A (Well A, sliding window (SL) size is 28 m), B (Well B, SL size is 38 m), C (Well C, SL size: 30 m), D (Well E, SL size: 30 m), E (Well D, SL size: 21 m), F (Well F, SL size: 19 m).

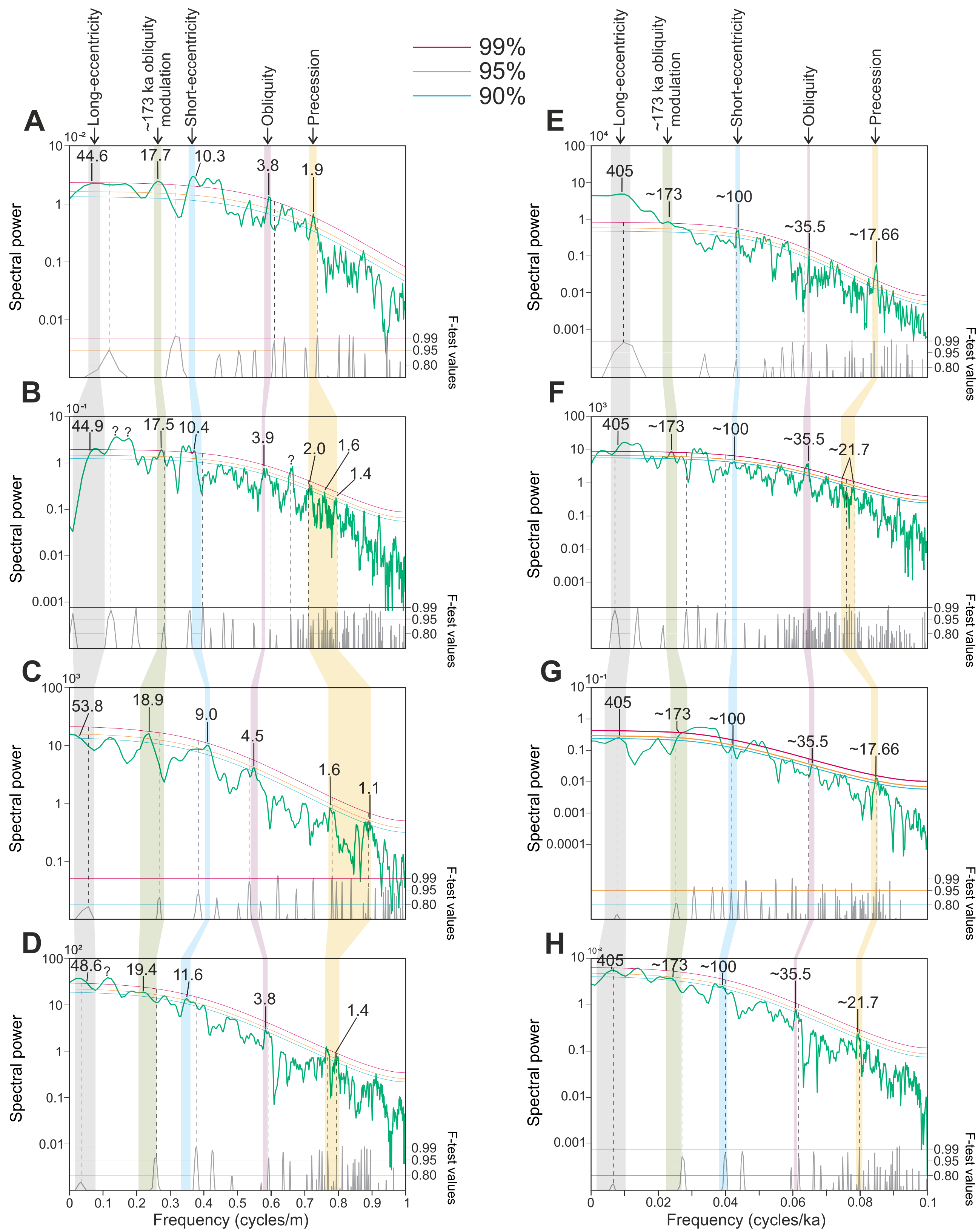

Fig. 5. The results of 2π MTM power spectra and F-test values of untuned SGR data at Well A (A), Well B (B), Well C (C), and Well E (D). The results of 2π MTM power spectra and F-test values of 405 ka tuned SGR time series at Well A (E), Well B (F), Well C (G), and Well E (H).

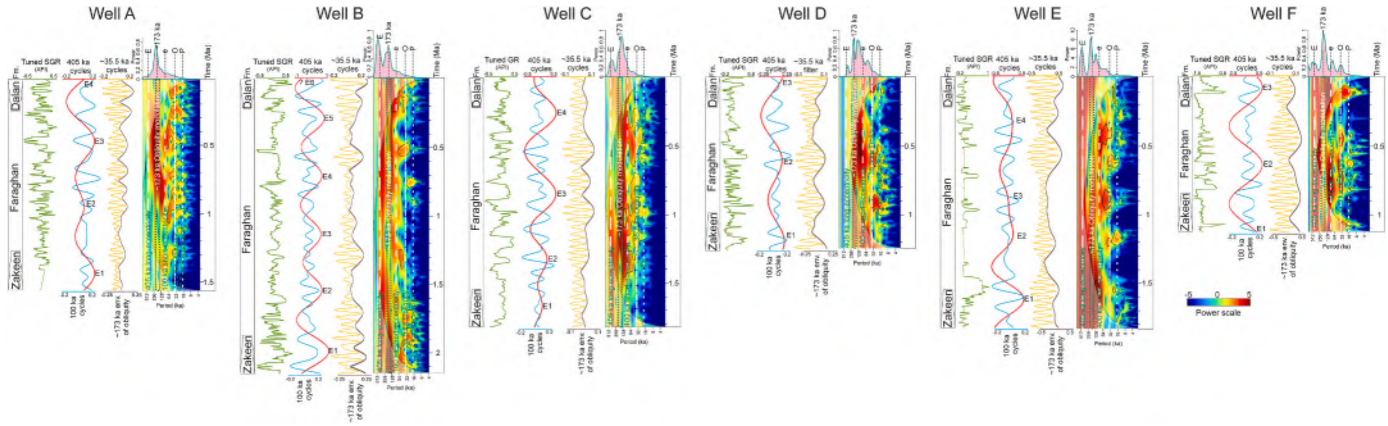

Fig. 6. Cyclostratigraphy analysis in the time domain of the Faraghan Fm. At the studied wells. The filters of orbital cycles and wavelet transform scalograms on the 405 ka tuned SGR time series are presented separately.

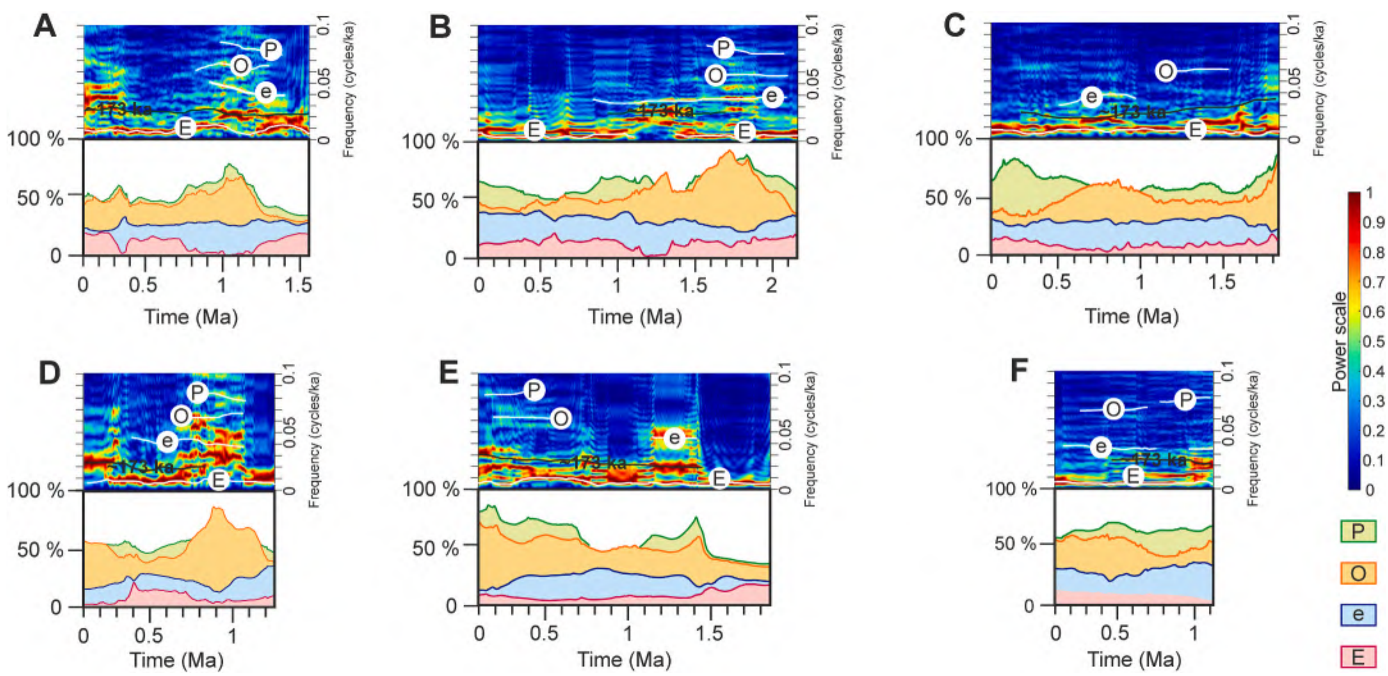

Fig. 7. The power decomposition analysis (PDA) and Fast Fourier transform (eFFT) spectrograms of the 405 ka tuned SGR time series at each studied well. Long-eccentricity cycles passbands are is 0.0020 ± 0.0003 ka^{-1}, short-eccentricity cycles passbands are 0.012 ± 0.002 ka^{-1}, obliquity cycles passbands are 0.024 ± 0.010 ka^{-1} and precession cycles passbands are 0.08 ± 0.02 ka^{-1}. All PDA calculations were performed at the studied wells using a 500-ka sliding window with the 2π MTM methods. A: Well A, B: Well B, C: Well C ….

