

Depositional environments and Tectonic Controls on Paleocene phosphorite-rich successions in the Marbat-Traibeel Basin, Western Desert of Iraq

Ibrahim Q. Mohammed^a, Ali H. Dohan^b, Anwar K. Mousa^c, Fadhil A. Lawa^d, Sawsan H. Alhazaa^e, Sherif Farouk^{f,*}, Khaled Al-Kahtany^g, John H. Powell^h

^a Al Maaref University College, Al Anbar, Iraq

^b Petroleum Engineering Department, College of Engineering, University of Kirkuk, Iraq

^c Department of Geology, College of Science, Baghdad University, Iraq

^d Department of Geology, University of Sulaimani, Kurdistan, Iraq

^e Department of Applied Geology, College of Science, University of Tikrit, Tikrit, Iraq

^f Exploration Department, Egyptian Petroleum Research Institute, Egypt

^g Geology and Geophysics Department, Geological Studies Center, College of Science, King Saud University, Riyadh, Saudi Arabia

^h British Geological Survey, Nottingham, UK

ARTICLE INFO

Handling editor: M. Mapeo

ABSTRACT

This study explores the depositional environments of Paleocene phosphorite-rich carbonate and siliciclastic successions along an NNE-SSW cross-section of the Marbat-Traibeel Basin, Western Desert, Iraq. This study examines over 500 thin sections from six vertical stratigraphic sections, encompassing boreholes and outcrops along a transect from the Rutbah High to the Iraqi-Jordanian border. It investigates lithofacies distribution, depositional sequences, and basin architecture through an integrated analysis of tectonic, sedimentological, biostratigraphic, and sequence stratigraphic data, providing insights into the basin's depositional history. It aims to elucidate the geological evolution of the Paleocene Akashat Formation and the Traifawi Member/Jeed Formation within the Marbat-Traibeel Basin, located on the northern margin of the southern Tethys Ocean. This region is characterized by complex interactions between shallow marine carbonate, siliciclastic, siliceous, and phosphatic lithofacies influenced by a submerged but tectonically active structural high (Rutbah High). The study identifies 26 lithofacies classified into seven associations based on lithological and sedimentological features, representing inner, middle, and outer ramp depositional environments. The phosphorite-rich carbonate succession, particularly the Upper Danian Hirri Member, indicates deposition on an open, distally steepened ramp and hosts substantial economic phosphate reserves. Syn-depositional tectonics influenced the ramp morphology and sedimentation of the phosphorite, which resulted in lateral variations in thickness and microfacies. Tectonic instability resulted in numerous depositional hiatuses (Cretaceous/Paleogene, Lower Danian - Upper Danian; Selandian - Thanetian, Upper Paleocene - Lower Eocene boundary) and eastward thinning of depositional sequences on the Rutbah High. Seven distinct Paleocene third-order depositional sequences are identified in the western part of the study area, near the Jordan-Iraq border, passing eastward to four third-order sequences, a pattern attributed to tectonic uplift on the Rutbah High. The depositional sequences are separated by boundaries characterized by vertical facies changes, including prominent *Thalassinoides* burrows/firmgrounds on transgressive surfaces with significant hiatuses that correlate with known eustatic sea-level falls associated with the Arabian Platform.

1. Introduction

During the Late Cretaceous–Early Paleogene period, extensive

phosphorite deposits formed along the southern margin of the Tethys Ocean, accounting for approximately two-thirds of the world's reserves (Notholt, 1985; Föllmi et al., 1992; Pufahl et al., 2003; El Bamiki et al.,

* Corresponding author.

E-mail address: geo.sherif@hotmail.com (S. Farouk).

<https://doi.org/10.1016/j.jafrearsci.2025.105802>

Received 10 October 2024; Received in revised form 4 August 2025; Accepted 5 August 2025

Available online 6 August 2025

1464-343X/© 2025 Elsevier Ltd. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

2021; Baoumy and Farouk, 2022). These globally important deposits are widely distributed, including North Africa, the Middle East, South America, Iran, and potentially Pakistan and India. Iraq, Jordan, Saudi Arabia, and Morocco are particularly notable for their substantial reserves (Al-Bassam, 2017). In the Western Desert of Iraq, phosphorite-bearing strata range in age from the Late Cretaceous to the Eocene. They are interbedded with chalky marl, siliciclastics, opal-CT porcellanite, chert, silica geodes, and smectite/palygorskite-rich shales, some of which are organic-rich in the subsurface (Al-Bassam, 2017; Mohammed, 1993; Mohammed et al., 2022). Located at the eastern edge of the Tethyan phosphorite belt, the Paleocene Akashat Formation contains extensive economic phosphorite beds (Al-Bassam, 2017) (Fig. 1). Biostratigraphic studies of the Paleocene succession have been conducted on both surface exposures and subsurface wells (Ctyroky and Karim, 1971; Karim in Jassim et al., 1984; Al-Jibouri and Gayara, 2015; Karim and Al-Kubaysi, 2020). However, these studies require updating to reflect the latest research. In addition, there are contrasting interpretations regarding the sedimentary environments north of the Western Desert and south of the Euphrates River (Al-Sammari et al., 1994; Al-Mutwali et al., 2002; Mohammed, 1993; Mohammed et al., 2022). Previous studies suggest an open, deep marine pelagic facies influenced by phosphorus and silica-bearing upwelling currents supplied to the Iraqi phosphorite basin from the northeast, with the basin opening and deepening in that direction (Al-Bassam, 2017; Ctyroky and Karim, 1971; Karim in Jassim et al., 1984; Al-Jibouri and Gayara, 2015; Karim and Al-Kubaysi, 2020). However, data reviews in the present study suggest no Paleocene phosphogenic deposits are present based on borehole records located north of the Akashat and Ga'ara region, such as the Anah Graben (e.g., Anah 1 and Anah 2 wells) (Ali, 1985; Al-Mutwali et al., 2002). Furthermore, sandstone and shallow marine mixed carbonate-siliciclastic facies south of the Anah Graben were deposited in a separate depositional basin not connected with the phosphorite-rich Paleocene Marbat-Traibeel Basin (Ali, 1985; Al-Mutwali et al., 2002) (Fig. 2). A contrasting scenario of basin configuration is presented in this paper. The northeastern Paleocene succession (BH12/7 well) is dominated by lagoonal dolomitic limestone facies (Mousa et al., 2023). These successions in the north and northwest Ga'ara Ramp exhibit hybrid facies comprising bone-rich coprolites, bivalve shell fragments, and sand to pebble grain-size siliciclastics. Contrary to a previous study that revealed a basin opening to the north and northeast (Al-Bassam, 2017; Mohammed et al., 2022) suggested the opposite: i.e. the basin shallows to the north and northeast, and that the northern and eastern shoreline is not far away (i.e., the Anah Graben). The Upper Maastrichtian – Lower Danian Jeed Formation, which is exposed and extends in the subsurface underlying the Paleocene Akashat Formation, passes from a proximal setting in the east and northeast (northeast Ga'ara) to distal in the west and southwest (Traibeel area) (Mohammed et al., 2022). The present study comprehensively analyzes the high-resolution stratigraphy and sedimentology of the Paleocene Akashat Formation and Traifawi Member (upper part of the Jeed Formation). It investigates the geological history and depositional processes responsible for the phosphate reserves in Iraq's Western Desert. By integrating paleo-oceanographic, stratigraphic and sedimentological approaches, this research addresses existing controversies relating to age assignments, depositional models, paleogeography, stratigraphic sequences and syndepositional tectonics. The findings highlight the significance of these analyses for advancing scientific understanding of Paleogene phosphate reserves in the region.

2. Geological setting

Since the Late Permian, the northern end of the Ha'il-Rutbah Arch has influenced sedimentary basins in western Iraq, southern Syria, and eastern Jordan (Meissner et al., 1989). During the Late Cretaceous to Early Paleogene, the Ha'il Arch extended northward into western Iraq, merging with the Rutbah High (Meissner et al., 1989). By the Late

Maastrichtian, the Rutbah Basin was divided into two distinct domains (Fig. 3): the East Rutbah Basin, dominated by carbonate deposits from the Late Maastrichtian to Eocene (represented by the upper parts of the Tayarat, Umm Er Radhuma, and Jaddala formations), and to the west, the Marbat-Traibeel Basin (MTB), characterized by phosphatic deposits during the same time interval (encompassing the Jeed, Akashat, and Ratga Formations) (Figs. 3–5), which is the focus of this study.

The Upper Cretaceous Maastrichtian–Eocene phosphorite deposits in Iraq are primarily located along the western flank of the Rutbah High in the west Rutbah Basin (Fig. 3), referred to, here, as the Marbat-Traibeel Basin (MTB). This area, considered part of Iraq's Stable Zone (Fouad, 2006), extends across the Western Desert, covering the northern and western edges of the Ga'ara Depression, the Akashat area, southern Traifawi, and H3 regions, reaching the Sirhan-Turayf Basin near the Saudi Arabian border (Fig. 3). Despite their extent, the boundaries of the phosphate depositional basin remain poorly defined, and its formal naming is still ambiguous.

Significant tectonic events, including hiatuses and unconformity surfaces with missing or incomplete depositional sequences, mark the evolution of the Late Cretaceous–Paleogene East Rutbah Basin and MTB, indicating long-term instability in the region. The pre-Paleocene unconformities are briefly outlined below:

In the Late Cretaceous, two major unconformity surfaces were identified in the Rutbah region prior to the development of the MTB (Jassim and Buday, in Jassim et al., 2006; Mohammed et al., 2022). The Pre-Cenomanian Wasia Unconformity (Fig. 2) marks a significant hiatus between the Triassic carbonates and the overlying Cenomanian Rutbah Formation. At the same time, the Pre-Aruma Unconformity represents a long hiatus and karstified surface between the Cenomanian (Turonian?) Ms'ad Formation and the Campanian Tayarat Formation, with most of the Turonian, Coniacian, and Santonian strata missing. Additionally, a critical unconformity separates the lower Maastrichtian carbonate sediments of the Tayarat Formation from the upper Maastrichtian phosphatic sediments of the lower part of Jeed Formation, potentially linked to reactivation on NNE–SSW faults. These unconformities demonstrate the tectonic instability of the Rutbah High/MTB area during the Late Cretaceous.

Four significant hiatuses were identified within the Paleocene succession. The first is marked by the base of the Traifawi Member (Danian) at the K/Pg boundary; this is followed by unconformities at the base of the overlying Hirri Member (intra-Danian), and the boundary between the Akashat Formation (Duwima Member) and the Ratga Formation (Paleocene–Eocene boundary) (Al-Bassam, 2017; Mohammed et al., 2022) (Fig. 2).

3. Materials and methods

The study is based on more than 500 thin sections collected from six vertical stratigraphic sections, two boreholes (BH5/6 and BH5/8) and four outcrops (Fig. 1) to obtain an insight into the distribution and composition of lithofacies, their sequence stratigraphy, and the architecture of the basin. Selected thin sections were stained with Alizarin Red S to distinguish between calcite and dolomite. The six localities were chosen on a transect passing from the crest of the Rutbah High (Ga'ara uplift) in the east (proximal) to the west (distal). They comprise: Marbat (NE Ga'ara), Outcrop-1 (near Akashat mine), Akashat Mine, Traifawi area (SW Rutbah City), Borehole 5/8 (SW Akashat), and Borehole 5/6 (west of the Iraqi – Jordanian border) (Fig. 1). Grain types, textures, and sedimentary formations formed the basis for lithofacies and microfacies. The phosphatic limestone/dolostone/siliciclastic (>5 % to < 50 % phosphatic grains) and phosphorite lithofacies (>50 % phosphatic grains) are characterized by adaptations and modifications of Al-Bassam et al. (2010), Trappe (2001), Dunham (1962), Zuffa et al. (1980) and Embry and Klován (1971). The biostratigraphic framework for this study is based on the lowest occurrence (LO) and highest occurrence (HO) planktic foraminiferal bioevents as defined by Wade

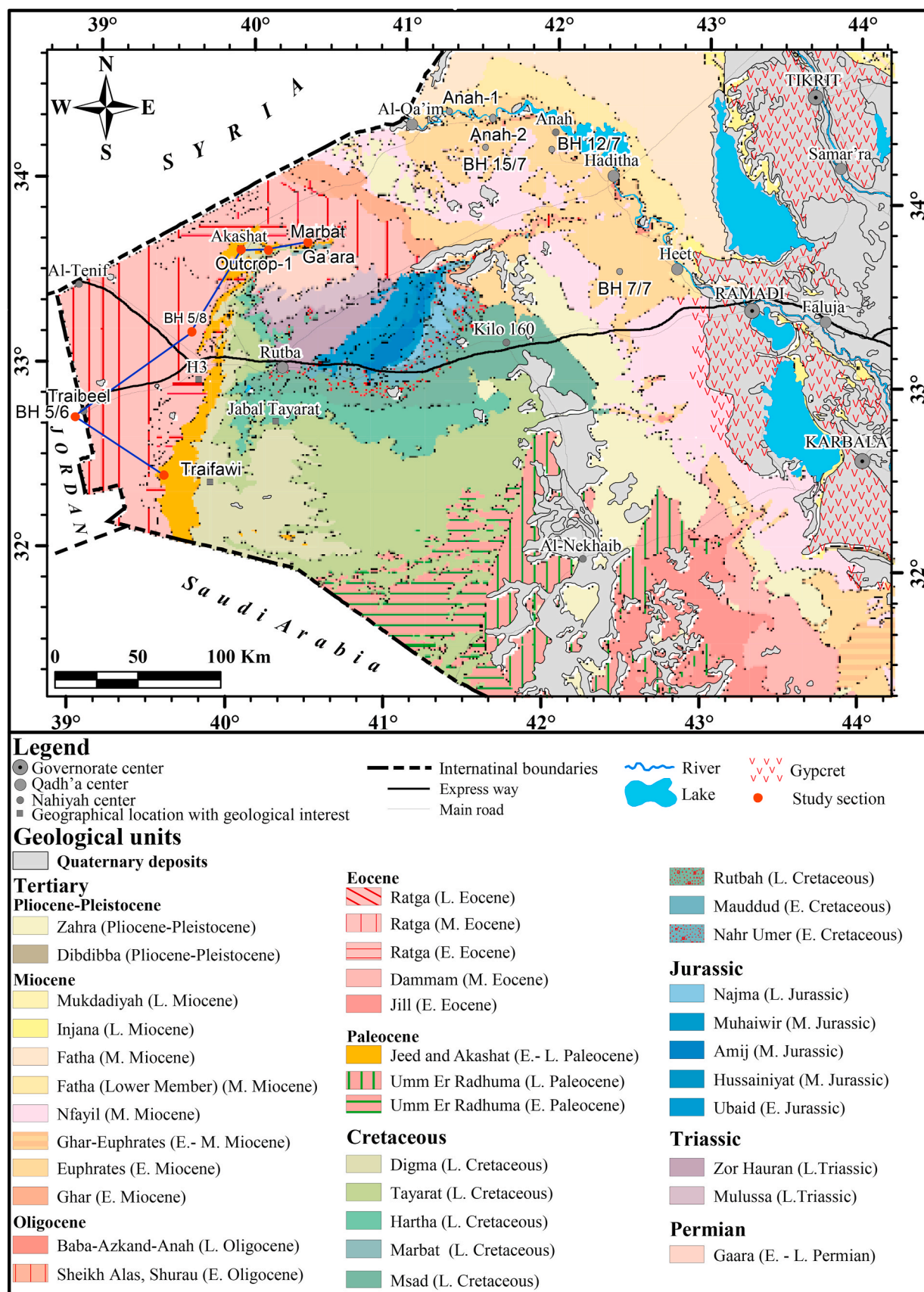


Fig. 1. Geological map of the Western Desert, Iraq, showing the sections and boreholes used in this study, indicated by a red circle (modified after Sissakian and Fouad, 2015).

4

Fig. 2. Lithostratigraphic scheme for the Upper Cretaceous–Lower Paleogene strata of Iraq’s western desert, showing the former nomenclature and that used in this paper, including Upper Maastrichtian Jeed Formation and modified Akashat Formation. This research places three phosphatic and siliceous formations, Jeed, Akashat, and Ratga, into a new Upper Maastrichtian – Eocene Samhat Group within the Marbet – Traibeel Basin (MTB).

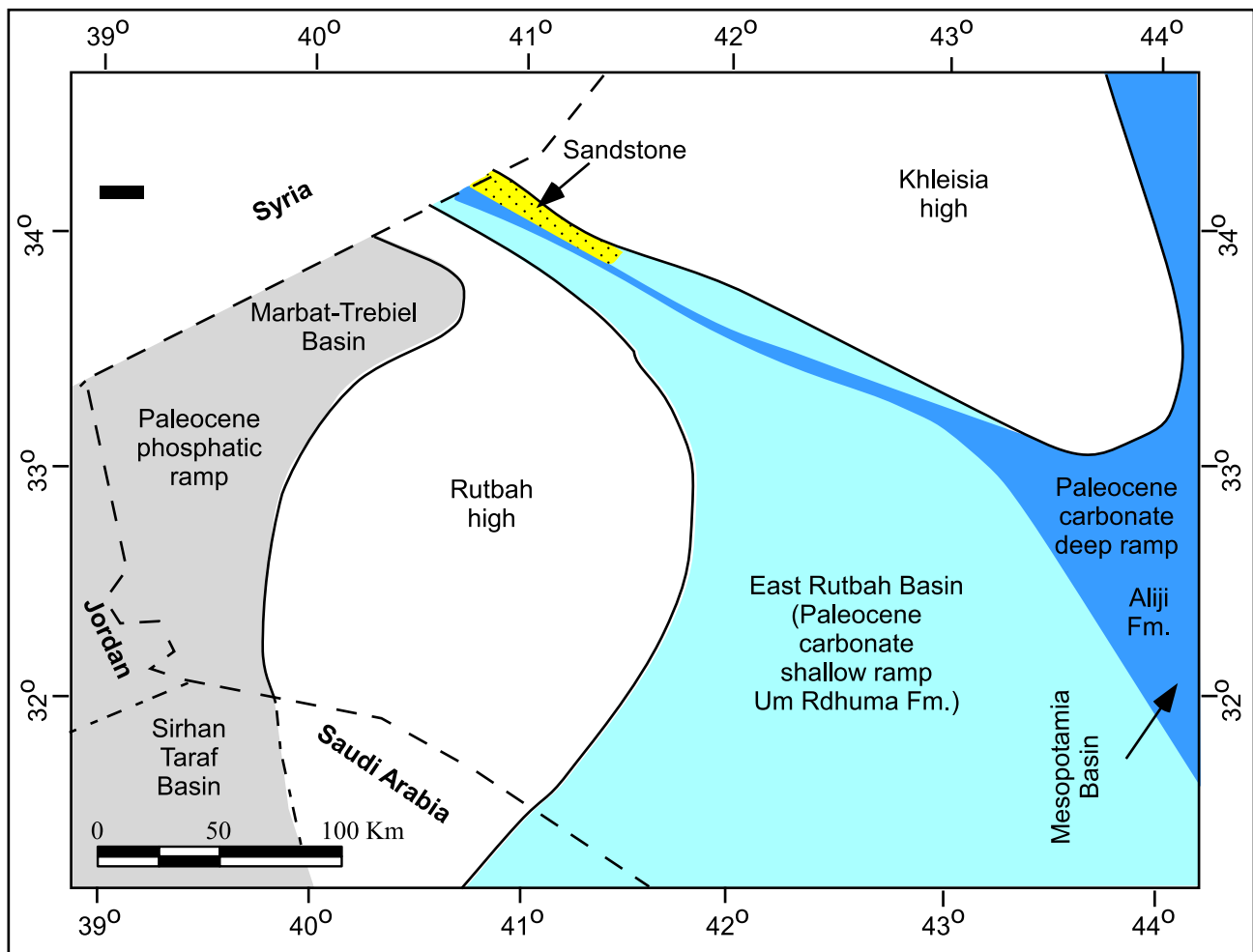


Fig. 3. Simplified paleogeographical map showing the distribution of the Paleocene basins in Western Iraq and surrounding countries.

et al. (2011, 2020) supplemented by benthic foraminiferal biozonations based on Serra-Kiel et al. (2020, 2019). The most critical planktic or benthic foraminifera species are shown in Figs. 6 and 7. According to sequence stratigraphic terminologies and concepts (Van Wagoner et al., 1988; Catuneanu, 2017; Catuneanu et al., 2011), the sequence stratigraphy framework is dependent on the identification of the sequence boundary (SB) and sequence tracts, as well as the regional sequence stratigraphy framework for the Arabian Plate provided by Sharland et al. (2001).

4. Results

4.1. Stratigraphy

During Late Maastrichtian to Eocene time, the recognized formations in the Marbat-Traibeel Basin (MTB) include the Jeed Formation (Upper Maastrichtian - Lower Danian), the Akashat Formation (Upper Danian - Thanetian), and the Ratga Formation (Eocene, Ypresian/Lutetian)) with significant unconformities (hiatuses) separating these units (Fig. 2). Notable sedimentary facies changes across the Marbat-Traibeel Basin have been reported (Mohammed et al., 2022; Karim and Al-Kubaysi, 2020). A brief description of the formations and their biostratigraphy is given below.

4.1.1. Jeed Formation (Upper Maastrichtian-Lower Danian)

The Jeed Formation, dating from the Upper Maastrichtian to the Lower Danian, is composed of two members:

The **Safra Member** (Upper Maastrichtian) and the Traifawi Member (Lower Danian) (Mohammed et al., 2022) (Fig. 4). The Safra Member is reported within the *Plummerita hantkeninoides* Zone at wells B5/6 and B5/8 with respective thicknesses of approximately 5 and 10 m. This zone is recognized globally for its **Latest Maastrichtian taxa** from 65.30 Ma to 65.00 Ma (Li and Keller, 1998). The zone is characterized by taxa such as *Abathomphalus mayaroensis*, *Hedbergella monmouthensis*, *Pseudoguembelina palpebra*, *Rugoglobigerina hexacamerata*, *R. rugosa*, and *Globotruncanella havanensis*. Benthic foraminifera in this zone include *Cibicides* sp. and *Lenticulina* sp. Previous studies in northern Iraq have documented this zone extensively (e.g., Al-Mutwali, 1992; Hammoudi, 2011; Sharbazheri et al., 2009; Lawa et al., 2017) and it was also documented in Western Iraq by Mousa et al. (2020).

The **Traifawi Member** (Danian), identified within the *Subbotina triloculinoidea* Zone (P1c; Danian), is present in wells B5/6 and B5/8, with thicknesses of approximately 5 m and 10 m, respectively. This zone is defined by the interval between the lowest occurrence (LO) of *Subbotina triloculinoidea* and the LO of *Morozovella angulata*. Significant paleobiological events within this interval include the first appearances of species such as *Globoconusa daubjergensis*, *Subbotina* spp., *Globanomalina* spp., and *Chiloguembelina* spp., alongside the extinction of taxa like *Globotruncana* and *Heterohelix*. Associated species within this zone include *Guembelitra* spp., *Globanomalina compressa*, and *Globigerina danica*. Notably, the K/Pg Transitional Zone lacks index planktic or benthic foraminifera, suggesting a potential hiatus during the earliest Danian. This zone correlates with the *Globoconusa daubjergensis* Zone in Iraq, as documented by researchers such as Bamerni et al. (2021),

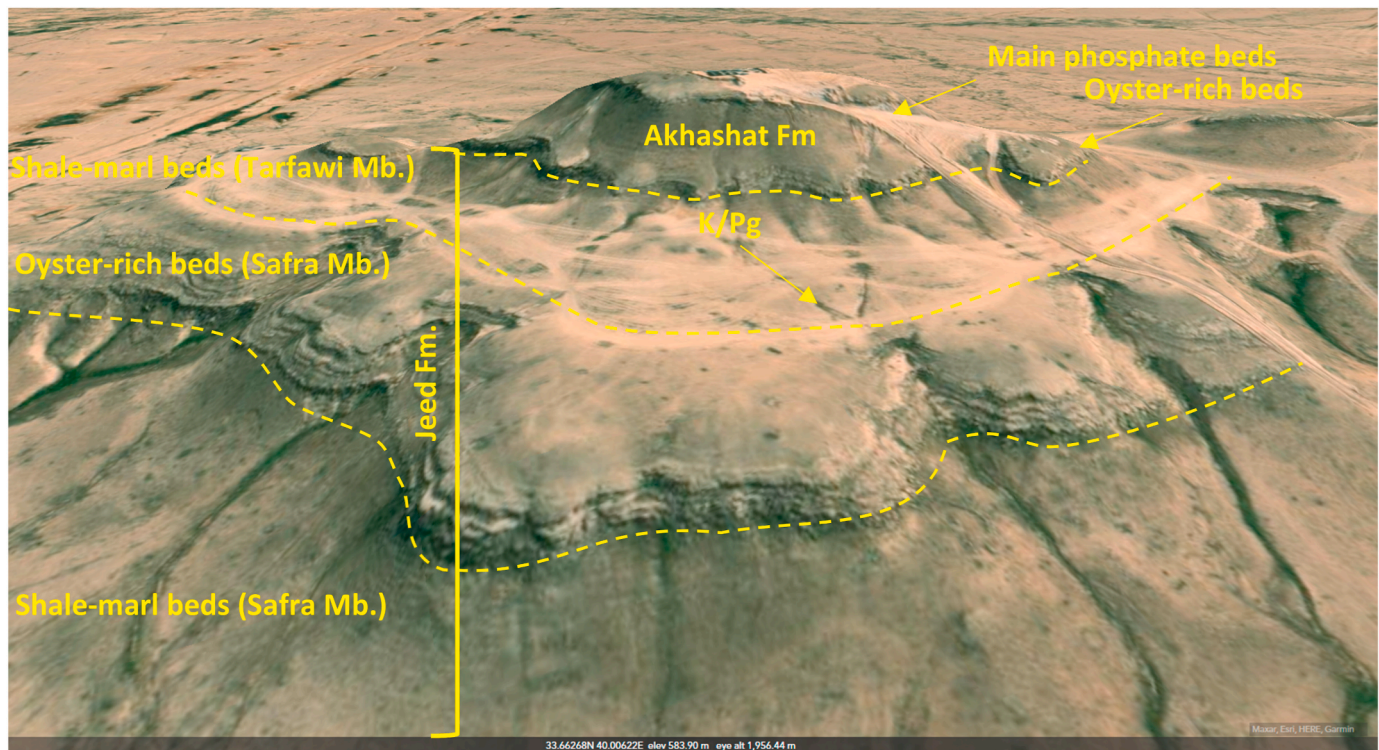


Fig. 4. Oblique satellite photograph from Google Maps showing the lithofacies of the Safra Member (Upper Maastrichtian) and Lower Danian Trefawi Member (Jeed Formation), as well as the phosphorite-rich Upper Danian Hirri Member (Akashat Formation) lithofacies. The height of the section is c. 40 m.

Ctyroky and Karim (1971), Karim in Jassim et al. (1984), Al-Mutwali et al. (2002), Lawa and Qadir (2023), Al-Jibouri and Gayara (2015), and Karim and Al-Kubaysi (2020a-b).

The Jeed Formation decreases in thickness from 99 m in BH5/6 and 60 m in BH5/8 wells in the west, to 4 m at Outcrop 1; the Traifwai Member thins to the northeast and is absent at Marbat El Hassan (Fig. 5). The formation was introduced by Mohammed et al. (2022), replacing the previous designation of the Upper Maastrichtian Digma Formation (Al-Bassam et al., 2017; Jasim and Buday, in Jassim et al., 2006; Sissakian and Mohammed, 2007). This formation features a diverse lithology from west to east; in the west, it is dominated by marl/carbonate rich in organic matter. In Jordan, west of the study area, coeval lithofacies comprise argillaceous limestone and marl (Muwaqqar Chalk Marl Formation) recorded in boreholes (RH1; QA1 in Andrews, 1992) and at outcrops farther west (Powell, 1989; Powell and Moh'd, 2011). In the east (Outcrop 1), the lithologies comprise limestone, rich in bivalves, chert and silica geodes and shale, passing laterally to mixed dolostone – siliciclastic facies at the Marbat El-Hassan section (Fig. 5). The previously defined Digma Formation, originally recorded in Anah –1 well ranges from the Upper Campanian to the Lower Maastrichtian and is not represented by strata of upper Maastrichtian age (Al-Mutwali et al., 2002). Furthermore, in the Anah-1 well the lithology is different, represented by planktic foraminiferal – rich, fine-grained limestone and marl and is characterized by the abundance of a glauconite – phosphate – pyrite assemblage typical of the deep water open marine environments typical of the Shiranish Formation exposed in Kurdistan Region of Iraq (Mohammed et al., 2025).

4.1.2. Akashat Formation (Upper Danian – Selandian/Thanetian)

this formation unconformably overlies the Traifwai Member (Jeed Formation) (Fig. 4). It contains substantial phosphate deposits and is subdivided into two members from base to top: the Hirri and Duwima members (Figs. 2, 4 and 5).

The **Hirri Member** (8–28 m. thick) consists of phosphatic oyster-rich limestone interbedded with thick phosphorite beds. This member

contains significant phosphate reserves, with estimates suggesting around ten billion tons of phosphorite in Iraq territory (Al-Bassam, 2017). To the west and southwest in Jordan, these sediments pass laterally to argillaceous limestone and marl of the Muwaqqar Chalk-Marl Formation, which contains only thin beds of phosphate and glauconite (Fig. 5) (Powell, 1989; Andrews, 1992; Messaoud et al., 2025). The upper part of Muwaqqar Chalk-Marl Formation (Jordan) and Hirri Member occurs within *Morozovella angulata-Igorina albeari* Subzone (P3a; Danian): the *M. angulata* Zone (P3) globally classified into P3a and P3b subzones of latest Danian– Selandian age. The P3b Subzone is defined from the LO of *M. angulata* to the LO of *Igorina albeari* characteristic of the latest Danian age. Historically, biostratigraphic research in Iraq has used the *M. angulata* Zone to denote the Selandian age (Lawa and Qadir, 2023; Al-Khalaif and Al-Mutwali, 2020) without subdivision. This study aligns the *M. angulata* Zone with the P3a Subzone, based on the LO of *M. angulata*, *Parasubbotina pseudobulloides*, *Subbotina triloculinoidea*, and *Globigerina haynesi*. This zone is associated with benthic foraminifera, including *Haymanella paleocenica*, *Daviesina praegarrumensis*, and *Neopinoidea duwi*, in addition to *Anomalina* sp., *Lenticulina* sp., *Valvulinaria ravni*, *Bulimina* cf. *danica*, *Dentalina* sp., *Gyroldina* sp., and *Cibicides* sp. The P3a Subzone in Iraq has historically been considered indicative of the Selandian age, but recent zonations by Wade et al. (2020) suggest it corresponds to the Late Danian age.