from fluctuations in the astronomical cycle frequencies (i.e., long-eccentricity cycles). The power ratios of the orbital cycles exhibited by the PDA technique are commensurate to the scattering of the orbital cycle frequencies in the eFFT spectrograms. The findings obtained by these two methods overlap (Fig. 7). The tuned SGR series in the examined wells are more sensitive to obliquity cycle signals than other orbital cycles. The power ratio of this cycle is more significant in general.

4.4. Amplitude modulation analysis

Amplitude modulation (AM) analysis is a critical method to analyze the cycles to determine whether the cycles recorded in the research were under orbitally-forced control (Hinnov, 2000). The AM envelopes of the observed ~35.5 ka obliquity cycles (Fig. 6) in the investigated wells (A, B, C, and E) reveal strong cyclicities of 1139 ka, 1010 ka, 1095 ka, 1152 ka, 168 ka, 179 ka, 170 ka and 180 ka, respectively (Fig. 8e, f, g and h). The mainstay of amplitude modulation analysis is also the 405 ka long-eccentricity stable cycles. The observed cycles with relatively adequate coherence have identical phase relationships (Fig. 8a, b, c and d). The long-period modulation cycles (1139 ka, 1010 ka, 1095 ka and 1152 ka) can be attributed to the s4-s3 term (~1.2 Ma orbital modulation cycles). The 168 ka, 179 ka, 170 ka, and 180 ka orbital cycles with negative phases and proper coherence can be a ~173 ka rare modulation of the obliquity band which has just once been recorded before this work from Paleozoic (Fig. 8). The orbital obliquity modulation cycles (~1.2 Ma and ~173 ka) were separated from SGR time series using the Taner-Hilbert transform.

4.5. Sedimentary noise modeling (DYNOT)

Sedimentary noise modeling (DYNOT) approaches are a new way of investigating the sequence stratigraphic framework of sediments in various sedimentary systems using hidden sedimentary noises in climate and sea level sensitive proxies (Li et al., 2018). Sedimentary noise occurs

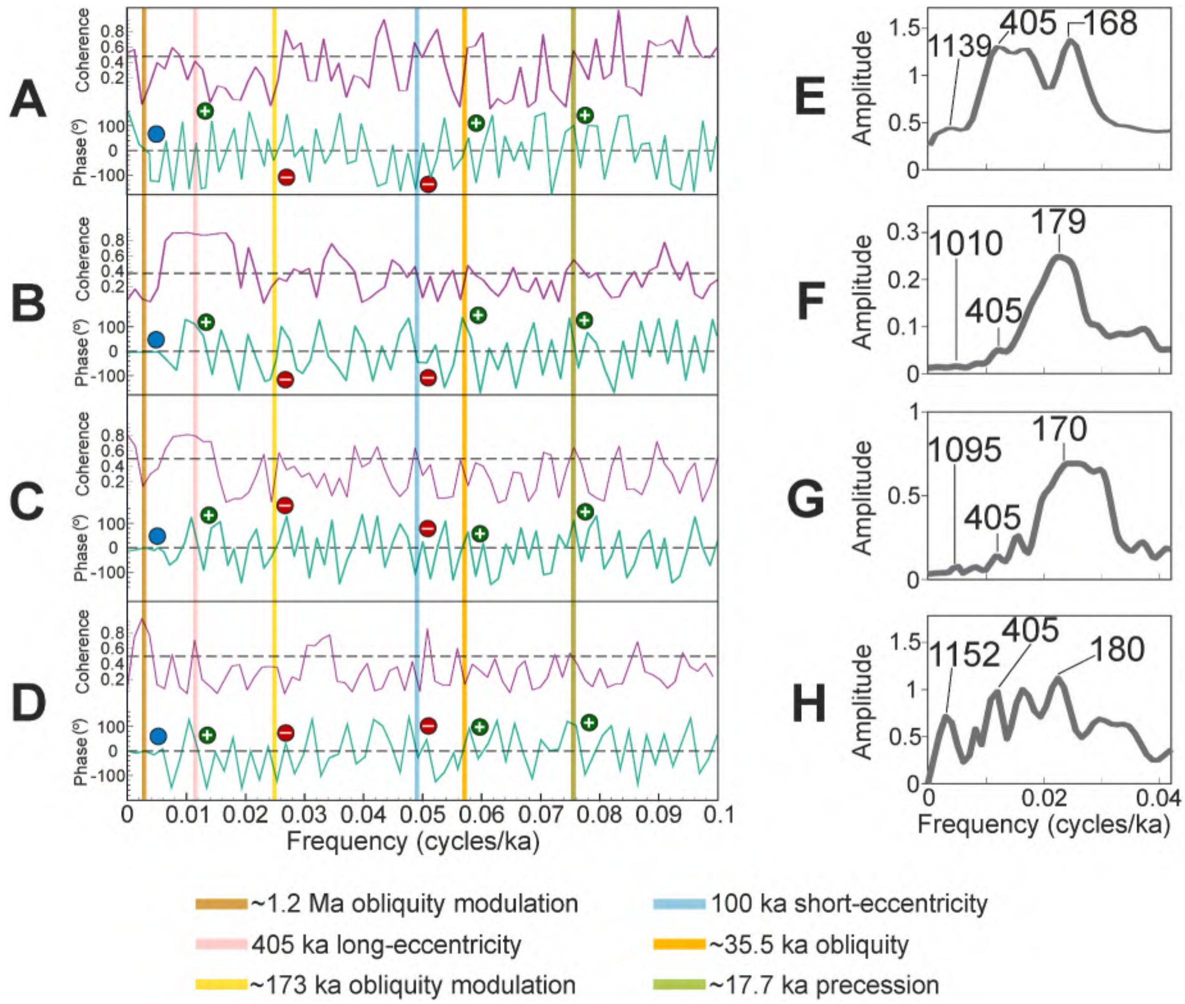

Fig. 8. Coherence and cross-phase spectrum analysis of the 405 ka tuned SGR time series at Well A (A), Well B (B), Well C (C), and Well E (D). Amplitude spectra of the AM envelopes at wells A (E), B (F), C (G), and E (H).

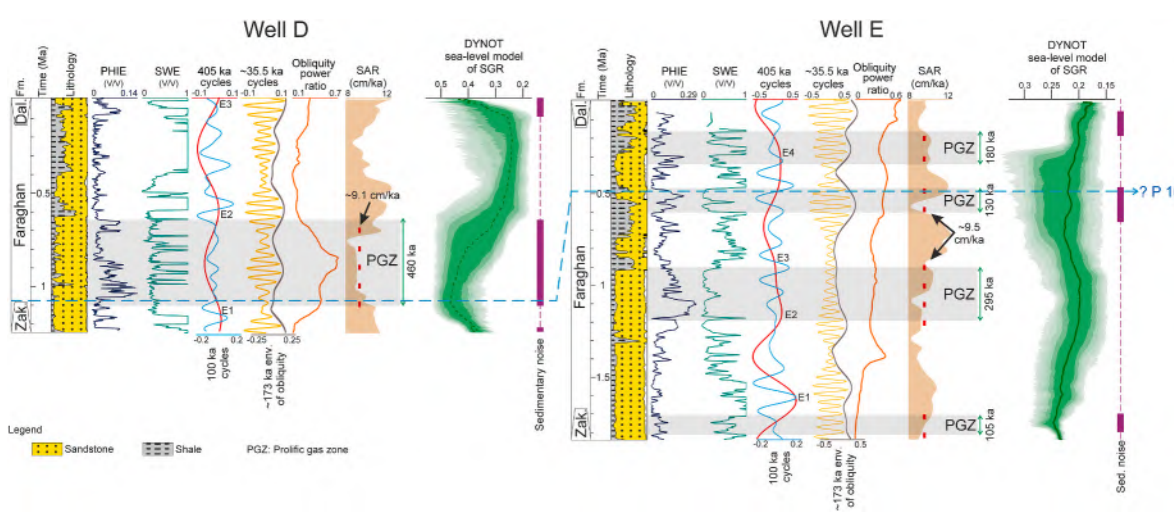

Fig. 9. Correlation of the prolific gas zones (PGZ) in Faraghan Formation with obliquity maxima, its vital power, sedimentary noise models and sediment accumulation rates (SARs) at wells D and E.

in water depths ranging from several meters to hundreds of meters as a result of storm wave bases, storms, tides, bioturbation, and varied sedimentation rates (Li et al., 2018). With the parameters of a 400 ka sliding window, 2000 Monte Carlo simulations, and a median data age of 280 Ma, these approaches were applied to SGR, GR and Uranium (U) time series of the Faraghan Formation in the wells A, B, C, D and E. In the studied wells, the DYNOT sea-level patterns present three sedimentary noises or three significant regional sea-level rises (Fig. 11). The spectral analysis of DYNOT median values in wells A, B, C, and E demonstrates 1660 ka, 1113 ka, 842 ka, 2592 ka, 1371 ka, 974 ka, 2732 ka, 1187 ka, 1810 ka, 1350 ka, and 991 ka long-term cycles (Fig. 11a, b, c and d). The cycles of 1113 ka, 1371 ka, 1187 ka, 1350 ka correspond to the ~1.2 Ma orbital obliquity modulation cycles identified previously using AM analysis.