The **Duwima Member** (2–20 m. thick) consists of limestone, chert and phosphorite. The formation is overlain unconformably by the lower Eocene Ratga Formation (Figs. 2 and 5).

The **Duwima Member** correlates with the *Morozovella velascoensis* Zone (Late Paleocene; Thanetian). In Iraq, this zone defined from LO of *M. velascoensis* to LO of *Numulites* spp. This zone is reported in Duwima Member BH 5/6 well with thickness 24 m. It is characterized by the presence of heavily keeled planktonic foraminifera such as *M. acuta* and *Subbotina triloculinoidea*, and this zone is indicative of a Thanetian age. In Iraq, this zone is used as an index for the Thanetian age and occasionally shows intercalation with shallow benthic foraminiferal assemblages as evidenced by *Ranikothalia soldadensis*, *R. sahnii*,

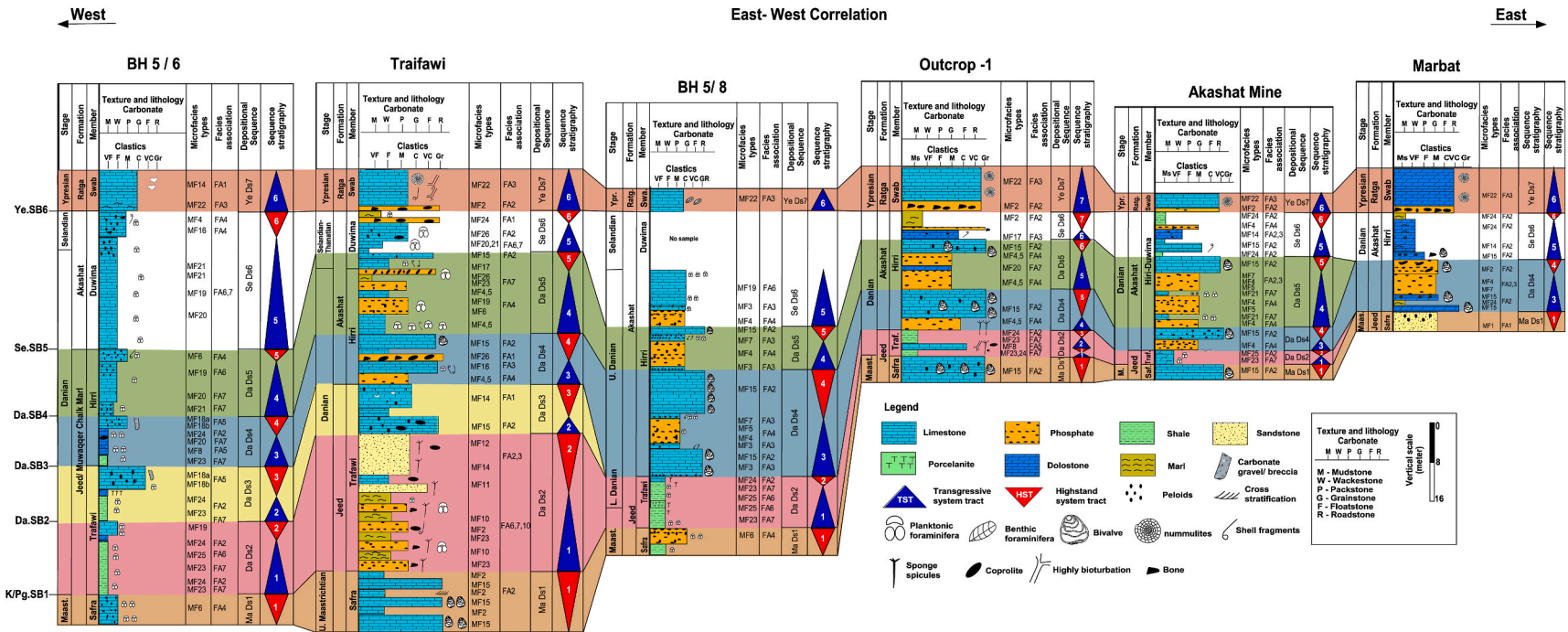
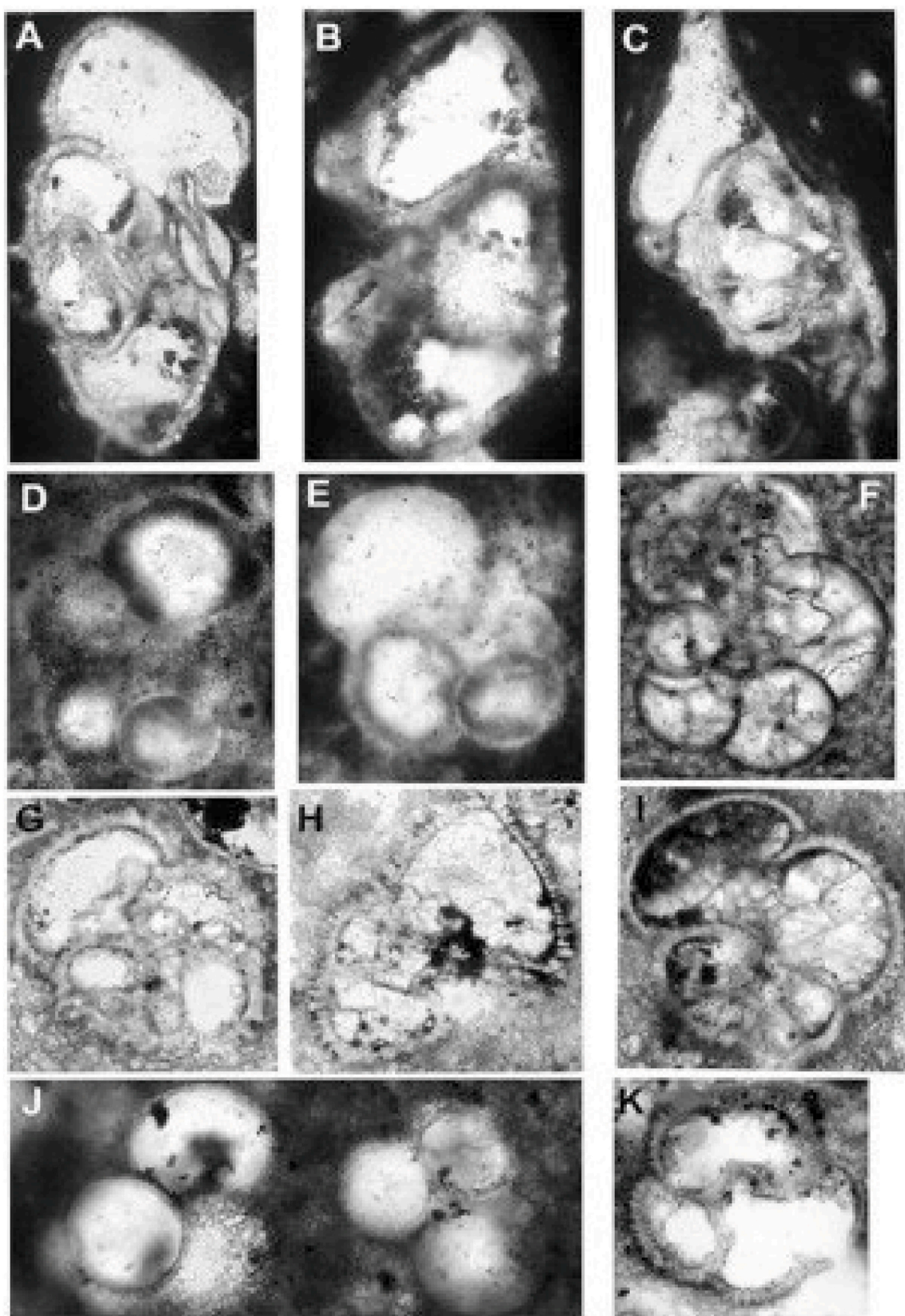


Fig. 5. Lithostratigraphic correlation chart across the Marbat-Traieel Basin from west (basinal) to east (proximal) along the transect shown in Fig. 1 showing the seven Depositional Sequences (DS, indicated by color bands) described in the text. Note the overall thinning from west to east and the absence of Depositional Sequences 3 and 5 in the west. Sequence Tracts are also indicated.

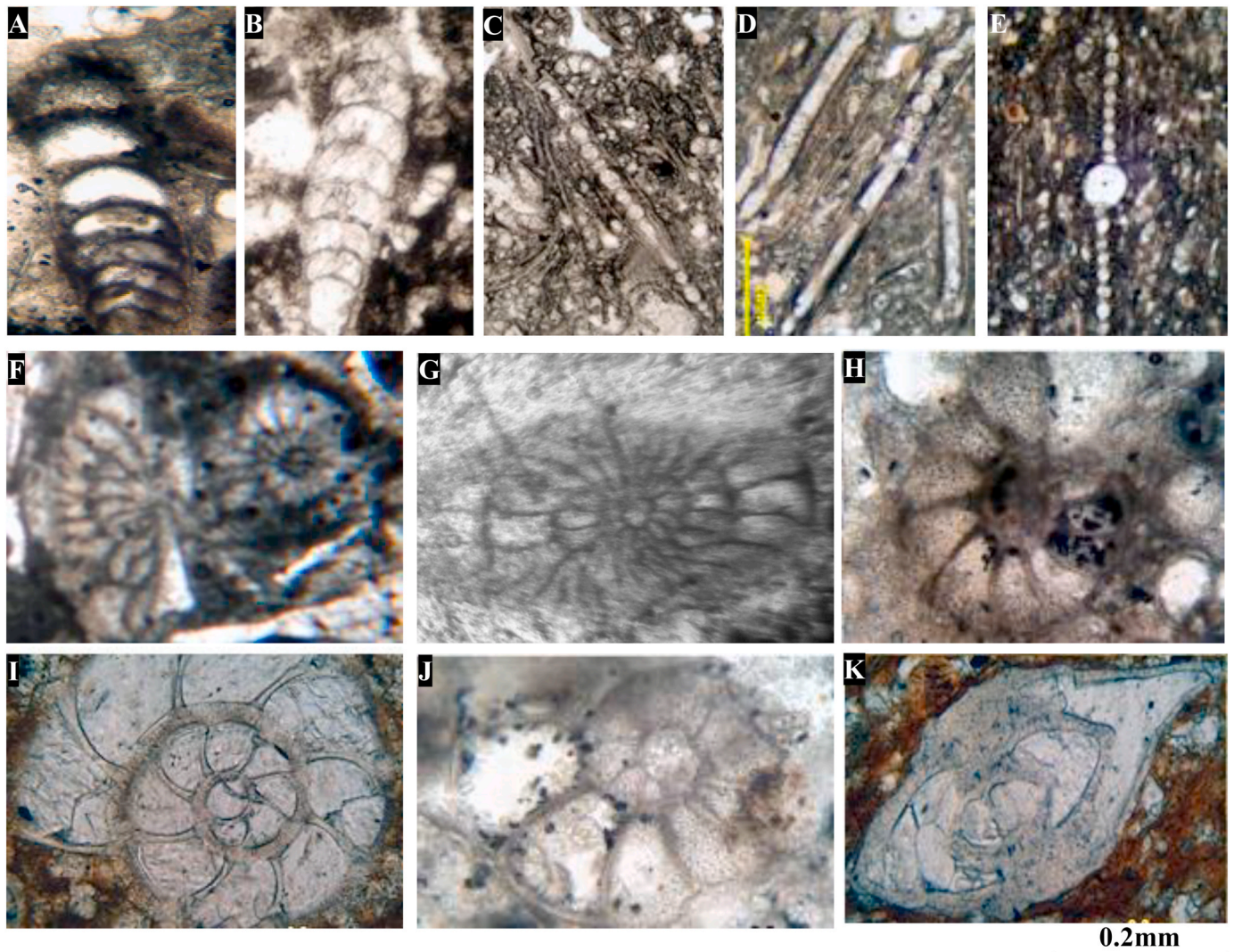


200µm

(caption on next page)

Fig. 6. Photomicrographs of planktic foraminifera; scale is 200 μ m.

- A) *Globotruncana aegyptiaca* Nakkady; Axial section; BH 5/6; (133m)
 B) *Globotruncana arca* Cushman; Subaxial section; BH 5/6; (133m)
 C) *Globotruncana falsocalcarata* Kerdany & Abdelsalam; Subaxial section; BH 5/6; (135m) D) *Parvularugoglobigerina eugubina* Luterbacher & Premoli Silva; Equatorial section; BH 5/6; (131.6m)
 E) *Parasubbotina pseudobulloides* Plummer; Equatorial section; BH 5/6; (124m)
 F) *Globanomalina compressa* Plummer; BH 5/6; (105m)
 G) *Morozovella angulata*; BH 5/6; (120m)
 H) *Morozovella angulata*; BH 5/6; (95m)
 I) *Morozovella* sp.; Equatorial section; BH 5/6; (129m)
 J) *Guembelitra cretacea* Cushman; Equatorial section; BH 5/8; (107m)
 K) *Morozovella angulata*; Equatorial section; BH 5/6; (99m).

**Fig. 7.** Photomicrograph of benthic foraminifera; scale is 0.2 mm.

- A) *Haymanella paleocenica* (Sirel, 1999; SBZ 2B), BH 5/8, depth of 67m.
 B) *Haymanella elongata* (Sirel, 2009; SBZ 2, Danian and Paleocene), BH 5/8, depth of 67m. C-D) *Ranikothalia soldadensis* (Vaughan and Cole, 1941)
 E) *Ranikothalia* sp., BH 5/8, depth of 67m.
 F-G) *Miscellanites globularis* (Rahaghi, 1978), BH 5/8, Depth 60m.
 H-J) *Neoponides duwi* (Nakkady, 1950), BH 5/8, Depth 130 m
 K) *Daviesina praegarumnensis* (Hottinger, 2014), BH 5/8, Depth 60m.

Daviesina praegarumnensis, in addition to *Fronicularia phosphatica*, *Bolivina midwayensis*, *Nodosaria macneili*, *Lenticulina wilcoxensis*, *Valvulinaria ravnii*, *Bulimina* sp., *Dentalina* sp., *Anomalina* sp., and others. This zone correlates well with previously recorded data in Iraq (Ctyroky and Karim, 1971; Karim in Jassim et al., 1984; Al-Mutwali et al., 2002; Lawa

and Qadir, 2023; Al-Jibouri and Gayara, 2015; Karim and Al-Kubaysi, 2020a-b). The base of the overlying Ratga Formation includes coprolite phosphate beds backfilling *Thalassinoides* burrows; this firmground represents a sequence boundary between the Akashat and Ratga formations. Here, we differ in the interpretation of previous authors, who

Table 1

Summary of the lithofacies, microfacies, and sedimentary environments of the Paleocene mixed lithofacies and sequences, which range from distal outer ramp/shelf to proximal inner ramp/foreshore settings. The phosphorite microfacies suggest a storm-dominated mid-ramp palaeoenvironment for the L. Danian Traifawi Member/Jeed Formation and the Upper Danian - Thanetian Akashat Formation in the Marbat–Traibel Basin, West Rutbah High, Iraq.

Lithofacies types	Microfacies types	Components and mineralogy	Texture and sedimentary structures	Geographic and stratigraphic locations	Depositional environments
LF1: Phosphorite	MF1: Quartz–coprolite bone packstone/rudstone (Fig. 8A).	Fragments include phosphatic bone teeth and coprolite: quartz sand, minor bivalve shells, and dolomite cement.	Hybrid gravel to sand grain size, angular to rounded, poorly sorted, medium- to fine-grained crystalline dolomite, massive and plane-bed, sharp base, phosphatic lag	NE – Ga'ara Depression (base of the Hirri Member).	The intertidal inner ramp has a medium to high energy tidal current and a swash zone above FWWB.
	MF2: Bone coprolite floatstone/rudstone (Fig. 8B).	Faecal pellets, oyster fragments, and small benthic foraminifera accompany phosphatic coprolites and bones.	Phosphatic gravel, angular to subrounded, moderately sorted, massive and sharp base plane-bed; passive infill in thick (3–4 cm diameter) <i>Thalassinoides</i> burrows	NE- Ga'ara is locally on the base of the main phosphorite bed, Hirri Member, and the base of the Ratga Formation (above the sequence boundary between the Akashat and Ratga formations).	Intertidal to shallow subtidal inner ramp. Medium to high-energy storm current above FWWB.
	MF3: shell fragment, peloid floatstone/packstone (Fig. 8C)	Ovoidal phosphatic peloids, bivalve shell fragments.	Gravel shell size and ovoidal phosphatic grains are fine- to medium-grained sand and massive, exhibiting gradational lower and upper boundaries that transition between the main phosphorite beds.	Recognized in all studied sections, with a noted decrease in thickness westward.	Proximal mid – ramp with medium, energy storm currents.
	MF4: Peloidal packstone/ grainstone (Fig. 8D).	Ovoidal, with some spherical, phosphatic grains, minor ooids, cortoids, and bone fragments with calcite as micrite matrix or cement	Phosphorite in sand-sized grains comprising well-rounded and sorted, semi-hard to a friable sandy texture, and locally silicified cement. Massive plane bed, in some outcrops and subsurface with HCS, normal grading and finning upward; base has passive infill <i>Thalassinoides</i> burrows.	Recognized in all studied sections, with a noted decrease in thickness westward	Sand shoal mid-ramp with medium to high energy proximal storm current deposits between FWWB and SWB.
	MF5: Peloid cortoid ooid packstone (Figs. 8E and 9A).	Ovoid phosphatic ooids, cortoids, peloids, bone fragments and small benthic foraminifera embedded within a calcite and phosphate matrix.	The phosphorite, present in sand-sized grains, is well-rounded and well-sorted, exhibiting a semi-hard to friable sandy texture. Massive plane bed in some outcrops and subsurface with HCS, normal grading and finning upward.	SW- Ga'ara, Traifawi Member and locally in the upper part of the main phosphorite bed in outcrops and subsurface (BH5/8 and BH5/6) of Hirri Mbr.	
	MF6: small benthic foraminifera - bone cortoid peloid packstone (Fig. 8F).	Fragmented bone, ovoidal cortoids and peloids, and calcareous small benthic foraminifera	Phosphorite in sand-sized grains; well-rounded, well-sorted massive plane bed.	Subsurface —within the Akashat Formation.	Mid-ramp with low to medium energy currents.
	MF7: Bioclastic packstone (Fig. 8G).	Fragmented bone, coprolite, and phosphatic intraclasts within calcareous matrix and cement.	Phosphorite in sand-sized grains; subrounded to rounded phosphatic lithoclasts and elongated to subrounded bone fragments in massive beds.	Subsurface in the lower part of the Hirri and Traifawi members.	Mid ramp with high energy proximal turbidites and storm currents between FWWB and SWB.
	MF8: Planktic foraminiferal peloid packstone (Fig. 8H)	Planktic foraminifera with phosphatic peloids and minor bone fragments	Phosphorite in sand-sized grains; well-rounded, well-sorted massive plane bed.	Subsurface sections are represented by the upper part of the Hirri Member and the lower part of the Traifawi Member.	Distal mid–ramp with medium energy distal storm deposits above SWB.
LF2: Sandstone	MF9: phosphatic quartz arenite	Mixed quartz, bone fragments, and coprolite with subordinate bivalve shell fragments.	Phosphatic – quartz arenite, subrounded to rounded, well sorted, thin massive plane bed	Recognized only at the base of the Traifawi Member, south Akashat area, and at the base of the Hirri Member in the NE Ga'ara Depression	Intertidal (foreshore), swash to backwash zone, and high energy tidal current. Above FWWB.
	MF10: Bioclasts phosphoclastic quartz arenite	Hybrid microfacies of reworked phosphatic coprolite bone fragments, quartz sand, small benthic foraminiferal mixed bioclasts, and carbonaceous materials.	Arenite to rudite size, poorly sorted, subangular to subrounded, (BI = 4–5); <i>Cruziana</i> distal, <i>Thalassinoides</i> - dominated	Sandstone layers (2–20 cm) interbedded with shale layers occurring at the base of the Traifawi member. Exposed from SW – Rutbah to the Saudi Arabia border.	Lower offshore, distal storm current and distal turbidites, above SWB.
	MF11: Completely bioturbated quartz arenite	Quartz, calcite, and locally silicified cement.	Arenite is a rounded, moderately well-sorted, thick bed. <i>Thalassinoides</i> bioturbated soft ground, with low diversity <i>Cruziana</i> proximal ichnofacies (BI = 6)	Top of the Traifawi Member, SW Rutbah.	Shallow -subtidal (shoreface), high energy storm, and fair weather above FWWB.
	MF12: Massive quartz arenite	Quartz, calcite, and locally silicified cement and chert nodules and geodes.	Arenite, rounded, well-sorted, thick sandstone bed— <i>Skolithos</i> - bioturbated soft ground, low diversity ichnofacies (BI = 2). Chert nodules and	Top of the Traifawi Member, graded from MF11, SW Rutbah.	Intertidal to subtidal (Upper shoreface), locally restricted hypersaline lagoon: high

(continued on next page)

Table 1 (continued)

Lithofacies types	Microfacies types	Components and mineralogy	Texture and sedimentary structures	Geographic and stratigraphic locations	Depositional environments
LF3: Carbonate			locally patch geodes with length–slow microcrystalline chalcedony representing gypsum pseudomorphs.		energy storm and fair weather above FWWB.
	MF13: Aphanitic dolostone	Dolomite, chert nodules, minor detrital quartz; no fossils	Finely crystalline dolomite, massive plane beds with horizontal chert nodules and randomly scattered	Top of the Hirri Member. Marbat El-Hossen, NE Ga'ara.	Lagoon, saline to hypersaline water. LFA4.
	MF14: Recrystallized lime mud with quartz in silt size (Fig. 9B)	Oyster shell ghost, microsparite, minor quartz and dolomite	Crystalline limestone is burrowed on top by <i>Thalassinoides</i> sp. Infilling by peloidal phosphorite and locally karstified.	Subsurface topmost of Traifawi and Hirri members.	Bivalve barrier bank, distal inner ramp, above FWWB, patch shoal, high energy storm, and tidal flow.
	MF15: Bivalve floatstone to rudstone (Fig. 9C)	Articulated and disarticulated bivalves, gastropods and ostracod shells, red and green algae, benthic foraminifera with micrite matrix. Calcite with dolomite increases eastward to the shoreline.	Gravel shell size, poorly sorted, thick, massive shell beds	Shell beds characterize the Hirri Member (lower and upper shell beds). One bed is highly recrystallized and karstified at the top of the Traifawi Member.	Bivalve barrier bank, distal inner -ramp near FWWB.
	MF16: Phosphopeloidal bioclastic floatstone/rudstone (Fig. 9D).	Bivalve shells, extensively reworked micro-bioclasts, minor occurrences of small benthic foraminifera, calcareous peloids, phosphatic peloids, coprolites, cortoids, and minor ooids are all embedded within a micrite matrix	Gravel size is poorly sorted, as are peloids and micrite matrix. Transitional facies between MF14 and MF4,5,6.	The thickness of the top and base of the lower and upper shell beds, Hirri Member, increases westward–basinward.	Mid ramp proximal storm medium to high energy deposits.
	MF17: Shell fragments benthic foraminifera rudstone (Fig. 9E)	Benthic foraminifera (<i>Nodosaria</i> and others), bivalve shell fragments, ostracods, minor phosphocoprolite. Calcite – dominated	Gravel to sand grain size, poorly sorted, elongated fauna mainly arranged parallel to the bedding plane in massive beds.	2-3 beds within the Akashat Formation. It is recognized in the subsurface western Akashat and H3 areas.	Mid-ramp deposits within proximal storm settings, indicative of a medium to high-energy environment.
	MF18a: phosphopeloidal small benthic foraminiferal packstone (Fig. 9F)	Small benthic foraminifera, microbioclasts, and planktic foraminifera are present, accompanied by phosphatic peloids within a micrite matrix and microsparite cement	Massive, well-sorted, well-rounded. Massive beds	Several beds in the Akashat Formation and Traifawi Member in the subsurface of western Rutbah and Akashat	Distal mid-ramp distal storm, medium energy deposits.
	MF18b: Gravelly limestone - phosphopeloidal – small benthic foraminifera packstone/floatstone (Fig. 9A).	Carbonate gavel, phosphopeloids, and small foraminifera, supported by carbonate micrite matrix.	Gravel carbonate conglomerate of pebble to cobble grain size; floatstone in peloidal, small benthic foraminifera, and micrite matrix, normal grading fining upward to phosphatic sandy sediments MF18a displays lensoidal and HCS.	Traifawi Member. Interbedded with granular phosphatic and small benthic foraminifera. Subsurface Traibeel area.	Distal mid-ramp above SWB, gravity-driven carbonate gravel sedimentation, and high to moderate energy storm currents.
	MF19: Phosphatic foraminiferal wacke/packstone (Fig. 10A).	Small benthic and planktic foraminifera, shell fragments, minor phosphatic grains, calcite, and clay matrix.	Mud to fine-grained sand, well sorted. Micritic matrix. Massive beds.	Several beds within the Akashat Formation and Traifawi Member subsurface western Rutbah and Akashat.	Proximal outer ramp low energy storm–derived zone.
	MF20: Phosphatic planktic foraminiferal wackestone (Fig. 10B).	Planktic small benthic foraminifera f, minor shell fragments, phosphatic grains, calcite, and clay matrix.	Muddy sediments are well-sorted and are massive bedded.	Akashat Formation; thin layers within the middle, and locally upper part, of the main phosphorite bed (MF5)	Distal outer ramp low energy current.
LF4: Shale – marl	MF21: Planktic foraminifera mudstone	Planktic foraminifera – dominated, a trace of small benthic foraminifera, sponge spicules fragments, and phospholithoclasts	Muddy sediments are fine-grained facies of the massive beds.	Akashat Formation. Subsurface, Iraqi – Jordan boundary Trebiel area	Distal outer ramp/distal shelf, low energy shelf.
	MF22: Shelly nummulite floatstone/rudstone	Nummulite-dominated and bivalve shell fragments, small benthic foraminifera	Poorly sorted, elongated, slightly oriented, micritic matrix	Ratga, Swab Member, overlain by coprolite facies	Shallow open marine, middle – mid ramp high energy currents.
	MF23: Smectite-dominated carbonaceous calcareous shale	Planktic foraminifera, bone, and lithoclastic phosphatic grains.	Carbonaceous-bearing shale and marl in thick beds, finely laminated structure, rare silt, and fine-grained quartz	Shale beds interbedded with MF10 and porcellanite in the Traifawi Member, W. Rutbah and W. Ga'ara	Distal outer ramp Suspension deposits in calm conditions, with distal turbidite deposits.
	MF24: Palygorskite-dominated dolomitic marl – -shale (Fig. 10D–F).	Unfossiliferous, highly dolomitic marl.	Finely crystalline dolomitic, laminated to massive beds, with a transitional lower boundary with MF23. Upper 50–60 cm showing firmground surface with <i>Thalassinoides</i> burrows and locally with bored hardground.	The upper part of the shale–marl beds of the Traifawi Member, also occurrence at the top of the Akashat Formation, underlying the sequence boundary and basal coprolite bed of the Ratga Formation	Shallow subtidal, inner ramp protected lagoon suspension low energy deposits.

(continued on next page)

Table 1 (continued)

Lithofacies types	Microfacies types	Components and mineralogy	Texture and sedimentary structures	Geographic and stratigraphic locations	Depositional environments
LF5: Porcellanite	MF25: Planktic – spiculitic siliceous packstone (Fig. 10E).	Sponge spicules, planktic foraminifera, bone and phosphoclasts, organic matter	Lutite, with siliceous matrix, massive plane beds, lightweight, white in outcrop, dark grey to black in subsurface	Three beds in the Traifawi Member.	Proximal outer ramp, low energy storm current, gravity flow, and accumulated sponge spicules.
LF6: Chert	MF26: Thin bedded microcrystalline chert	Authigenic silica, ghosts of silicified fossils, organic matter, locally phosphatic	Finely cryptocrystalline and microcrystalline chalcedony, with fibrous chalcedony, massive thin layers interbedded with LF 5 and LF 13.	Common lithofacies recognized in the Traifawi Member and Akashat Formation.	Inner to outer ramp diagenetic facies.

place the coprolite bed at the top of the Akashat Formation (Al-Bassam, 2017; Al-Jibouri and Gayara, 2015; Karim and Al-Kubaysi, 2020).

4.1.3. Ratga Formation (Eocene)

It unconformably overlies the Duwima Member of the Akashat Formation and is characterized by nummulitic limestone with coprolite phosphate beds that infill *Thalassinoides* burrows within the upper part of the shale bed. These features mark significant sedimentary hiatuses and contribute to the distinctive lithology of the formation.

4.2. Lithofacies types

The Paleocene phosphorite-rich Traifawi Member (Jeed Formation) and Akashat Formation are characterized by six primary lithofacies: phosphorite, sandstone, carbonate, shale–marl, porcellanite and chert with silica geodes; each lithofacies is further subdivided into twenty-six distinct microfacies (see Table 1 for details). The primary lithofacies and their respective microfacies are as follows.

- **Phosphorite (LF1)** has two main textures: coarse-grained and fine-grained sandy phosphorite microfacies. The lithofacies comprises eight microfacies (MF1 to MF8) and is characterized by massive, hard-to-friable, horizontal bedding that is occasionally cross-laminated. The main phosphatic components are peloids, ooids, cortoides, coprolite, and bone fragments: carbonate shell fragments, small benthic foraminifera, planktic foraminifera, and detrital quartz sand.
- **Sandstone (LF2)**: Consists of four facies/microfacies (MF9 to MF12), ranging from fragmented, massive phosphatic quartz arenitic sandstones to bioturbated quartz arenites.
- **Carbonate (LF3)**: Encompasses eight microfacies (MF13 to MF20), including a spectrum of dolomitic and limestone textures, from aphanitic to highly crystalline and foraminifera-rich limestone.
- **Shale-Marl (LF4)**: Includes two microfacies (MF21 to MF22) characterized by carbonaceous smectite-rich marl/shale and palygorskite-rich marl and shale.
- **Porcellanite (LF5)**: Defined by one microfacies (MF23): planktic foraminiferal spiculitic packstone porcellanite.
- **Chert (LF6)**: Represented by one microfacies (MF24), consisting of microcrystalline chalcedony beds along the studied successions and occasionally including siliceous geodes near the K/Pg boundary.