5. Discussion

5.1. Possible factors affecting the SAR shifts of the Faraghan Formation

As mentioned, extraordinary geological events were taking place before the deposition of the Faraghan Formation in the Zagros region; however, no evidence of the Permian glacial deposits has been reported in the Zagros Basin. Despite this, Oman and Saudi Arabia's glacial deposits are known in the sedimentary records of the Latest Carboniferous and Asselian-Sakmarian (Martin et al., 2008; Le Heron et al., 2009; Asghari, 2014). In the examined area, the lower boundary of the Faraghan Formation with the Zakeen Formation is defined by a long-term abrupt unconformity (Ghavidel-Syooki, 2003), implying that the Late Carboniferous glacial episode played a significant role in the emergence of this phenomena (Ruban et al., 2007). Also, in the Artinskian-Kungurian (Cisuralian) it is inferred that the Arabian Plate has undergone the second major phase of crustal extension, which eventually triggered the continental separation (Sharland et al., 2001).

In addition, extensive climate change took place during the deposition of the Faraghan Formation. The correlative successions of the Faraghan Formation in Saudi Arabia were deposited in the semi-arid (Unayzah A member with eolian deposits) and glacial conditions (Unayzah B member with glaciogenic deposits) (Melvin and Sprague, 2006; Melvin et al., 2010). The Arabian Plate is displaced throughout the Permian time from relatively low latitudes to higher latitudes. Therefore, the distance or proximity of the Arabian Plate to the equator is another factor influencing the deposition of the Faraghan Formation (Konert et al., 2001; Haq and Al-Qahtani, 2005; Zamanzadeh, 2008).

In turn, eustatic, regional and local sea-level fluctuations influenced the sedimentation of the Faraghan Formation. For instance, eustatic sea level stabilized during the Cisuralian and was accompanied by a modest decline compared to the Latest Carboniferous (Haq and Schutter, 2008). However, the Cisuralian regional sea-level cycles were affected by multiple tectonic phases (extension, rifting) and were associated with low sea levels (Haq and Al-Qahtani, 2005). While the local sea level rose throughout the Cisuralian (Zamanzadeh, 2008). Therefore, sedimentation rate variations of the Faraghan Formation were generally governed by multiple vital factors.

5.2. The calculation of the hiatus, average SAR and highlighting of the? P10 MFS through sedimentary noise modeling for the Faraghan Fm

Cyclostratigraphic analysis of the Faraghan Formation in six separate subsurface sections reveals varied SARs and dissimilar depositional time spans, implying inconsistent and discontinuous depositional conditions in the studied area. Physical evidence of discontinuity has been recorded from the Faraghan Formation in the Zagros Basin, including the development of a reactivation surface, subaerial exposure, erosional surfaces, phosphatic fragments, and Thalassinoides ichnofabric (Zamanzadeh, 2008). It has been shown empirically that SARs decline systematically with increasing average duration in most depositional settings, notably shallow shelf seas (Sadler, 1981). The Faraghan Formation has a roughly similar pattern of SAR fall in wells B, C and E with a longer depositional time span, while the SAR is substantially greater in wells A, D and F with a shorter depositional time span (Table 1, Figs. 4 and 6). In wells B, C and E, the SAR trends in eCOCO maps are nearly consistent and characterized by low values, with an overall single increase in SAR (Fig. 4). In contrast, wells A, D and F exhibit the same continuous trends with low values, but they show at least two or three separate increases in distinct intervals, which is the main difference between the SAR of the preceding wells. This research reveals clear hiatuses in the observed sedimentary sequences and it is hypothesized that the Faraghan Formation contains at least a ~1 Ma hiatus interval. The Faraghan Formation clearly has a higher SAR in these wells (A, D and F). However, because the Faraghan Formation is relatively thick (510 m) in some regions, such as the High Zagros (Bordenave, 2008), this hiatus could be bigger.

Table 1
The results of the astrochronology and SARs estimation from the eCOCO maps in the studied wells. The minimum average SAR is derived by taking all increasing and declining trends into consideration.

	Well A	Well B	Well C	Well D	Well E	Well F
Depositional time spam (Ma)	1.55	2.14	1.83	1.24	1.835	1.12
Estimated minimum average SAR (cm/ka)	12.3	7.1	8.2	11.1	7.5	11.3

Massive bedding with a primary sedimentary origin is occasionally encountered in the Faraghan Formation, which is often the consequence of a huge sediment load influx by rivers or storm processes (Zamanzadeh, 2008). Also, disruptions can be found in the stromatolite layers, which are most likely the result of an abrupt increase in environmental energy, such as the advent of a storm resulting in cluttering in these beds (Zamanzadeh, 2008). Hiatus, short-term breaks, mixed layers, storm conditions and bioturbation are all markers of the emergence of depositional noise events. These signals may also be tracked in the investigated sedimentary sequences using DYNOT modeling; particularly, three sedimentary noises for the Faraghan Formation can be found in each studied well using this methodology (Fig. 11). The detected sedimentary noises cover the Faraghan Formation sequence stratigraphic framework established by Zamanzadeh (2008) and Asghari (2014) that can be divided into major and minor noises. In particular, in all wells, the middle noise is read as major noise, whereas the two lower and upper noises are interpreted as minor noise. The middle noise, which can clearly be distinguished from other noises in each well, may indicate to a transregional sea-level rise event and most likely corresponds with MFS P10 of the late Sakmarian age in the Arabian Plate's sequence stratigraphic framework (Sharland et al., 2001). Interestingly, the MFS P10 is found in bioturbated shales in the Lower Gharif Member of Oman (Sharland et al., 2001). This somehow makes the existence of the sedimentary noise event, as well as the development of an MFS as a result of it, look more tangible in the area. Despite the fact that it is described (Sharland et al., 2001), the MFS P10 can be found in the ?limestones of the lower part of the Faraghan Formation in southern Iran. The designed sedimentary noise patterns sometimes show this mfs in the higher intervals of the Faraghan Formation (Fig. 11). Furthermore, due to the limitations of age measurement in the study area, it is not possible to go into greater detail on this subject.

The sedimentation rates of the Faraghan Formation fluctuate from ~3.0 cm/ka to ~18.5 cm/ka in all wells, according to eCOCO maps (Fig. 4). Based on similar statistical methods, the SAR of the Upper Dalan Member (Upper Permian) has also been calculated to be in the range of 3.5–18 cm/ka (Falahatkhah et al., 2021b). The examined sequences in the Persian Gulf are thought to have a minimum average sediment SAR of ~10 cm/ka. In order to establish relatively accurate sedimentation rates in wells D and E that demonstrate first-order fluctuations of SAR in the depth domain, the SM analysis was applied with an average SAR of 10.4 cm/ka. The SM analysis reveals noteworthy variations in the sedimentation rates of the Faraghan Formation in ranges of 8–12 cm/ka in both wells, and novel suppositions regarding the possible relationship between these changes and their repercussions in the gas reservoir zones are proposed below (Fig. 9).

5.3. Cycle-bounding erosive surfaces and rhythmites

Investigations on sedimentary cores at well B yielded a record of pyrite, bioturbation, minor non-glacial erosive surfaces, and sedimentary structures (Fig. 10). In the core, four incidences of minor erosive surfaces were found, practically all of which exhibit synchrony with the obliquity nodes. Two of these four instances have a considerable overlap with the sedimentary noise curve and can be regarded depositional noise events indicating regional sea-level rise (Fig. 10). These erosive surfaces are almost concave-convex and may be categorized as reactivation surfaces. However, time missing (albeit in the short-term) at these surfaces is unavoidable. But, the trend of the SAR in the eCOCO map of well B is almost identical to the sedimentation rates in other wells (Fig. 4), indicating that these minor erosive surfaces could not cause a disruption in the prediction of the Faraghan Formation's accumulation rate and depositional duration (Fig. 10). The synchronization of erosive surfaces with obliquity nodes is clear proof of this astronomical cycle's influence on sea-level changes and, more broadly, on the framework of sedimentary sequence creation. The presence of a cycle-bounding erosive surface and its relationship to sea-level fluctuations can be an indicator of changes in climate trends as well as glacioeustasy's impact on the Faraghan Formation, such evidence has already been recorded since the Late Paleozoic Ice Age (LPIA) (e.g., Davies et al., 2008; Bishop et al., 2010). Such erosive surfaces are important in sequence stratigraphy because they reveal evidence of sea-level rising (Ghienne et al., 2014). The coeval of these surfaces with the obliquity nodes in the LPIA, where sea-level variations were driven by glacioeustasy forcing, demonstrates the orbital cycles' combined participation on sea-level regulation in the studied area.