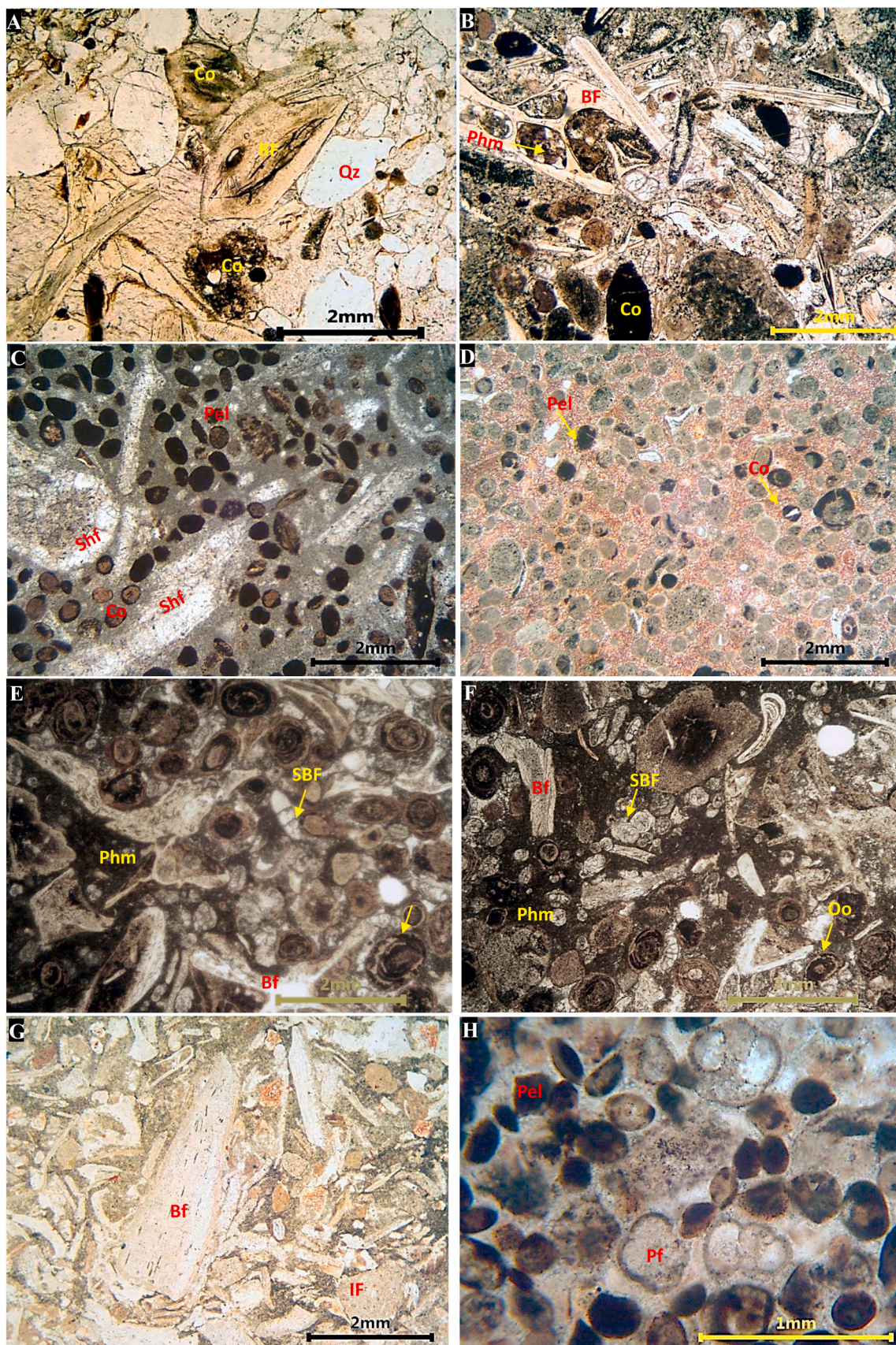
4.3. Depositional environments

The lateral and vertical variations in the NNE-SSW transect (Figs. 1 and 5) reveal significant variations in depositional environments and planktic turnover. The phosphorite-rich carbonate succession indicates an open, distally steepened ramp environment, consistent with Read's (1985) ramp model. This model includes inner, middle, and outer ramp zones outlined by Burchette and Wright (1992) and Powell and Moh'd (2011).

Seven sedimentary environmental zones characterize these environments based on their lithological and sedimentological characteristics (Table 1, Fig. 11).

4.3.1. Inner ramp depositional environment

Shallow marine conditions characterize the inner ramp environment, indicated by the broad distribution of oysters, gastropods, ostracods, fish and marine reptile bones, different sizes of marine coprolites, and trace fossils with a high density of *Thalassinoides* and, locally, *Skolithos* burrows. Lithologies range between coarse-to fine-grained rudstone, floatstone, packstone, mudstone textures, fossil-poor shale, and marl and sandstone. This environment is subdivided into two main sedimentary zones: proximal and distal inner ramp environments.



(caption on next page)

Fig. 8. Photomicrographs of selected microfacies (scales are variable):

- (A) **MF1:** Quartz-coprolite bone packstone/rudstone. Features include bone fragments (Bf), coprolite fragments (Co), and fine-to coarse-grained quartz (Qz) (Intertidal inner ramp).
- (B) **MF2:** Bone-coprolite floatstone/rudstone. Contains oyster fragments, bone fragments (BF), and coprolite fragments (CO) (Intertidal to lagoonal inner ramp).
- (C) **MF3:** Mixed bivalve shell fragments (Shf) phosphatic peloids (Pel) and coprolite fragments (Co) in a floatstone, exhibiting a packstone texture within a calcitic micrite matrix (Subtidal inner ramp).
- (D) **MF4:** Bedded packstone/grainstone with localized cross-laminations, dominated by phosphatic peloids (Pel) with minor cortoids (Co) containing bone nuclei (Sand shoal mid-ramp).
- (E) **MF5:** Packstone with abundant phosphatic ooids (Oo), large bone fragments (Bf), and minor small benthic foraminifera (SBF), with phosphomicrite (Phm), organic matter, and a calcitic micritic matrix (Cm) (not shown on slide) (Middle mid-ramp).
- (F) **MF6:** Packstone containing small benthic foraminifera (SBF), bone fragments (Bf), corticoids (Co), phosphatic peloids (Pel), and ooids (Oo). These microfacies transition from phosphorite to fine-grained limestone, featuring SBF and minor planktic foraminifera in a mid-ramp setting.
- (G) **MF7:** Highly fragmented phosphatic bone (Bf) and phosphatic lithoclasts (IF), dominated by large and small fragments of phosphatic bone and small phosphatic lithoclasts within microsparite, micrite, and organic matter.
- (H) **MF8:** Packstone with -planktic foraminifera (PF) and phosphatic peloids (Pel) within a sparite matrix (distal mid-ramp).

4.3.2. Proximal inner ramp: lithofacies and microfacies types

The Gaa'ra Uplift and the southwest Rutbah region are known to have LFA1, which comprises the microfacies MF1, MF9, MF12, MF2, MF11, NF13, and MF24. Phosphatic bone and coprolites, represented by quartz-rich, bone packstone to rudstone and phosphatic-quartz arenite (MF1, MF9), are combined in various ratios with quartz sand and small bivalve fragments. Overlying the dolomitic marl microfacies (MF24) is bone coprolite floatstone to rudstone (MF2) or graded from MF1 to MF9. Large coprolites, small bivalve shell pieces, trace amounts of quartz grains, and subordinate bone fragments have been found in MF2. Large to small silica geodes and chert nodules after evaporite are additional characteristics of massive sandstone (MF12), often completely bioturbated with *Thalassinoides* and *Skolithos* burrows. Completely bioturbated sandstone with abundant *Thalassinoides* burrows (up to 3–4 cm diameter) and quartz sandy arenite (MF11), characterize the upper part of the Traifawi Member. Palygorskite-dominated marl and shale with minor phosphatic peloids and bioclasts of phosphate and bivalve fragments (MF24) occur where the proportion of clay minerals decrease and dolomite increases. *Thalassinoides* burrows, back-filled by phosphatic grains, are associated with locally oxidized iron crusts; desiccation cracks are present at the top of these microfacies. Aphanitic dolostone (MF13), with dispersed fossils and phosphatic grains, are sometimes replaced by MF24 or interbedded with the MF1, MF9, MF24, and other carbonate microfacies.

Interpretation: The proximal inner-ramp exhibits a regressive phase from M11 to MF12 or transgressive-regressive cycles in the lower portion of intertidal to intertidal-subtidal microfacies (MF1, MF9, MF2). Seaward environments are limited to semi-restricted, low-energy lagoons (MF13, MF14). An erosional surface with coarse-grained phosphate forms the boundary of this depositional zone. Following significant transgressive phases, transgression lags are present comprising reworked coprolites, bone fragments, and peloids of phosphate-rich mud or silt deposited in the swash and backwash zones. Coprolite, quartz sand, and broken bone pieces provide evidence of marine tidal and storm currents in the subtidal proximal inner ramp (Ahmed et al., 2022; Catuneanu et al., 2013; Dashtgard et al., 2021; Föllmi et al., 1992; Pufahl et al., 2003).

4.3.3. Distal inner ramp

4.3.3.1. Lithofacies and microfacies types. This zone includes microfacies M14 and MF15, which are arranged in one bed near the top of the Traifawi Member in the Traifawi region, as well as two beds below and above the Akashat Formation's main phosphorite bed, with transitional boundaries into the phosphorite beds. Both microfacies are massive rudstone and floatstone: articulated and disarticulated bivalves, and subordinate gastropods, ostracods, and phosphatic grains. High recrystallization, fossil dissolutions and karstic surfaces characterize MF14.

Interpretation: As siliciclastic inflow decreased on the proximal inner ramp, these two microfacies record the presence of marine

bivalves and related fauna that were established on the Rutbah High following Maastrichtian time. In low-energy events, a micrite matrix enclosing the bivalves and other bioclasts has also penetrated the bivalve (Fig. 9C), which was deposited in a high-energy environment. The in-situ bank formed by articulated and disarticulated bivalve shells trapped micrite and phosphatic grains in the interstitial spaces, creating the bivalve bank barrier (coquina bank). In the intertidal to the shallow subtidal distal inner ramp, near fair weather wave base, the rudstone texture with its prominent erosional lower surface and extensive accumulations of large shell fragments indicate high-energy tidal and storm currents. (Catuneanu and Zecchin, 2013; Brito et al., 2024). The distribution of these two microfacies suggests that bank barriers were oriented parallel to the shoreline, thicker near the northeast Ga'ara uplift, and influenced by the shallow-water environments on the western flank of the Rutbah High.

4.3.3.2. Mid-ramp depositional environment. The mid-ramp depositional environment, situated between the Fair Weather Wave Base (FWWB) and the Storm Wave Base (SWB), is characterized by ten microfacies (MF16, MF7, MF3, MF6, MF5, MF4, MF22, MF18a, MF18b, MF10, MF17, MF8). It is divided into three depositional zones.

4.3.3.3. Proximal mid – ramp. Lithofacies and microfacies types: The proximal mid-ramp includes MF3, MF7, and MF16 microfacies. Bioclastic – phospeleoidal floatstone and packstone with abundant bivalve shell fragments float within phospeleoidal packstone to wackestone and micrite matrix (MF3); they are transitional to MF15 bivalve-dominated microfacies. Phosphatic bioclastic packstone (MF7) comprises phosphatic gravel and sand with occasional shell fragments and containing coprolite, bone, peloids, and reworked phosphate lithoclasts. Phospeleoidal, bioclastic floatstone – rudstone with phospeleoidal and micro-bioclasts with extensively reworked bivalve shells and sparse small benthic foraminifera (NF16) are also present.

Interpretation: The bivalve bioclasts and coarse- and fine-grained phosphatic-dominated microfacies in a mud-support texture laterally transitional to the shoreward bivalve bank and the seaward phosphorite lithofacies, together with the presence of a micritic matrix, and the first appearance of the subtidal, open marine small benthic foraminifera, suggest a moderate to high hydrodynamic regime within a proximal part of the mid-ramp, below the FWWB. Bivalve fragments are generally broken (MF15) and are mixed with well-sorted phosphatic grains within the mid – ramp (e.g., Flügel, 2010; Gil-Gil et al., 2024; Pratt et al., 2012; Zhang et al., 2023)

4.3.3.4. Phosphatic sand shoal. Lithofacies and microfacies. The phosphatic sand shoal, represented by the MF4, MF5, and MF6, is composed of massive packstone to grainstone that ranges in thickness from 0.50 to 10 m. It is dominated by peloids (MF4) and vertically includes cortoids and ooids (MF5). Small benthic foraminifera and minor planktic foraminifera associated with peloids, corticoids, and bone pieces can be

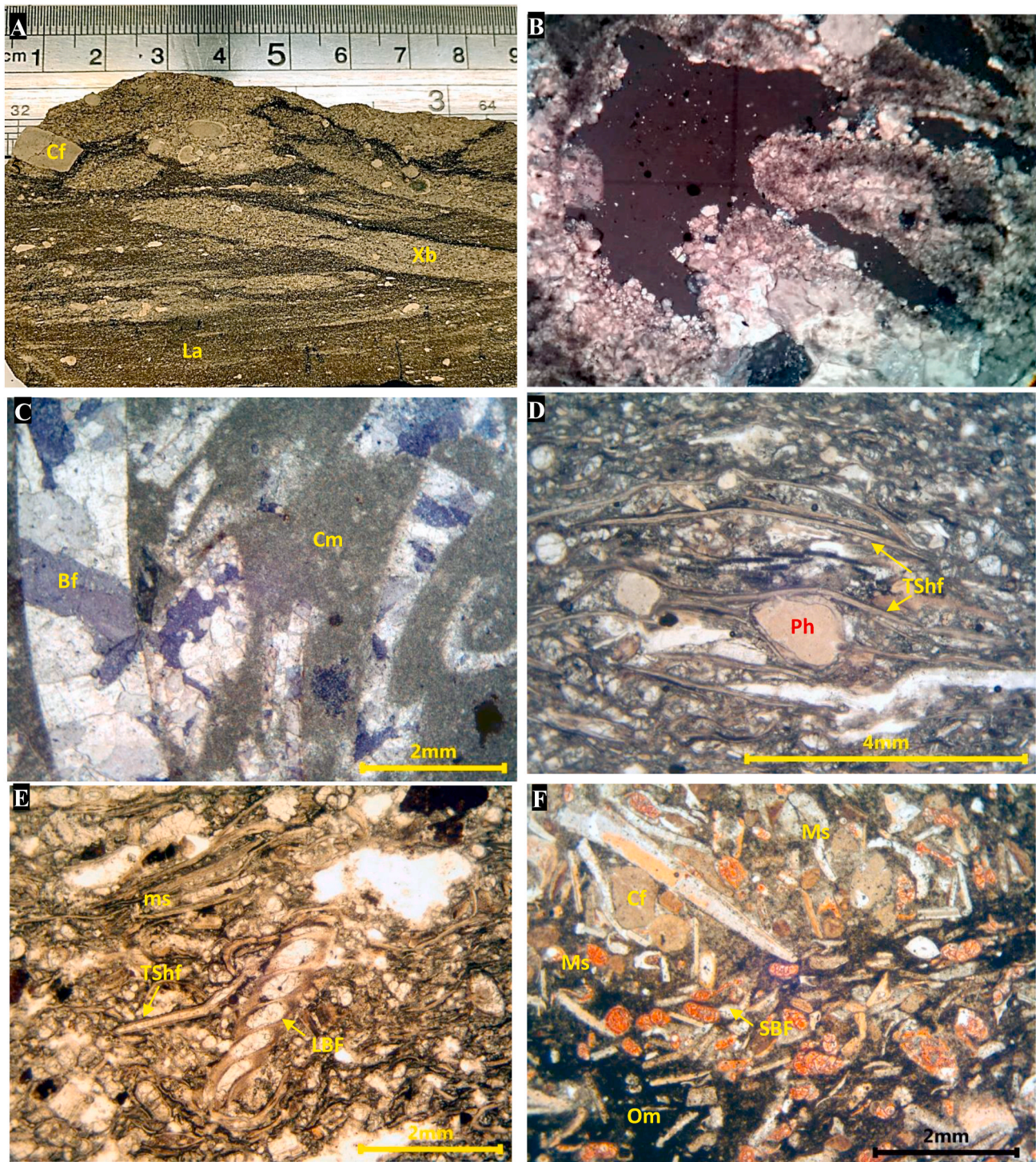


Fig. 9. Photomicrographs of Selected Microfacies:

- (A) **MF10:** Horizontally laminated peloidal phosphorite (La) in the lower part, with an inclined erosion surface at the base of the upper part comprising cross-laminated (Xb) peloidal phosphorite with gravel-sized coprolite and carbonate lithoclasts (Cf) (mid-ramp).
- (B) **MF14:** Highly recrystallized lime mud with coarse crystalline calcite, voids and silt grade quartz, marking the lower and upper Danian unconformity (Traifawi type section).
- (C) **MF15:** Articulated and disarticulated bivalve floatstone to rudstone. The floatstone to rudstone is rich in skeletal bivalve shells (Bf) with a notable calcitic micrite (Cm) presence.
- (D) **MF16:** Massive-bedded shell accumulation of phosphopeloidal (Ph) microbioclastic rudstone with thin, long bivalve shells (TShf), indicating storm currents on the mid-ramp.
- (E) **MF17:** Microfacies image showing large benthic foraminifera (LBF), thin shell fragments (TShf), with minor phosphatic grains displaying a rudstone texture.
- (F) **MF18A:** Microfacies showing an increase in SBF/phosphopeloidal content, microbioclasts (Ms), and other bivalves with an organic matrix (Om) which accumulated on the distal mid-ramp.

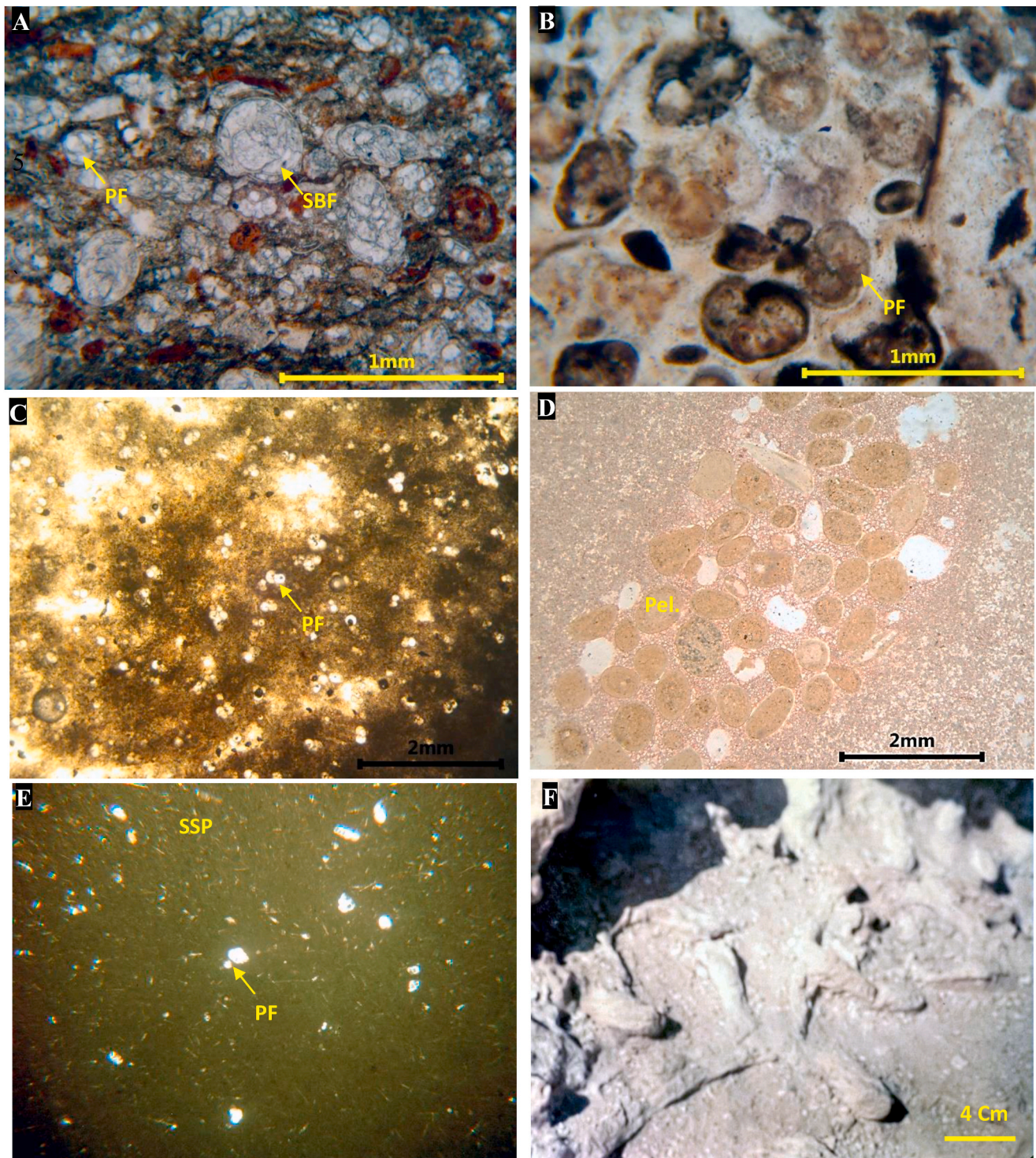


Fig. 10. Photomicrographs of Selected Microfacies:

(A) MF19: Planktic (PF) and SBF foraminiferal wacke/packstone. Packstone texture with localized wackestone is rich in SBF and has less abundant planktic foraminifera.

(B) MF20: Wackestone microfacies with abundant planktic foraminifera (PF), minor SBF, phosphatic peloids, and a silicified matrix.

(C) MF23: Laminated shale microfacies, carbonaceous-rich planktic mudstone to wackestone texture, rich in smectite and organic matter with minor phosphatic grains. Contains small-sized planktic foraminifera (PF).

(D) MF24: Unfossiliferous, dolomitic marl transitioning from MF23, with a firmground surface marked by *Thalassinoides* burrows infilled with phosphatic peloids (Pel).

(E) MF25: Planktic, foraminiferal-bearing porcellanite-rich in sponge spicule. Packstone texture with localized silicification forming chert pockets containing sponge spicules (SSP) and small planktic foraminifera (PF).

(F) Field photograph of a firmground surface marked by *Thalassinoides* burrows, displaying cylindrical branches with vertical and inclined shafts. Scale 4 cm.

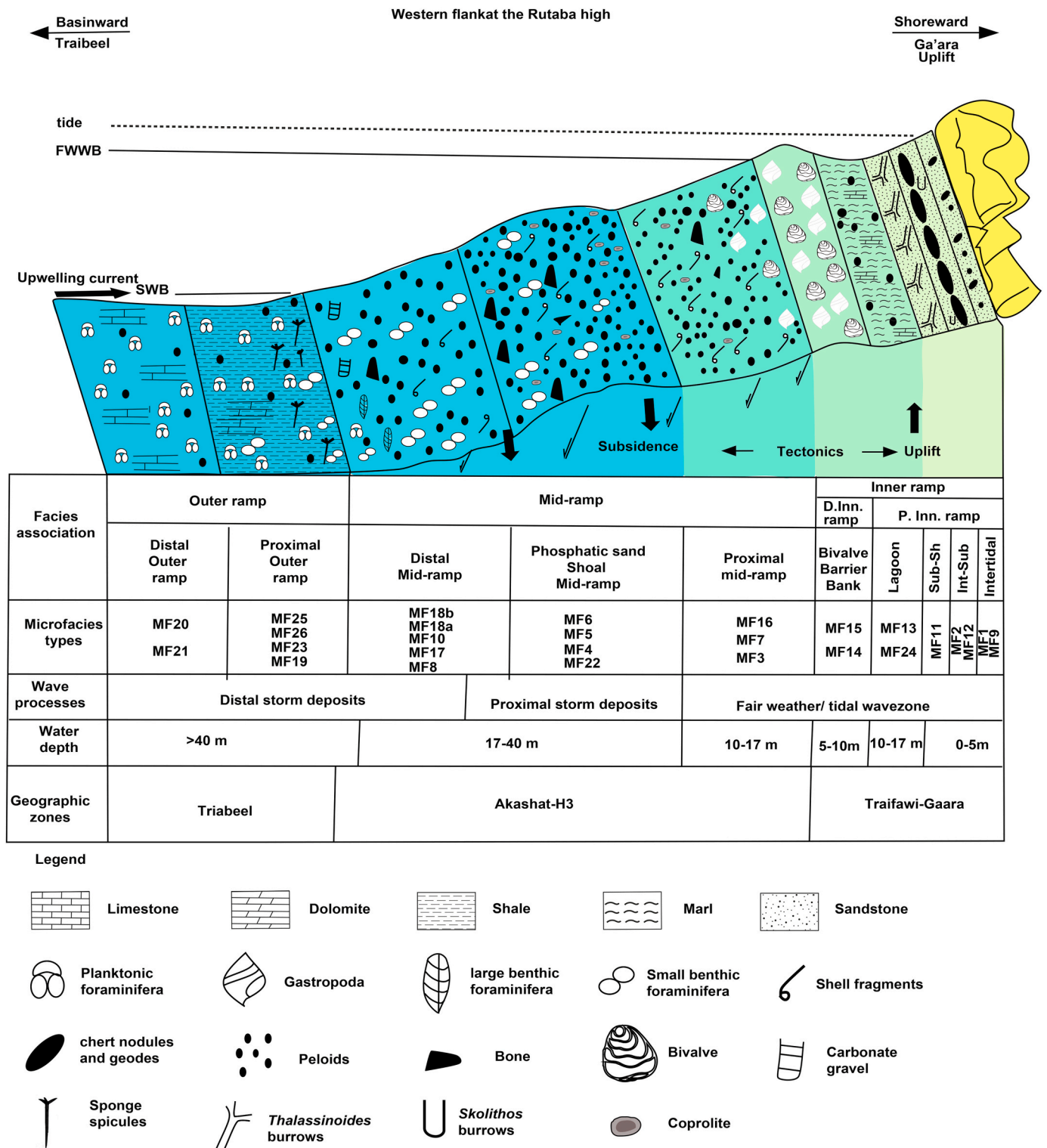


Fig. 11. Schematic depositional models for the Marbat-Traibeel Basin during the Paleocene, illustrating an open marine distally steepened ramp system composed of mixed Paleocene phosphorite, carbonate, and siliciclastics. The models highlight the depositional dip, which increases westward from the inner ramp in the east to the outer ramp and basinal facies associations, extending into the Risha area west of the Iraq-Jordan border.

found in the phosphorite bed as it when traced westward to the Traibeel region (MF6). The friable to hard phosphate ranges from sand to granule grade and is cemented by silica, sparite and micrite. Hummocky cross-stratification (HCS) is locally distributed, with a typical finning upward profile. *Thalassinoides* burrows passively infill the base of the Eocene Ratga Formation. Nummulitic floatstone to rudstone microfacies

(MF22) with oyster shell pieces are present on top of the bone coprolite phosphorite microfacies.

Interpretation: Granular phosphatic grains, very well sorted and rounded to elongate, with a grain-supported texture, erosional base, finning upward profile, HCS, benthic and planktic foraminifera, indicate deposition in storm and wave current settings. This is supported by a

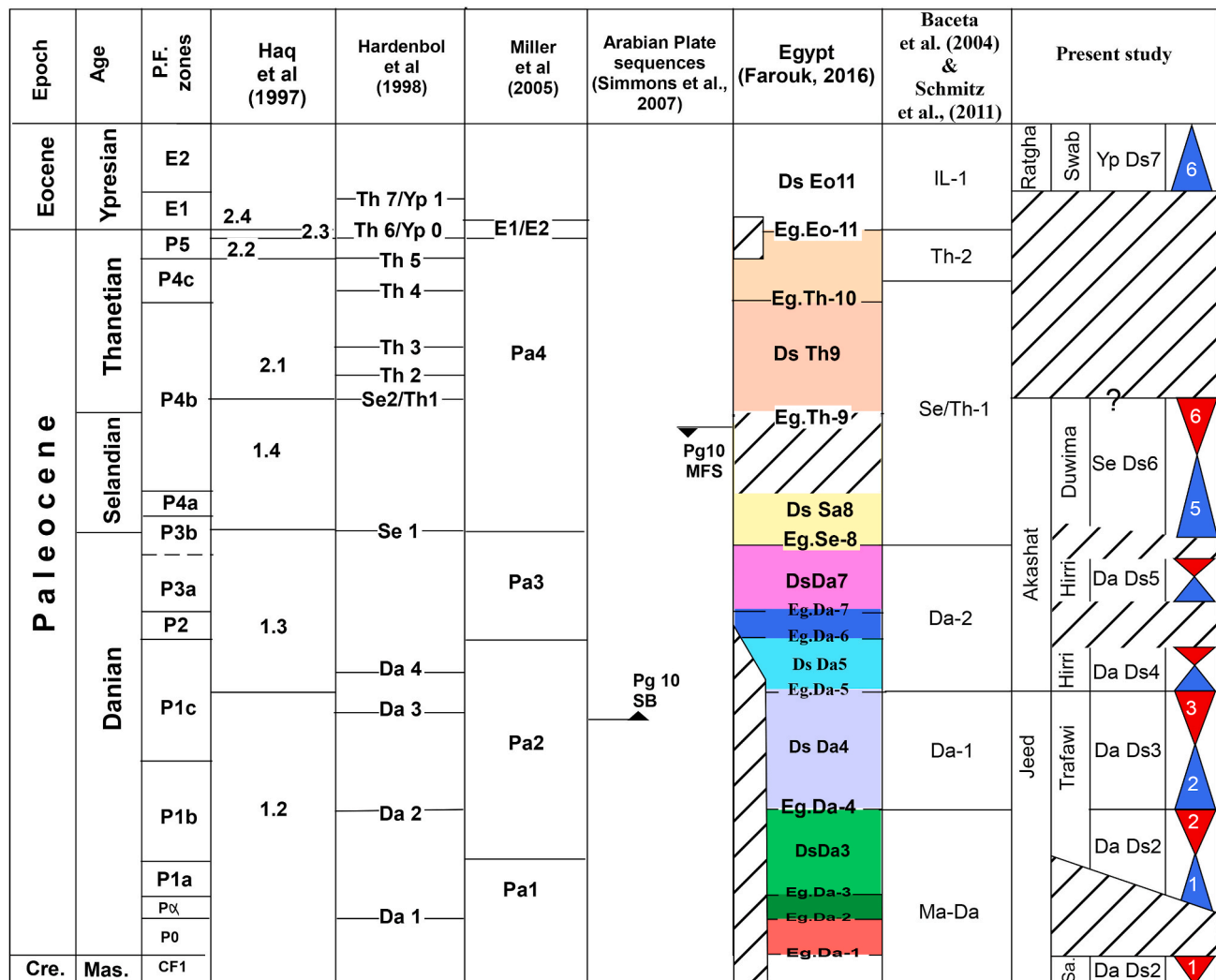


Fig. 12. Comparison of global and local sequence boundaries with those identified in the present study, highlighting the influence of eustatic changes and tectonic activity in the Western Iraqi Desert.

high energy, winnowed sediment matrix, re-depositing economic packstone to grainstone phosphate sand in the mid-ramp zone. Granular phosphorite microfacies represent deposition of phosphatic sand shoals in a mid-ramp setting (Schlager, 2005; Pratt et al., 2012). The presence of *Thalassinoides* burrows backfilled by overlying peloidal phosphorite indicate firmground conditions (hiatuses) and low sedimentation rates with periods of oxygenation (Wignall, 1994; Soudry et al., 2006; Rodríguez-Tovar et al., 2008; MacEachern and Pemberton, 1992; Pratt et al., 2012; Ulmer-Scholle et al., 2014; Föllmi, 2016).

4.3.3.5. *Distal mid-ramp.* Lithofacies and microfacies: MF10, MF17, MF18a, and MF18b are found in the subsurface Traifawi Member in the westernmost part of the western desert and are included in this zone. Mixed quartz sand, reworked phosphatic grains, benthic foraminifera, shell bioclasts, and carbonaceous components make up hybrid microfacies. Shell fragments with benthic foraminifera rudstone (MF17), peloidal phosphate packstone with small benthic foraminifera and minor planktic foraminifera packstone and floatstone, and carbonate gravelly peloidal phosphate are present, together with, phosphatic lithoclasts, and carbonate (MF18b). The features that distinguish these three microfacies include small sand to gravel grade, upward fining HCS, large and small benthic foraminifera, and poor sorting. Flattened clasts are orientated parallel to the bedding plane. Planktic foraminifera are more abundant than small benthic foraminifera. Peloids, bone fragments

and carbonaceous clasts terminate the microfacies association above phospheloidal packstone. Additionally, the association is dominated by *Cruzaiana*, passing distally to *Thalassinoides*.

Interpretation: Hybrid composition, grain-size, texture, finning upward profiles, and HCS sedimentary structures indicate moderate-energy passing to high-energy distal storm and turbidity currents above the SWB, with gravity-driven sedimentation (Arnott, 2010; Playton et al., 2010).

4.3.3.6. Outer-ramp depositional environment. The outer ramp observed in the western and southwestern regions (BH5/6 and BH5/8) is transitional to the basinal facies of the Paleocene outer ramp located to the west (Tethys Levant Superbasin). This outer ramp is interpreted as being influenced by a west-to-east flow of cold, nutrient-rich upwelling currents towards the Rutbah High. The outer-ramp depositional environment includes MF19, MF23, MF25, MF26, MF21, and MF20, divided into proximal and distal outer ramp zones.

4.3.3.7. Proximal outer ramp. Lithofacies and microfacies: The proximal outer ramp consists of fine-grained, black to dark grey limestone, marl, shale, and porcellanite mud-support microfacies. Microfacies (MF19) comprises phosphatic foraminiferal wackestone to packstone consisting of fine-grained limestone with small benthic and planktic foraminifera, shell fragments, minor phosphatic grains, together with micrite and clay

minerals and a carbonaceous matrix. In contrast, MF23 is represented by black shale rich in carbonaceous materials and planktic foraminifera, with bone and bioclastic phosphatic grains and horizontal lamination. MF25 is a unique microfacies, composed of opal – CT-rich sponge spicules with planktic foraminifera and siliceous porcellanite. The colour is black in the subsurface and white/pale grey (oxidized) in surface exposures. The MF26 diagenetic chert microfacies has a wide distribution in this lithofacies.

Interpretation: According to Schlager (2005), the fine-grained mudstone to wackestone texture implies that deposition occurred in an open, proximal outer ramp environment with low-energy conditions in the deep subtidal zone below the SWB. The presence of planktic and small benthic foraminifera suggests deep subtidal habitats (Haak and Schlager, 1989) (see Table 1 for more information). A siliceous, carbonaceous and calcareous mud matrix and a horizontal lamination indicates accumulation under low-energy storm currents and gravity flows. This accumulation has preserved sponge spicules on the deep subtidal proximal outer ramp.

Distal Outer Ramp.

Lithofacies and microfacies: MF20 and MF21 represent the distal outer ramp sedimentary environment. It is found in the western portion of the MTB and is composed of marly limestone and black to dark grey fine-grained limestone. The texture of MF20 is mudstone to wackestone, with planktic foraminifera, minor small benthic foraminifera, minor small shell fragments and phosphate grains. However, MF21 has smaller shards of sponge spicules and benthic foraminifera in a mudstone texture. In addition to micrite, the matrix includes a mixture of clay minerals and organic materials.

Interpretation: Foraminifera types, muddy matrix, and sparse lithofragments suggest deposition in a distal storm zone in a low-energy distal outer ramp setting (Flügel, 2010; Arnott, 2010).

4.4. Sequence stratigraphy

The analysis of depositional sequences in the studied successions has led to the identification of seven major sequence boundaries, one at the base of the Safra Member (Maastrichtian) and six within the Paleogene succession resulting in the division of sequences into seven third-order depositional sequences (Fig. 5). These sequences are characterized by transgressive systems tracts (TST) and highstand systems tracts (HST), separated by maximum flooding surfaces (MFS). The absence of falling stage and lowstand systems tracts is attributed to the proximal location, limited accommodation space, and continued pulsatory marine onlap during the Maastrichtian-Paleocene within the study area. This section presents an overview of these depositional sequences within a Late Maastrichtian to Ypresian chronostratigraphic framework (Figs. 2 and 5). The sequences from the base to the top are named DS1 to DS7 and are associated with the observed Stage boundaries (e.g., Maastrichtian-Ma, Danian-Da, Selandian -SE, Thanetian-Th, Ypresian-YP) (See Fig. 5). The Jeed Formation (Safra and Traifawi members) is represented by the MaDS1 and DaDS2 (upper Maastrichtian Safra Member), DaDS3 and DaDS4 by the Lower Danian Hirri Member. In contrast, the Akashat Formation is represented by DaDS5 and SeDS6 (Hirri and Duwima members), and YpDS7 (Ratga Formation), representing Ypresian time, tops the succession. The six Paleocene-Eocene sequence boundaries (e.g., K/PgSB1; DaSB2; SeSB5) separating this depositional sequence are shown in Fig. 5

4.4.1. MaDS1

This uppermost Maastrichtian sequence represents the last depositional sequence of the Safra Member/Jeed Formation, situated below the K/Pg boundary.

Only the HST1 of MaDS1 was studied in the present study. The HST1 is well developed in the type area of the Jeed Formation, southwest of Rutbah and at Tel Al Safra, east Akashat, and is characterized by 5–6 parasequences of oyster-limestone and marly dolostone cycles (MF15

and MF24); most of the cycles are terminated by *Thalassinoides* burrows within firmground surfaces representing depositional hiatuses (Fig. 5).

4.4.2. DaDS2

This is the lowermost sequence in the Paleocene phosphatic succession of Iraq, within the lower part of the Traifawi Member. It represents repeated cycles in the Traifawi type section southwest of Rutbah city and is recognized in all the studied sections, except at Marbat (NE Ga'ara); it increases in thickness westward, from 2 m to 13 m. The sequence is bounded at the base by Sequence Boundary 1 (K/Pg.SB1), marking the transition between the Safra and Traifawi members. DS3 is marked by distinct vertical facies change across the K/Pg boundary. The latter is marked by a significant depositional gap, characterized by the absence of the Maastrichtian planktic biozone *Plummerita hantkeninoides* (CF1) and the Danian planktic Zone P1a (Fig. 12). Additionally, this hiatus marks the absence of the following planktic foraminiferal zones: *Guembelitria cretacea* Interval Zone (P0) and the *Parvularugoglobigerina eugubina* Total Range Zone (Pα), spanning approximately 300,000 years (65.0–64.7 Ma). This time interval corresponds to the sequence boundary of Tectonic Megasequence AP9 (Sharland et al., 2001; Simmons et al., 2007). During this interval, some sequence boundaries were overlapped and amalgamated due to tectonic pulses associated with the uplift of the Rutbah High. This regional hiatus with different magnitudes across the K/Pg boundary can be traced across the Arabian Plate at several locations, including Iraq, Jordan, and Saudi Arabia (Farouk et al., 2014; Messaoud et al., 2025). Depending on the region, this depositional hiatus differs in duration and level of erosion. The irregular paleotopography and sea-level fluctuations observed in various parts of the Middle East (e.g., Klitzsch and Wycisk, 1987; El-Azabi and Farouk, 2011; Razmjooei et al., 2014; Farouk et al., 2014) are indicative of local tectonic activity that coincides with this surface. Most of the Arabian Plate was affected by the wider regional consequences of this tectonic activity represented by the Cretaceous/Paleogene unconformity. However, the Early Paleocene Ophiolite obduction episodes at the plate boundaries had less impact on basinal areas in the northern United Arab Emirates and the southeast Iranian Zagros basin. Biostratigraphic analysis in the present study confirms the presence of the earliest Danian, represented by the P0 and Pa Zones also recorded in paleo-low areas in northern Iraq (e.g., Al-Khalaif and Al-Mutwali, 2020).

The TST1 of the DaDS2 is composed of cycles of distal shelf facies (carbonaceous – smectitic shale, opal – CT porcellanite, planktic mudstone and wackestone, and pulses of turbid quartz sand – phosphate facies) (Mohammed et al., 2022). The MFS is represented by MF23 (Fig. 5). A rapid shift from outer ramp facies toward the lower/upper shoreface (bioturbated and massive sandstone (MF11 and MF12), is present which represents the HST2 in the type Traifawi section (about 7 m. thick). The HST2 becomes thinner (about 2 m) from the south to the north in the west Ga'ara area (e.g., Akashat Mine, Outcrop –1 and BH5/8), where it is represented by lagoonal/upper shoreface facies (MF24). Westward (BH5/6), the TST becomes deeper and is defined by the proximal outer ramp (MF20).

4.4.3. DaDS3

The DaDS3 depositional sequence is recognized in the southwest (Traifawi section, 7 m) and (BH5/6, 18 m thick) but it is missing in the sections located to the east (BH5/8, Outcrop-1, Akashat, and Marbat sections) (Fig. 5). The sequence boundary (DaSB2) with the underlying DS3 is a transgressive surface characterized by bivalve shell fragments, phosphatic bone fragments, and lithoclasts. In contrast, the upper sequence boundary DaSB3 is a type 1 boundary marked by a karstified, highly recrystallized, and weathered limestone. This karstified – recrystallized limestone bed differentiates the mixed siliciclastic – carbonate Traifawi Member/Jeed Formation from the mixed phosphorite – limestone of the Akashat Formation above. MA7, FA2, and FA5 represent the TST2 of this sequence, and the MFS is marked by the transition of the MF7 from floatstone/rudstone to wackestone/packstone texture,

which was deposited under shallow-water shoal barrier conditions. Upwards, the sequence gradually shallows, representing the HST3, characterized by the upper part of the karstification surface and very coarse recrystallized limestone (Fig. 5).

4.4.4. DaDS4

This sequence is recorded in all the study sections and corresponds to phosphorite-dominated deposits (FA4) of the Hirri Member/Akashat Formation. It ranges in thickness from 9 to 22 m, with a maximum thickness in the Akashat Mine (Fig. 5). The lower sequence boundary (DaSB3) characterized by *Thalassinoides*-rich *Glossifungites* ichnofacies corresponding to an amalgamated surface (TS/SB). The TST3 consists of planktic foraminifera-rich limestone in the western sections (BH5/6, Traifawi), changing towards the east, where it is dominated by granular phosphorite lithofacies (MF4) with thin foraminiferal limestone (MF7). The HST4 is characterized by carbonate turbidite MF18 representing the distal mid-ramp depositional environment. The boundary between TST3/HST4 is represented by the MFS (Fig. 5). The DaDS4 deepens westward (basinward) like the other depositional sequences; the TST3 and MFS in BH5/6 are represented by phosphate-free, distal shelf and outer ramp, planktic foraminiferal-rich shale and mudstone/wackestone (MF21 and MF25).

4.4.5. DaDS5

This sequence was recognized in BH5/6, BH5/8, the Traifawi, outcrop and the Akashat Mine sections, where it ranges from 10 m to 16 m thick within the upper Hirri Member (Fig. 5). However, it is missing in the Marbat section. The base of DaDS5 is characterized by DaSB4, resulting from a hiatus represented by the absence of the *Praemurica uncinata* (P2) Zone, similar to localities reported in Jordan (Farouk et al., 2014, Fig. 12). Additionally, it is marked by highly recrystallized limestone and local karstification, with DaDS4 absent from the Akashat and Marbat sections, where DaSB2 and DaSB3 are amalgamated (Fig. 5). A new transgression within the basin west of the Akashat and Traifawi areas resulted in the deposition of open, deep marine outer to mid-ramp facies association (FA6 and FA7), representing the TST4 and MFS, respectively. In the BH5/6, the TST4 is represented by FA6 and the MFS by FA7. Mid-to outer-ramp facies in the Traifawi section, including phosphorite MF4 and chert lithofacies, and the TST4 is represented by shallower facies in BH5/8, where it is represented by phosphorite MF4 and MF5. A sea-level fall is indicated by the deposition of the mid-ramp lithofacies in the western borehole (BH5/6) and by the bivalve shoal barrier, distal inner ramp facies association in BH5/8 and the Traifawi outcrop section. The shallow mid-ramp to inner ramp facies confirms the HST5 in the western part of the MTB, prior to a basinward shift of the shoreline in SeDS6 (see below).