Clear rhythmites were discovered in several parts of the Faraghan Formation, two of which are shown in Fig. 10. These rhythmites feature sand and shale alternations that have generated centimeter-scale cycles and clearly indicate cyclic sedimentation. Rhythmites occur frequently in the studied succession and almost definitely have a strong origin. Similar rhythmites were found in LPIA, indicating that their deposition was governed by orbital forcing (e.g., Franco et al., 2012; Kochhann et al., 2020 and references therein). However, they disagreed on the extrinsic causes of rhythmite generation, these research indicated various factors of obliquity, precession, and sub-Milankovitch cycles (Kochhann et al., 2020). Given the size of these laminae and the fact that precession is shown to be the smallest cycle in this work, we conclude that precession is the forced mechanism causing these centimeter-scale cycles in the rhythmites. These rhythmites were most likely to record the rapid change in temperature from hot to cold that occurs in sync with precession. The precession cycle affects the distribution of solar radiation on the Earth's surface, which in turn influences climate patterns. In regions with seasonal rainfall, such as in the tropics, precession can cause the timing and intensity of monsoons to vary over time. These variations can result in changes in the rate of sediment deposition, which can lead to the formation of rhythmites. Rhythmites are often formed in environments with fluctuating water levels, such as in lakes or coastal regions. Considering that the study location is close to the equator and the Faraghan Formation's depositional settings is a shallow marine coastal shelf that has experienced numerous sea-level variations and been influenced by precession, the prerequisites for rhythmite formation are clearly there.

Precession can affect the deposition of sediment in two ways. First, changes in the timing and intensity of monsoons can lead to variations in the amount of sediment that is transported and deposited in a given area. Second, precession can also influence the position of the shoreline, which can affect the distribution of sediment. For example, during times of high precipitation, a river may transport more sediment to a lake or coastal region, resulting in thicker sediment layers. During times of low precipitation, the same river may transport less sediment, resulting in

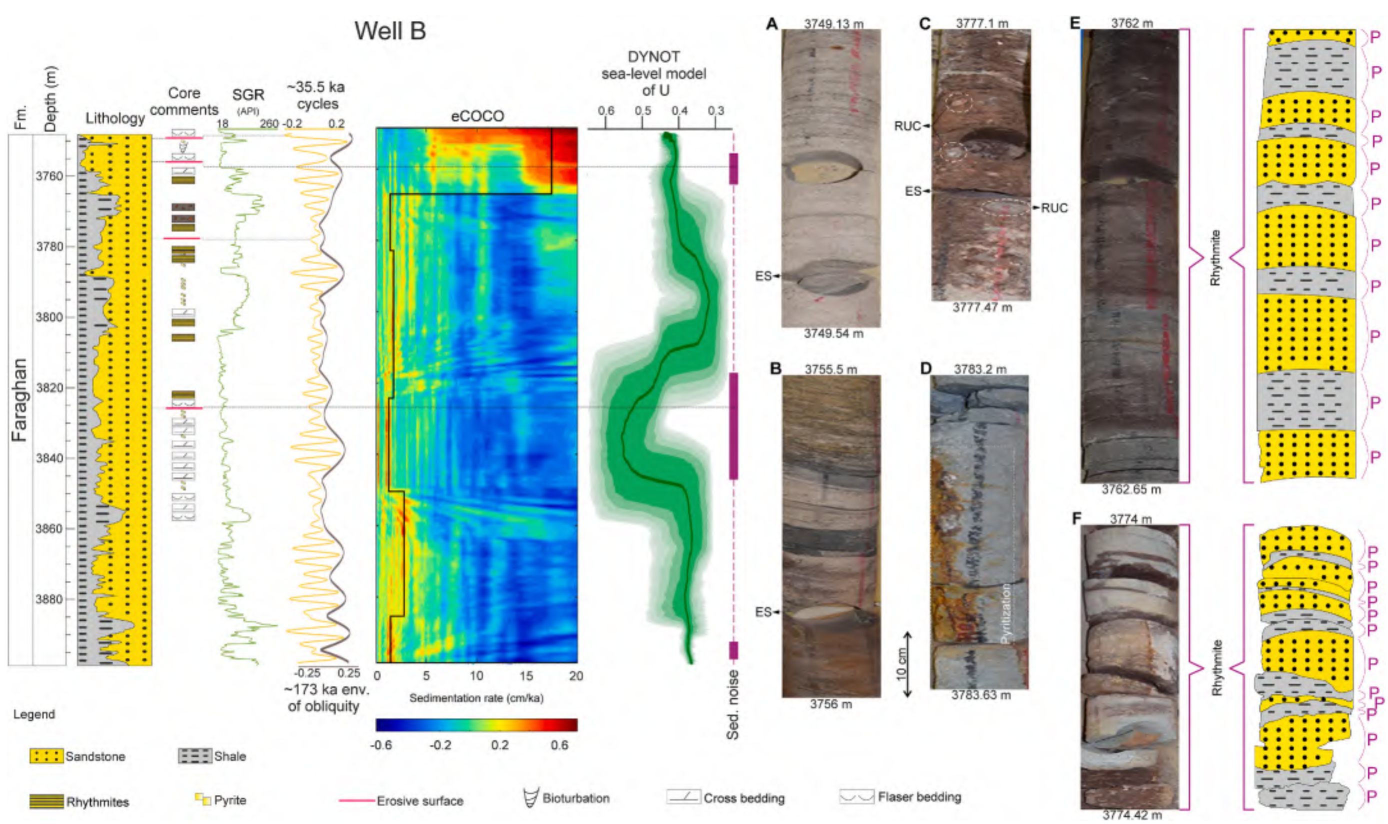

Fig. 10. Stratigraphy of the Faraghan Formation in well B along with eCOCO map, DYNOT curve, and sedimentary core photographs. A) Laminar shale with one erosive surface (ES). B) Alternation of shale and sand with one ES. C) Shale layers with rip-up clasts (RUC) with one ES. D) Shale layers with clear pyritization. E and F) rhythmites of sand and shale.

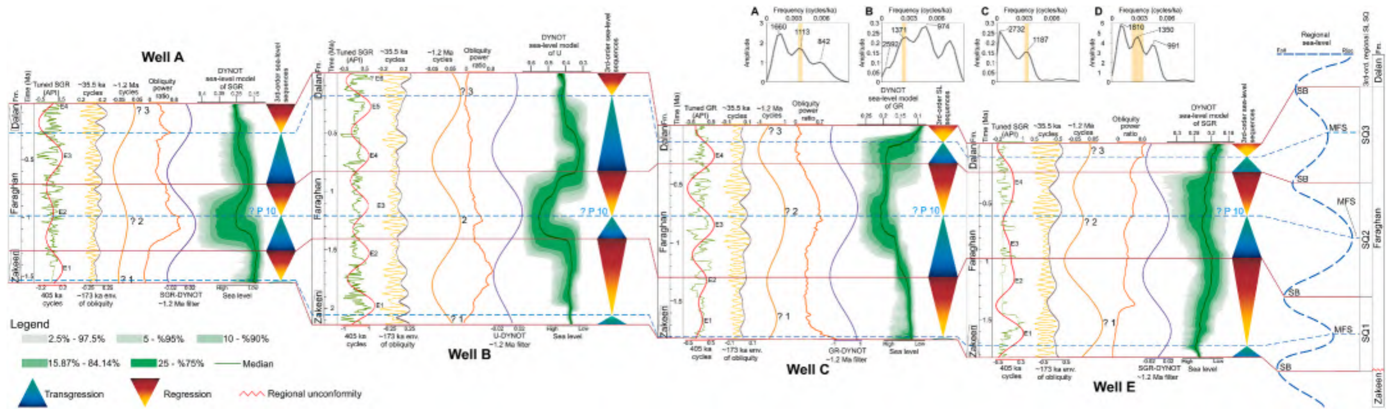

Fig. 11. Comparison of sea-level changes obtained from DYNOT sedimentary noise models applied on SGR, GR and U time series at wells A, B, C and E with regional sea-level swings and 3rd-order sequences (with slight modifications taken from Zamanzadeh, 2008). ~1.2 Ma orbital obliquity modulation filters with band-pass of 0.0016 ± 0.018 (cycles/ka), 0.0019 ± 0.017 (cycles/ka), 0.0020 ± 0.016 (cycles/ka) and 0.0015 ± 0.014 (cycles/ka) of wells A, B, C and E, respectively. ~1.2 Ma orbital obliquity modulation filters of SGR median DYNOT values with band-pass of 0.0019 ± 0.016 (cycles/ka), 0.0018 ± 0.015 (cycles/ka), 0.0014 ± 0.019 (cycles/ka) and 0.0016 ± 0.02 (cycles/ka) of wells B and F, respectively. Amplitude power spectra of the SGR median DYNOT values at Well A (A), Well B (B), Well (C) and Well F (D). The 3rd-order sedimentary sequences in each well were interpreted through the DYNOT model.

thinner sediment layers. Similarly, changes in the position of the shoreline can lead to changes in the distribution of sediment, which can also result in rhythmic layering. Overall, precession can play an important role in the formation of rhythmites by influencing the deposition and distribution of sediment in environments with fluctuating water levels.

5.4. Possible role of the orbitally-forced cycles in prolific gas zones development

The Faraghan Formation responded unambiguously to cyclostratigraphic analyses. Significant orbital cycles were revealed in these siliciclastic sediments, indicating that these extrinsic cycles played an essential role in the formation's depositional conditions. The Faraghan reservoir Formation is one of the gas-bearing stratigraphic units in the Zagros and Persian Gulf sectors, on which extensive hydrocarbon explorations have been made (Szabo and Kheradpir, 1978 ; Zamanzadeh et al., 2009a, b). The PGZ are highlighted by high values of effective porosity (PHIE) and low values of effective water saturation (SWE) parameters (Fig. 9). The PHIE log, typically determined from NPHI, DT, and RHOB well logs, and is influenced by various lithological controls, including the nature of the clays (their type, content, and hydration), the heterogeneity of grain sizes, and the grain packing and cementation. In contrast, the SWE is essential for calculating the hydrocarbon reservoir storage capacity. Therefore, both parameters are functional for reservoir quality assessment (Tiab and Donaldson, 2015). The PGZ across the Faraghan Formation is labeled in the two wells D and E using the signature of these data, where the variations in astronomical cycles and SARs are interesting. As an abiotic parameter, orbital cycles may produce appropriate sedimentary depositional for the production or preservation of PGZ in the Faraghan Formation. The orbital cycle amplitudes may coincide with the onset and termination of various types of events, i.e., the beginning of specific sedimentation such as chert beds/sapropels or oxidation-reduction periods that are associated with oceanic anoxic events, and exhibit sensitive changes (Herbert and Fischer, 1986; Lourens et al., 2001; Mitchell et al., 2008). U sing the PDA approach, it was discovered that the obliquity's power ratio is more significant than in the other orbital cycles (Fig. 7). The obliquity maxima strongly correlate to the PGZ intervals in both wells, and we consider this coincidence as indicative of probable influence on reservoir quality development (Fig. 9). Unexpectedly, the obliquity power ratio is greatest at the PGZ intervals. Variations in obliquity forcing greatly influence annual and seasonal insolation, sea-level, snowfall, moisture transport, and the variability of global ice volume (Lee and Poulsen et al., 2008; Naish et al., 2009). Precipitation and chemical weathering are reduced at obliquity minima periods due to lower moisture and heat exchange towards the pole, which is expressed in arid episodes. On the other hand, precipitation and chemical weathering increase in the obliquity maxima intervals, improving productivity and intensifying hydrological cycles entering sedimentary basins (Li et al., 2022). These factors can impact the nature and arrangement of depositional facies with specific mechanisms. Because the diagenetic processes in the Faraghan Formation were not to the extent distorting the primary origin of the sediment and we are facing an obliquity maximum in the PGZ intervals, this hypothesis is proposed that orbital cycles play a role in improving the conditions for reservoir quality development. Using cyclostratigraphic analysis, we discovered that the PGZ intervals in both wells are not chronostratigraphically similar and formed within the time duration of 460 ka (Well D) and 710 ka (Well E). The amount and distribution of organic matter in sedimentary rocks can be related to the sedimentation rate in a number of ways. Here are three ways that organic matter and sedimentation rates are related: 1- Preservation potential: The rate at which sediment accumulates has an impact on organic matter's ability to be preserved. If sedimentation rates are higher, organic matter may be preserved better because it won't eventually decay and disappear. This is so that the exposure to oxygen, microbes, and other elements that hasten deterioration can be minimized through fast burial. This appears to represent the rate of burial below the oxygenated and bioturbated zone in general. 2- Primary productivity: The rate at which sediment accumulates affects how much organic matter is produced in a sedimentary environment. Increased primary productivity and increased organic matter production may result from higher sedimentation rates, which may also provide more nutrients and a more stable environment for photosynthetic organisms to thrive. In these circumstances, it can be said that the rate of water exchange exceeds the rate of sediment influx. 3-Dilution effect: Lower sedimentation rates can result in the dilution of organic matter. In other words, as sediment accumulates more slowly, organic matter may become more dispersed and less concentrated. This can make it harder to identify and quantify organic matter in the sediment. Dilution most likely signifies a larger ratio of inert sediment grains to the organic content, which may result in a higher sedimentation rate. Overall, the sedimentation rate is an important factor that can influence the distribution, preservation, and concentration of organic matter in sedimentary rocks. Also, there is typically a good link between sedimentation rate and the quality of organic matter (gas-prone) at low sedimentation rates under oxic conditions (Katz, 2001). Similarly, sedimentation rates in both wells at the PGZ intervals are ~9 cm/ka, which is lower than those in other parts of the Faraghan Formation (Fig. 9). However, based on the Faraghan Formation's palynofacies analysis, it has been shown that this formation experienced an oxic to anoxic-dysoxic condition, which has finally led to the temporary blockage of carbonate production (Spina et al., 2021).

Depositional noise events (within the DYNOT sea-level model) have developed in four of the five PGZ intervals in the two wells E and D when obliquity maxima occurred (Fig. 9). The ~1.2 Ma orbital obliquity modulation cycles have impacted sedimentary noises that reveal sea-level rise. The in-phase relationships between the output filters from the DYNOT patterns and the output filters from the paleoclimate proxies provide evidence for this impact. All of this indicates unequivocally that the ~1.2 Ma obliquity-forced cycles with the triggers of sea level and paleoclimate have played a significant role in the evolution of sedimentary conditions and the development of sedimentary noise events and reservoir quality. Additionally, DYNOT modelling can be a crucial tool for locating hydrocarbon zones in deposits related to the shallow marine coastal shelf that are impacted by orbital cycles.

5.5. ~173 ka orbital obliquity modulation cycles

The time series analysis of our paleoclimatic proxies in six subsurface sections on the Cisuralian Faraghan Formation reveals a ~173 ka obliquity AM cycle with at least a 95% confidence level (Fig. 5). The ~173 ka cycle signal is recognizable with persistent spectral powers in the bottom segments of WT scalograms of tuned SGR time series (dark red) (Fig. 6). Remarkably, these cycles indicate comparative phase relationships, which turn out to have originated from one identical origin (Fig. 8). The ~173 ka cycle is one of the rare obliquity modulations which has been recorded in a handful of stratigraphic archives. This component arises from s3-s6 secular frequencies and is associated with the orbital inclinations rate interference between Earth and Saturn (Boulila et al., 2018; Laskar, 2020; Huang et al., 2021; Zhang. et al., 2022b). The discovered cycle, found as a phenomenon in rock records during the Cenozoic and Mesozoic, has been identified as a potent geochronometer and paleoclimate decoder (Boulila et al., 2018; Huang et al., 2021). For instance, during the Cenozoic and Mesozoic, the ~173 ka cycle influenced the processes of organic carbon burial in mid-to-high latitudes. This cycle also regulates some climate systems that are amplified by internal climate feedbacks of the carbon cycle under various geographical and climatic conditions (Huang et al., 2021). Recently, Boulila et al. (2018) confirmed that this periodicity has been stable for at least 50 Ma and can be utilized to close the "middle Eocene timescale gap". The ~173 ka cyclicity, defined as the beat of obliquity-related frequencies (s3-s6 term), could be a strong candidate for creating sedimentary sequences containing orbital oscillation fingerprints (Boulila et al., 2018; Zhang et al., 2022a, b). Because of significant variability in sea level and sediment influx, HST sediments in the study area are broadly formed of overlaid parasequences with distinct erosion surfaces (Zamanzadeh et al., 2009a, b). The parasequences are mostly associated with climato-eustatic oscillations. They are controlled by Earth's astronomical parameters (Boulila et al., 2011). Interestingly, the causative mechanism of fifth-order sequences in sedimentary settings is the ~173 ka obliquity modulation cycles (Boulila et al., 2020). This study accurately recognized this cycle within the Faraghan Formation, indicating that it can be the key instrument for the building stratigraphic parasequences during the Permian.

5.6. ~1.2 Ma orbital obliquity modulation cycles and sedimentary noise modeling of the Faraghan Fm

New findings imply that in the forming of sedimentary sequences over time scales of more than a multi-Ma during the stratigraphic record, the scales are tilted heavily in favor of the astroclimate signal against tectonics (Boulila et al., 2020). Sea level in the studied area fluctuated wildly during the deposition of the Faraghan Formation. It was influenced by astronomically forced climate change, resulting in the development of many sequences and parasequences (Zamanzadeh, 2008). This research also highlighted that in the development of sedimentary sequences, the climate-forcing signal had appeared widely throughout the sedimentary record. Also, the findings of this investigation indicate that obliquity had a notable impact on the depositional condition of the Faraghan Formation in the Zagros and Persian Gulf Basins, so that ~1.2 Ma and ~173 ka obliquity modulation cycles matched to the third-order and fifth-order sequences, respectively.

Depositional noise event, which typically occurs in sedimentary sequences, can reveal information about circumstances that are normally invisible to the naked eye. More consideration should be given to the previously mentioned factors, such as bioturbation, etc., in order to access and track these events. Depositional noise can be beneficial in stratigraphic interpretation because it can provide further information about geological events that may be difficult to observe or interpret from the sedimentary record alone. By looking at disturbances or variations in sedimentary sequences, geologists can learn more about the processes that occurred during the formation of the rocks, including changes in the environment, sedimentation rates, and even climate. The nature of depositional noises resulting from bioturbation is such that it can reflect the presence of oxygenated sediments or the proximity of the shoreline. Erosion and breaks are another sort of sedimentary noise that might be useful in stratigraphic interpretation. Unconformities are voids in the sedimentary record that develop when sedimentation or non-sedimentation takes place before re-sedimentation and erosion ends. Geologists can learn more about the tectonic and environmental events that took place during the relevant time period by examining the characteristics of unconformities, such as the type of erosion that took place or the size of the gap in deposition. In general, new perspectives are opened by investigating sedimentary noises that can help with significant stratigraphic record enigma.

Sedimentary noise models produce regional sea-level swings that retain the impacts of long-period orbital cycles (Li et al., 2018). These sedimentary noises commonly correspond to the maximum flooding surfaces (mfs) in the Sequence stratigraphy framework, which has been thoroughly tested in previous studies (Li et al., 2018; Wang et al., 2020). The Faraghan Formation was found to be heavily influenced by astronomically forced climate change in the current study. Accordingly, it is possible to implement DYNOT sedimentary noise modelling and to compare its results with regional sea level to elucidate the impact of ~1.2 Ma orbital obliquity modulation cycles on it. Based on sedimentary noise modeling (DYNOT) for the Faraghan Formation in wells B and F, three prominent sedimentary noises were discovered in each well (Fig. 9). Furthermore, in terms of the sequence stratigraphic division framework, the Faraghan Formation within the study area is settled in the form of three third-order sequences (Zamanzadeh, 2008; Asghari, 2014). The spectral analysis of the DYNOT median values in both wells expressed the ~1.2 Ma orbital obliquity modulation cycles, indicating that these long-term cycles were the major driver of regional sea level (Fig. 11). The ~1.2 Ma cyclicity is one of the relatively large modulations of obliquity related to s4-s3 secular frequencies and is driven by the orbital inclinations of Earth and Mars (Laskar et al., 2004). Significantly, the ~1.2 Ma obliquity modulation cycles during the Permian were recognized as a key driver of changes in climate, sea level, and, as a result, sedimentary processes (e.g., Fang et al., 2015, 2018; Huang et al., 2020). The filtered cycles from DYNOT median values time series are in-phase with the ~1.2 Ma obliquity modulation cycles and overlap pretty well with each other (Fig. 11). This feature demonstrates that the ~1.2 Ma obliquity cyclicities have mainly influenced regional sea level. The ~1.2 Ma obliquity modulation cycles are one of the mechanisms responsible for the creation of the third-order sequences, which are most cases correlated with these orbitally-forced long-period cycles (Boulila et al., 2011, 2020). T his feature is also visible in the Faraghan Formation. Each third-order sequence can be matched with each of the ~1.2

Ma obliquity cycles of this study, indicating that these cycles existed within the context of the region's sedimentary processes. The ~1.2 Ma obliquity periodicities of the Faraghan Formation are an in excellent fit with regional sea-level fluctuations (taken from Zamanzadeh, 2008), demonstrating the influence of extrinsic forcing on sea level (Fig. 11).

6. Conclusions

Exciting signs of orbitally-forced climate change were discovered in several subsurface sections of the Cisuralian Faraghan Formation in different parts of the Persian Gulf Basin, indicating that the depositional conditions of this formation were controlled by extrinsic forcing. The following five sentences list the key findings reached in this study:

1. The sedimentation rates of the Faraghan Formation were found to vary between ~3 and ~18 cm/ka based on eCOCO analysis. A ~1 Ma hiatus was identified by comparing the Faraghan Formation's depositional time and sedimentation rates in six separate wells.
2. It's instructive to note that the obliquity maxima in the Faraghan Formation correlate to the prolific gas zones (PGZ), and these intervals have particularly excellent obliquity power. The notion that the orbitally-induced cycles have brought appropriate sedimentary conditions for establishing the reservoir quality of the Faraghan Formation is presented in this paper based on this connection.
3. Depositional noise events were particularly common in the PGZ intervals where obliquity maxima occurred in the Faraghan Formation. The major sedimentary noise in this study was traced from the Faraghan Formation at the analyzed subsurface sections, which clearly has a larger scale than the other two sedimentary noises and most likely corresponds to a transregional sea-level rise, which we assign to MFS P10.
4. In addition, across the Paleozoic, considerable evidence was gained by documenting the orbital variability of the Earth-Saturn cycles (~173 ka obliquity modulation cycles) in the Cisuralian Faraghan Formation. The obliquity evolution in the Faraghan Formation has significantly affected the depositional conditions. This study found that ~1.2 Ma and ~173 ka obliquity modulation cycles are compatible with the third and fifth-order sequences, respectively.
5. Cisuralian regional sea level was reconstructed in northeastern Gondwana using sedimentary noise (DYNOT) patterns from two independent paleoclimate proxies. The DYNOT models express three distinct sedimentary noises in the Faraghan Formation, which confirms the sequence stratigraphic division of this formation, which consists of three third-order sequences. The ~1.2 Ma obliquity modulation cycles recorded in the Faraghan Formation are consistent with the formation's third-order sequences, indicating that these long-term orbital cycles were the major drivers of regional sea level.

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

Acknowledgments

The authors would like to appreciate the anonymous reviewers for their scientific and efficient comments that improved the quality of this work. National Iranianian Oil Company (NIOC) provided the data to conduct this regional research which we are grateful of. We also thank Mr. Houshang Mehrabi for macroscopic description of the sedimentary cores.

References

Abadi, M.S., Soreghan, G.S., Hinnov, L., Heavens, N.G., Gleason, J.D., 2021. Atmospheric dust flux in northeastern Gondwana during the peak of the late Paleozoic ice age. GSA Bulletin 133 (5–6), 992–1006.

Al-Husseini, M., 1992. Upper Palaeozoic tectono-sedimentary evolution of the Arabian and adjoining plates. J. Geol. Soc. London 149, 419–429.

Al-Laboun, A.A., 1987. Unayzah Formation: a new permian carboniferous unit in Saudi Arabia. AAPG (Am. Assoc. Pet. Geol.) Bull. 71 (1), 29–38.

Abu-Ali, M.A., Rudkiewicz, J.L.L., McGillivray, J.G., Behar, F., 1999. Paleozoic petroleum system of central Saudi Arabia. GeoArabia 4 (3), 321–336.

Asghari, A., 2014. Sedimentary Environment, Sequence Stratigraphy and Paleogeography of Paleozoic Pre-khuff Succession in Southern Iran (Zagros and Persian Gulf), PhD Thesis. Applied Geology. Université de Bourgogne, France, p. 226.

Bishop, J.W., Montañez, I.P., Osleger, D.A., 2010. Dynamic carboniferous climate change, arrow canyon, Nevada. Geosphere 6 (1), 1–34.

Bordenave, M.L., 2008. The origin of the Permo-Triassic gas accumulations in the Iranian Zagros foldbelt and contiguous offshore areas: a review of the Palaeozoic petroleum system. J. Petrol. Geol. 31 (1), 3.

Bosmans, J.H.C., Hilgen, F.J., Tuenter, E., Lourens, L.J., 2015. Obliquity forcing of low-latitude climate. Clim. Past 11 (10), 1335–1346.

Boulila, S., Galbrun, B., Miller, K.G., Pekar, S.F., Browning, J.V., Laskar, J., Wright, J.D., 2011. On the origin of Cenozoic and Mesozoic "third-order" eustatic sequences. Earth Sci. Rev. 109 (3–4), 94–112. https://doi.org/10.1016/j.earscirev.2011.09.003.

Boulila, S., Vahlenkamp, M., De Vleeschouwer, D., Laskar, J., Yamamoto, Y., Pälike, H., et al., 2018. Towards a robust and consistent middle Eocene astronomical timescale. Earth Planet Sci. Lett. 486, 94–107.

Davies, S.J., Fielding, C.R., Frank, T.D., Isbell, J.L., 2008. The Record of Carboniferous Sea-Level Change in Low-Latitude Sedimentary Successions from Britain and Ireland during the Onset of the Late Paleozoic Ice Age, vol. 441. Geological Society of America Special Papers, pp. 187–204.

Drysdale, R.N., Hellstrom, J.C., Zanchetta, G., Fallick, A.E., Sánchez Goñi, M.F., Couchoud, I., McDonald, J., Maas, R., Lohmann, G., Isola, I., 2009. Evidence for obliquity forcing of glacial Termination II. Science 325 (5947), 1527–1531. https://doi.org/10.1126/science.1170371.

Falahatkhah, O., Kadkhodaie, A., Ciabeghodsi, A.A., Li, M., 2021a. Cyclostratigraphy of the lower triassic kangan Formation in the salman gas field, eastern Persian Gulf, Iran. Palaeogeogr. Palaeoclimatol. Palaeoecol. 561, 110045 https://doi.org/10.1016/j.palaeo.2020.110045.

Falahatkhah, O., Kadkhodaie, A., Ciabeghodsi, A.A., Wood, D.A., 2021b. Astronomical forcing variations of the upper dalan member (late permian) in the South Pars gas field, Persian Gulf, Iran. J. Asian Earth Sci. 209, 104689 https://doi.org/10.1016/j.jseaes.2021.104689.

Fang, Q., Wu, H.C., Hinnov, L.A., et al., 2015. Geologic evidence for chaotic behavior of the planets and its constraints on the third-order eustatic sequences at the end of the Late Paleozoic Ice Age. Palaeogeogr. Palaeoclimatol. Palaeoecol. 440, 848–859. https://doi.org/10.1016/j.palaeo.2015.10.014.

Fang, Q., Wu, H., Hinnov, L.A., Tian, W., Wang, X., Yang, T., Li, H., Zhang, S., 2018. Abiotic and biotic responses to Milankovitch-forced megamonsoon and glacial cycles recorded in South China at the end of the Late Paleozoic Ice Age. Global Planet. Change 163, 97–108. https://doi.org/10.1016/j.gloplacha.2018.01.022.

Franco, D.R., Hinnov, L.A., Ernesto, M., 2012. Millennial-scale climate cycles in Permian–Carboniferous rhythmites: permanent feature throughout geologic time? Geology 40 (1), 19–22.

Ghavidel-Syooki, M., 1984. Palynological study and age determination of Faraghan Formation. In: Kuhe-Faraghan, Southeast of Iran. J. Sci., University of Tehran, pp. 41–50.

Ghavidel-Syooki, M., 1988. Palynostratigraphy & Paleoecology of the Faraghan Formation of Southeastern Iran. Ph.D.Thesis, Michigan State University, p. 249.

Ghavidel-Syooki, M., 1994. Biostratigraphy and paleo-biogeography of some paleozoic rocks at Zagros and alborz mountains. In: Hushmandzadeh, A. (Ed.), Treatise on the Geology of Iran. Ministry of Mines and Metals. Geological Survey of Iran, pp. 1–169.

Ghavidel-Syooki, M., 2003. Palynostratigraphy of devonian sediments in the Zagros Basin, southern Iran. Rev. Palaeobot. Palynol. 127 (3–4), 241–268. https://doi.org/10.1016/S0034-6667(03)00122-2.

Ghavidel-Syooki, M., Álvaro, J.J., Popov, L., Pour, M.G., Ehsani, M.H., Suyarkova, A., 2011. Stratigraphic evidence for the hirnantian (latest ordovician) glaciation in the Zagros mountains, Iran. Palaeogeogr. Palaeoclimatol. Palaeoecol. 307 (1–4), 1–16. https://doi.org/10.1016/j.palaeo.2011.04.011.

Ghienne, J.F., Desrochers, A., Vandenbroucke, T.R., Achab, A., Asselin, E., Dabard, M.P., et al., 2014. A Cenozoic-style scenario for the end-Ordovician glaciation. Nat. Commun. 5 (1), 4485.

Gibbs, M.T., Rees, P.M., Kutzbach, J.E., Ziegler, A.M., Behling, P.J., Rowley, D.B., 2002. Simulations of Permian climate and comparisons with climate-sensitive sediments. J. Geol. 110 (1), 33–55.

Haq, B.U., Al-Qahtani, A.M., 2005. Phanerozoic cycles of sea-level change on the Arabian Platform. GeoArabia 10 (2), 127–160.

Haq, B.U., Schutter, S.R., 2008. A chronology of Paleozoic sea-level changes. Science 322 (5898), 64–68. https://doi.org/10.1126/science.1161648.

Henderson, C.M., Davydov, V.I., Wardlaw, B.R., Gradstein, F.M., Hammer, O., 2012. The permian period. In: Geologic Time Scale. Elsevier, pp. 653–679.

Heydari, E., 2008. Tectonics versus eustatic control on supersequences of the Zagros Mountains of Iran. Tectonophysics 451 (1–4), 56–70. https://doi.org/10.1016/j.tecto.2007.11.046. .

Hilgen, F.J., Krijgsman, W., 1999. Cyclostratigraphy and astrochronology of the Tripolo diatomite formation pre-evaporite Messinian, Sicily, Italy. Terra. Nova 11 (1), 16–22.

Hinnov, L.A., 2000. New perspectives on orbitally forced stratigraphy. Annu. Rev. Earth Planet Sci. 28, 419–475. https://doi.org/10.1146/annurev.earth.28.1.419.

Hollaar, T.P., Baker, S.J., Hesselbo, S.P., Deconinck, J.F., Mander, L., Ruhl, M., Belcher, C.M., 2021. Wildfire activity enhanced during phases of maximum orbital eccentricity and precessional forcing in the Early Jurassic. Commun. Earth Environ. 2 (1), 1–12.

Huang, H., Gao, Y., Jones, M.M., Tao, H., Carroll, A.R., Ibarra, D.E., Wu, H., Wang, C., 2020. Astronomical forcing of Middle Permian terrestrial climate recorded in a large paleolake in northwestern China. Palaeogeogr. Palaeoclimatol. Palaeoecol. 593, 109735 https://doi.org/10.1016/j.palaeo.2020.109735.

Huang, H., Gao, Y., Ma, C., Jones, M.M., Zeeden, C., Ibarra, D.E., Wang, C., 2021. Organic carbon burial is paced by ã 173-ka obliquity cycle in the middle to high latitudes. Sci. Adv. 7 (28), eabf9489.

Huybers, P., Denton, G., 2008. Antarctic temperature at orbital timescales controlled by local summer duration. Nat. Geosci. 1, 787–792.

Katz, Barry Jay, 2001. Lacustrine basin hydrocarbon exploration–current thoughts. J. Paleolimnol. 26 (2), 161–179.

Kochhann, M.V.L., Cagliari, J., Kochhann, K.G.D., Franco, D.R., 2020. Orbital and millennial-scale cycles paced climate variability during the Late Paleozoic Ice Age in the southwestern Gondwana. G-cubed 21 (2), e2019GC008676.

Kodama, K.P., Hinnov, L., 2015. Rock Magnetic Cyclostratigraphy. Wiley-Blackwell, p. 176pp.

Konert, G., Afif, A.M., AL-Hajari, S.A., Droste, H., 2001. Paleozoic stratigraphy and hydrocarbon habitat of the Arabian Plate. GeoArabia 6, 407–442.

Kutzbach, J.E., Gallimore, R.G., 1989. Pangaean climates: megamonsoons of the megacontinent. J. Geophys. Res. 94, 3341–3357.

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A.C.M., Levrard, B., 2004. A long-term numerical solution for the insolation quantities of the Earth. Astron. Astrophys. 428 (1), 261–285. https://doi.org/10.1051/0004-6361:20041335.

Laskar, J., 2020. Astrochronology. In: Geologic Time Scale. Elsevier, pp. 139–158.

Lee, S.Y., Poulsen, C.J., 2009. Obliquity and precessional forcing of continental snowfall and melt: implications for orbital forcing of Pleistocene ice ages. Quat. Sci. Rev. 28 (25–26), 2663–2674.

Le Heron, D.P., Craig, J., Etienne, J.L., 2009. Ancient glaciations and hydrocarbon accumulations in North Africa and the Middle East. Earth Sci. Rev. 93 (3–4), 47–76. https://doi.org/10.1016/j.earscirev.2009.02.001.

Li, M., Hinnov, L.A., Huang, C., Ogg, J.G., 2018. Sedimentary noise and sea levels linked to land–ocean water exchange and obliquity forcing. Nat. Commun. 9 (1), 1–12. https://doi.org/10.1038/s41467-018-03454-y.

Li, M., Hinnov, L., Kump, L., 2019a. Acycle: time-series analysis software for paleoclimate research and education. Comput. Geosci. 127, 12–22. https://doi.org/10.1016/j.cageo.2019.02.011.

Li, M., Huang, C., Ogg, J., Zhang, Y., Hinnov, L., Wu, H., Chen, Q.Z., Zou, Z., 2019b. Paleoclimate proxies for cyclostratigraphy: comparative analysis using a Lower Triassic marine section in South China. Earth Sci. Rev. 189, 125–146. https://doi.org/10.1016/j. earscirev.2019.01.011.

Li, X., Huang, Y., Zhang, Z., Wang, C., 2022. Chemical weathering characteristics of the late cretaceous nenjiang formation from the songliao basin (northeastern China) reveal prominent milankovitch band variations. Palaeogeogr. Palaeoclimatol. Palaeoecol. 601, 111130.

Lourens, L.J., Wehausen, R., Brumsack, H.J., 2001. Geological constraints on tidal dissipation and dynamical ellipticity of the Earth over the past three million years. Nature 409, 1029–1033.

Mann, M.E., Lees, J.M., 1996. Robust estimation of background noise and signal detection in climatic time series. Climatic Change 33 (3), 409–445. https://doi.org/10.1007/BF00142586.

Martin, J.R., Redfern, J., Aitken, J.F., Fielding, C.R., Frank, T.D., Isbell, J.L., 2008. A regional overview of the late Paleozoic glaciation in Oman. Resolving the late Paleozoic ice age in time and space: Geol. Soc. Am. Spec. Pap. 441, 175–186.

Melvin, J., Sprague, R.A., 2006. Advances in Arabian stratigraphy: origin and stratigraphic architecture of glaciogenic sediments in Permian-Carboniferous lower Unayzah sandstones, eastern central Saudi Arabia. GeoArabia 11, 105–152.

Melvin, J., Sprague, R.A., Heine, C.J., 2010. From bergs to ergs: the late Paleozoic Gondwanan glaciation and its aftermath in Saudi Arabia. In: Lopez-Gamundi, O.R., Buatois, L.A. (Eds.), Late Paleozoic Glacial Events and Postglacial Transgressions in Gondwana, vol. 468. Geological Society of America Special Paper, pp. 37–80.

Naish, T., Powell, R., Levy, R., Wilson, G., Scherer, R., Talarico, F., et al., 2009. Obliquity-paced pliocene west antarctic ice sheet oscillations. Nature 458 (7236), 322–328.

Peyravi, M., Rahimpour-Bonab, H., Nader, F.H., Kamali, M.R., 2016. Chemo-stratigraphy as a tool for sequence stratigraphy of the early triassic kangan formation, north of the Persian Gulf. Carbonates Evaporites 31 (2), 163–178. https://doi.org/10.1007/s13146-015-0253-6.

Roy, D.K., Roser, B.P., 2013. Climatic control on the composition of carboniferous–permian Gondwana sediments, khalaspir basin, Bangladesh. Gondwana Res. 23 (3), 1163–1171. https://doi.org/10.1016/j.gr.2012.07.006.

Ruban, D.A., Al-Husseini, M.I., Iwasaki, Y., 2007. Review of Middle East Paleozoic plate tectonics. GeoArabia 12 (3), 35–56.

Sabbaghiyan, H., Aria-Nasab, M., 2019. Early carboniferous (mississippian) miospore assemblage from Persian Gulf, southwest Iran. Geopersia 9 (1), 195–202.

Sabouri, J., Mahmoudi, M., Sabbaghiyan, H., Aria–Nasab, M., 2014. The first evidences of Carboniferous (Middle–? Late Mississippian) sediments in Zagros Basin, Iran and its palaeogeographic implications. Abstract Volume and Proceedings of the Third International Symposium of the IGCP– 589, Development of the Asian Tethyan Realm: Genesis, Process and Outcomes 29–34.

Sadler, P.M., 1981. Sediment accumulation rates and the completeness of stratigraphic sections. J. Geol. 89 (5), 569–584.

Scotese, C.R., 2014. Atlas of Permo-Carboniferous Paleogeographic Maps (Mollweide Projection), Maps 53–64, Volumes 4, the Late Paleozoic, PALEOMAP Atlas for ArcGIS. PALEOMAP Project, Evanston, IL.

Sharland, P.R., Archer, R., Casey, D.M., Davies, R.B., Hall, S.H., Heward, A.P., Horbury, A.D., Simmons, M.D., 2001. Arabian Plate Sequence Stratigraphy, GeoArabia Special Publication, vol. 2. Gulf PetroLink, Bahrain, p. 371.

Šimíček, D., Bábek, O., Leichmann, J., 2012. Outcrop gamma-ray logging of siliciclastic turbidites: separating the detrital provenance signal from facies in the foreland-basin turbidites of the Moravo-Silesian basin, Czech Republic. Sediment. Geol. 261, 50–64. https://doi.org/10.1016/j.sedgeo.2012.03.003. .

Sinnesael, M., Zivanovic, M., De Vleeschouwer, D., Claeys, P., 2018. Spectral moments in cyclostratigraphy: advantages and disadvantages compared to more classic approaches. Paleoceanogr. Paleoclimatol. 33 (5), 493–510. https://doi.org/10.1029/2017PA003293.

Spina, A., Stephenson, M.H., Cirilli, S., Aria-Nasab, M., Rettori, R., 2018. Palynostratigraphy of the permian faraghan Formation in the Zagros Basin, southern Iran. Riv. Ital. Paleontol. Stratigr. 124 (3), 573–595. https://doi.org/10.13130/2039-4942/10706.

Spina, A., Cirilli, S., Sorci, A., Schito, A., Clayton, G., Corrado, S., Fernandes, P., Galasso, F., Montesi, G., Pereira, Z., Rashidi, M., Rettori, R., 2021. Assessing thermal maturity through a multi-proxy approach: a case study from the permian Faraghan Formation (Zagros Basin, southwest Iran). Geosciences 11 (12), 484. https://doi.org/10.3390/geosciences11120484.

Szabo, F., Kheradpir, A., 1978. Permian and triassic stratigraphy, Zagros Basin, southwest Iran. J. Petrol. Geol. 1 (2), 57–82.

Tiab, D., Donaldson, E.C., 2015. Petrophysics: Theory and Practice of Measuring Reservoir Rock and Fluid Transport Properties. Gulf professional publishing., p. 894.

Thomson, D.J., 1982. Spectrum estimation and harmonic analysis. Proc. IEEE70 1055–1096. https://doi.org/10.1109/PROC.1982.12433.

Tuenter, E., Weber, S.L., Hilgen, F.J., Lourens, L.J., 2003. The response of the African summer monsoon to remote and local forcing due to precession and obliquity. Global Planet. Change 36 (4), 219–235.

Vennin, E., Kolodka, C., Asghari, A., Thomazo, C., Buoncristiani, J.F., Goodarzi, H., Desaubliaux, G., 2015. Discussion on palaeozoic discontinuities in the kuh-e surmeh area (Zagros, Iran). Mar. Petrol. Geol. 66, 1073–1092.

Waltham, D., 2015. Milankovitch period uncertainties and their impact on cyclostratigraphy. J. Sediment. Res. 85 (8), 990–998. https://doi.org/10.2110/jsr.2015.66.

Wang, M., Chen, H., Huang, C., Kemp, D.B., Xu, T., Zhang, H., Li, M., 2020. Astronomical forcing and sedimentary noise modeling of lake-level changes in the Paleogene Dongpu Depression of North China. Earth Planet Sci. Lett. 535, 116116 https://doi.org/10.1016/j.epsl.2020.116116.

Wei, R., Zhang, R., Li, M., Wang, X., Jin, Z., 2023. Obliquity forcing of lake-level changes and organic carbon burial during the Late Paleozoic Ice Age. Global Planet. Change, 104092.

Zamanzadeh, S.M., 2008. Sedimentary Petrology/environment and Sequence Stratigraphy of Zakeen and Faraghan Formations in Their Type Section (Bandar-Abbas Area). Ph.D. Thesis. University of Tehran, Iran, p. 280.

Zamanzadeh, S.M., Amini, A., Kamali, M.R., 2009a. Burial history reconstruction using late diagenetic products in the early Permian siliciclastics of the Faraghan Formation, Southern Zagros, Iran. J. Petrol. Geol. 32 (2), 171–192. https://doi.org/10.1111/j.1747-5457.2009.00442.x.

Zamanzadeh, S.M., Amini, A., Rahimpour-Bonab, H., 2009b. Eogenetic dolomite cementation in Lower Permian reservoir sandstones, southern Zagros, Iran. Geol. J. 44 (5), 501–525. https://doi.org/10.1002/gj.1151.

Zhang, J., Jiang, Z., Liang, C., Baars, T.F., Wang, Y., Abels, H.A., 2022a. Astronomical forcing of meter-scale organic-rich mudstone–limestone cyclicity in the Eocene Dongying sag, China: implications for shale reservoir exploration. AAPG (Am. Assoc. Pet. Geol.) Bull. 106 (8), 1557–1579.

Zhang, R., Li, X., Xu, Y., Li, J., Sun, L., Yue, L., et al., 2022b. The 173-ka obliquity cycle pacing the asian monsoon in the eastern Chinese loess plateau from late miocene to pliocene. Geophys. Res. Lett. 49 (2), e2021GL097008.

Zoleikhaei, Y., Amini, A., Zamanzadeh, S.M., 2015. Integrated provenance analysis of zakeen (devonian) and faraghan (early permian) sandstones in the Zagros belt, SW Iran. J. Afr. Earth Sci. 101, 148–161. https://doi.org/10.1016/j.jafrearsci.2014.09.012.