4.4.6. SeDS6

This sequence corresponds to the shallower and final depositional sequence of the Akashat Formation represented by the Duwima Member. Based on planktic and benthic foraminifera biostratigraphy, DS7 is assigned herein to a late Paleocene age (Fig. 2), thinning eastwards from 24 m. in BH5/6 (west) to 8 m. in BH5/8, and 6 m in the Traifawi section. The base of SeDS6 is characterized by a **Danian/Selandian (Da/Se) hiatus**, revealing an erosional unconformity with the most pronounced hiatus. This significant time gap is likely to be the result of tectonic uplift and erosion, and is interpreted as indicating local structural movements on Rutbah High. In these eastern areas of the basin, the Lower Eocene (Ypresian) strata directly overly Danian strata, indicating a substantial hiatus resulting from tectonic uplift with the absence of Selandian and Thanetian age sediments. In well BH 5/8, planktic zones P4a and P4b are missing, with subzones 3b and 4c either poorly developed or absent. This hiatus may have extended for more than 2 million years, while in well BH 5/6, the hiatus duration is approximately 1 million years, with the presence of shallow benthic foraminiferal assemblages such as *Ranikothalia* and *Neoepinoides*. The Late Danian sea-level fall is well-

documented across various global eustatic curves (Hardenbol et al., 1998; Miller et al., 2005; Kominz et al., 2008; Westerhold et al., 2011; Baceta et al., 2004; Farouk, 2016; Haq et al., 1987; Schmitz et al., 2011; Gradstein et al., 2012; Farouk and Faris, 2013; Haq, 2014; Messaoud et al., 2025) (Fig. 12). The Danian/Selandian hiatus is correlatable with the absence of the P2 and P3 zones in Jordan (Farouk et al., 2014; Messaoud et al., 2025) and has also been reported in Egypt (Farouk and El-Sorogy, 2015). This reflects the tectonic activity on the Arabian Plate and matches well with the global eustatic sea-level fall (Sharland et al., 2004; Haq, 2014; Kalifi et al., 2025).

The TST6 of the SeDS6 is rich in bioclastic and bivalve-rich limestone with chert nodules in the lower part representing a shallow marine inner ramp setting overlain by phosphorite lithofacies in BH5/8 that was deposited in a mid-ramp setting. In the westernmost section of the basin (BH5/6), the lower part represents the outer ramp facies association of small planktic foraminifera and planktic foraminiferal mudstone, and wackestone becomes more prominent. MF20 represents TST6 in the middle part of the basin; this system tack, is marked by MF21 in the BH5/6, MF19 in BH5/8, MF7 in Outcrop 1, and MF7 in the Marbat section. Fossil-poor, palygorskite – rich dolomitic marl/shale (MF 24) indicates a sea-level fall and a change in the depositional environment from open marine to restricted lagoonal with the development of the HST7. The top of the MF24 at the uppermost part of the Paleocene succession at many localities along the east-west transect of the MTB (Fig. 5) indicates regional regression and development of a sequence boundary representing an unconformity surface between Paleocene and Eocene. This boundary is marked by the *Glossifungites* ichnofacies, with inclined, vertical, relatively large-sized *Thalassinoides* burrows.

4.4.7. YaDS7

The absence of upper Paleocene and lower Ypresian fossils marks the Paleocene/Eocene Hiatus (P/E).

This hiatus is characterized by significant changes in benthic foraminiferal assemblages at the Thanetian/Ypresian boundary and the absence of the marker basal Eocene Zonal taxa *Acarinina sibaiyaensis*. The succession below the hiatus represents a shallowing-upwards cycle and the termination of Paleocene phosphatic facies due to the development of deeper water conditions in the Eocene. Global temperature rises at the Paleocene/Eocene Thermal Maximum (PETM) led to warm, low-oxygen bottom waters, widespread carbonate dissolution, and a significant extinction event affecting benthic foraminifera (e.g., Stassen et al., 2012; Schmidt et al., 2018). Records suggest correlations between global sea-level changes and hyperthermal intervals were potentially caused by melting ice sheets in Antarctica, thermal expansion of seawater, or both. Regional sea-level rise preceding the PETM may have been influenced by tectonic uplift in the North Atlantic Igneous Province (e.g., Stassen et al., 2012; Pandey et al., 2021).

The YaDS8 formed during the lower Eocene marine transgression as it overlapped across the MTB. This paper deals only with the lower part of the YaDS7, which is about 10 m. thick in the Marbat El Hassan section in the northeast to 1 m. in the Traibeel area in the west (Fig. 5). In the latter area, the base of the Ratga Formation is marked by a regional bone coprolite phosphorite bed (MF2) deposited in a lagoonal setting; however, it is absent in deeper marine settings in BHs 5/8 and 5/6. It comprises a 1-m-thick bed that infills bioturbated marl/shale in the underlying Paleocene Duwima Member. The MF2 and overlying nummulite-rich limestone, mid-ramp facies association represents the early TST6 of the YaDS7 (Fig. 5).

5. Discussion

5.1. Depositional model and tectonic implications

A complex tectonic framework is supported by the Rutbah High basement structure, which dominates the Western Desert of Iraq and is an extension of the Ha'il Arc. This feature is surrounded by active

Mesozoic faults (N-S, NE-SW, E-W; Dunnington, 1958) and forms a broad anticlinorium (Riddler et al., 1989), with its core exposing Permo-Carboniferous rocks at the Ga'ara antiform. Significant tectonic elements are added further north in Iraq by the younger Eocene-Oligocene Walash-Naopurdan arc-backarc complex and the Cretaceous Kata-Rash arc assemblage (Sarmad et al., 2013, 2016). The region's subsequent lateral and vertical stratigraphic development was primarily controlled by the prominent paleotopography (highs and lows) created by the interaction of these arcs and fault systems. In this study, the Paleocene succession in wells BH5 and BH6 is approximately 91 m thick, consisting of fine-grained limestone, black mudstone, and porcellanite. Thickness decreases to 30 m on the Rutbah High, where phosphorite and bivalve-rich limestone predominate. Syn-depositional faulting along the western Rutbah High significantly influenced the deposition of the economic phosphorite bed (~10 m thick) at the Akashat mine (Fig. 11). The ramp morphology and phosphorite sedimentation were shaped by NE-SW syn-depositional faulting (Dunnington, 1959; Baban et al., 2000). Al-Bassam (2017) identified fault sets in the phosphatic basin and proposed a northeastward-deepening basin, contrary to this study's paleogeographic interpretation of an open marine, upwelling setting towards the west (Fig. 4). The tectonic events on the High created a steep ramp profile, transitioning from a homoclinal ramp to a distally steepened ramp. Offshore, deeper-water subtidal microfacies were deposited to the west, while local uplift on the Rutbah High resulted in shallowing conditions and repeated hiatuses. These hiatuses occurred at key boundaries, including the Lower Danian Traifawi, Upper Danian Hirri, Selandian-Thonetian Duwima members, and the Upper Paleocene-Lower Eocene Ratga boundary.

Poorly documented in the Western Desert of Iraq, the Late Cretaceous events are better studied in the phosphorite-rich Levant Super-Basin (Abed, 2013; Soudry et al., 2006; Powell and Moh'd, 2011; Messaoud et al., 2025). These authors linked Campanian-Eocene phosphorite deposits to regional structural developments such as the Syrian Arc Folds (Levant area) and Hail-Rutbah Arc. Sharland et al. (2001, 2004) and Kalifi et al. (2025) attributed widespread uplift across the Arabian Platform to obduction events at the boundaries of the Arabian Plate (e.g. Oman and Zagros mountains). Powell and Moh'd (2011) associated upwelling currents along the Southern Tethys Ocean with obduction tectonics in northern and northeastern Arabia.

5.2. The Marbat-Traibeel basin (MTB) and regional tectonic framework

The MTB, newly proposed in this study, represents an active Upper Cretaceous to Eocene phosphatic-siliceous-carbonate basin on the eastern margin of the Southern Tethys in Iraq's Western Desert, forming the eastern boundary of the Levant Super-Basin (East Mediterranean Phosphorite Basin). Bounded by the Rutbah High to the east and north (Fig. 3), the MTB extends southwest into the Sirhan-Turayf Basin in Saudi Arabia. The latter basin trends northeast to southwest, deepening westward. The Ha'il-Rutbah Arc formed a secondary shoreline, while the main shoreline of the MTB lay along the southern Arabian Plate in present-day Jordan and Saudi Arabia.

Depositional facies in the MTB reflect a ramp setting, steepening westward, with lithofacies such as phosphorite, porcellanite, carbonate, carbonaceous marl, and shale transitioning to proximal siliciclastic sandstones towards the paleo-shoreline in the south (e.g. south Jordan and Saudi Arabia) (Fig. 11; Abed, 2013; Brew, 2001; Powell and Moh'd, 2011). These basins may have been epicontinental seaways defined by structural highs like the Sirhan, Ha'il, and Rutbah structures. Late Cretaceous to Early Paleogene phosphorite deposition in Jordan, Iraq, and Saudi Arabia was associated with intraplate deformation associated with subduction between the Southern Tethys and Afro-Arabian plates (Powell and Moh'd, 2011; Abed, 2013; Kalifi et al., 2025).

Late Maastrichtian uplift of the NE-SW Rutbah High partitioned the Upper Cretaceous Rutbah Basin into the MTB (west) and East Rutbah Basin (ERB, east and north). This uplift created deep subtidal and pelagic

outer ramp environments westward, forming a seaway connected to the deeper ocean basin in Jordan. NE-SW faulting increased accommodation space on the western Rutbah High, while, in contrast, continuous carbonate ramp sedimentation occurred in the ERB, linked to the Mesopotamian Basin.

5.3. Phosphorite deposition and paleogeography

Phosphorite deposits in the MTB indicate westward-deepening marine conditions and were controlled by tectonics and paleogeography. Lower Danian proximal inner ramp deposits (DS3) thinned toward the Rutbah High, and are absent in the Ga'ara outcrops located to the northeast (Fig. 5). Overlying mixed phosphorite-carbonate-rich facies reflect a steep ramp model (Fig. 11). Mohammed et al. (2022) demonstrated that nutrient-rich upwelling currents transported P-Si-bearing waters from deep oceanic waters of Neo-Tethys ocean westward towards the shallower MTB, a single depositional trough unaffected by fault-bounded troughs as proposed by Aqrabi et al. (2010). Lower Danian marine inner ramp (shoreface) sandstones and smectite-rich shales (DS3, DS4) suggest seasonal warm-humid/arid climates with detrital input from the Arabian Plate (Mohammed et al., 2022). In contrast, palygorskite-rich marl and shale in the Akashat Formation (DS5-DS8) and the lower part of the Ratga Formation reflect more arid conditions (Fig. 5). The presence of evaporites in equivalent formations in southwest Iraq further support this climatic shift (Al Naqib, 1967; Saleh and Tamar-Agha, 2016).

The Risha area in Jordan, basinward from the MTB, contains thin Paleocene phosphorite beds (<4 m) in the Maastrichtian – Paleocene Muwaqqar Chalk Marl Formation as proved in the Risha 1 well (Andrews, 1992). These correspond to the Traifawi Member, highlighting reduced phosphorite content basinward. Environmental conditions conducive to phosphorite deposition migrated eastward, up-sequence, reflecting marine onlap onto the Arabian Plate. This migration contrasts with central Jordan's thicker Campanian phosphorites (Abed and Amireh, 1999; Pufahl et al., 2003; Powell and Moh'd, 2011; Messaoud et al., 2025).

6. Conclusions

- **Tectonic setting of the Rutbah Basin:** The current study indicates that the tectonically active Rutbah High physically divided the Rutbah Basin during the Late Maastrichtian into two distinct basins: the Marbat-Traibeel Basin (MTB) on the western flank and the East Rutbah Basin (ERB) to the east.
- **Biostratigraphy:** The current biostratigraphical study suggests that the phosphate-rich Hirri Member (Akashat Formation) dates to the late Danian, based on planktonic foraminifera in the P3a Zone. The upper part of the Akashat Formation (Duwima Member) extends into the Selandian and the Thanetian. In contrast, previous studies incorrectly indicated that the *Morozovella angulata* Zone, reported in the Hirri and Duwima Members, spans the Middle Paleocene Selandian stage.
- **Burrowing and Ichnofacies:** Inner ramp dolomitic marl lithofacies have abundant large-diameter *Thalassinoides* burrows, especially at hiatus levels, suggesting still stands, fluctuating oxygen and salinity levels in nutrient-rich, semi-restricted lagoonal conditions. In contrast, the mid and outer ramp settings are characterized by smaller-diameter *Thalassinoides* burrows. The presence of *Glossifungites* Ichnofacies indicates omission surfaces and firmgrounds and is crucial for recognizing hiatuses, unconformities, sequence boundaries and transgressive surfaces within the Paleocene succession.
- **Depositional Model and Tectonic Controls on Sedimentary Evolution in the Western Desert of Iraq:** The Paleocene Marbat-Traibeel Basin (MTB) exhibits vertical and lateral changes in lithofacies and microfacies, interpreted as a steepened ramp system

developed to the west of the Rutbah High. The Traifawi, Hirri, and Duwima members were deposited in mixed siliciclastic-carbonate-siliceous-phosphorite ramp environments. The depositional model suggests a westward migration of the basin, with increasing sediment thickness, decreasing energy gradients, and a rise in small benthic and planktic foraminifera and sponge spicules. Shallower, tidal, and storm-controlled settings dominate the central and extreme northeast of the basin, influenced by episodic upwelling of nutrient-rich waters. These depositional patterns reflect a basinward-to-shoreward transition from phosphorite-rich carbonate to siliciclastic-rich successions. Paleocene deposits are predominantly of Danian age in the shoreward Akashat and Ga'ara areas, while the Traibeel and Traifawi areas to the west include sediments of the Danian, uppermost Selandian, and Thanetian ages. The Traibeel area indicates distal, deeper water conditions, while the Ga'ara and Akashat areas are influenced by shallower, tectonically controlled conditions near the Rutbah High. Previous studies suggested an open, deep-water environment sourced by upwelling currents from the northeast (Anah Graben); however, this study demonstrates that the MTB was connected to the phosphate-rich Levant Superbasin of the Neo-Tethys Ocean to the west. In contrast, the Anah Graben recorded hiatuses and phosphate-free, shallow marine carbonate-siliciclastic sediments during the Paleocene. Lithofacies and microfacies variations in the MTB reflect deposition on a steepened ramp, deepening westward and transitioning to distal outer-ramp and basinal facies, similar to the deeper-water lithofacies of the Muwaqqar Chalk Marl and Umm Rijam Chert-Limestone formations in Jordan. This evidence suggests that the MTB was part of the Levant Superbasin, deepening towards the west, with the main shoreline extending into southern Jordan/Saudi Arabia. A total of twenty-six microfacies and sub-lithofacies were identified and grouped into seven depositional environments across the inner, mid-, and outer ramp settings. In the Akashat Ramp, two primary phosphorite microfacies were identified: coarse-grained phosphorite (MF1 and MF2), associated with high-energy inner ramp carbonate and siliciclastic lithofacies, and fine-grained, ovoid phosphatic sand microfacies, indicative of a medium-to-high energy mid-ramp depositional environment. These microfacies form the main economic phosphorite beds of the Paleocene Akashat Formation.

- The sedimentary evolution of the MTB is marked by six sequence boundaries, with hiatuses observed at the Maastrichtian/Danian, Lower Danian/Upper Danian, Danian/Selandian, and Thanetian/Ypresian boundaries. These hiatuses, correlated with similar boundaries in regions like Jordan and Saudi Arabia, reflect the influence of regional tectonic activity on sequence boundaries and hiatus surfaces, particularly around the Rutbah High and associated structural features. These hiatuses divide the succession into seven depositional sequences, characterized by transgressive and highstand systems tracts, highlighting the dynamic nature of sedimentary processes. Sea-level fluctuations and tectonic forces played a significant role in shaping depositional patterns, with the absence of falling stage and lowstand systems tracts attributed to regional eastward onlap. The tectonic uplift of the Rutbah High significantly influenced basin development and the formation of these depositional sequences within the MTB. Notably, the Anah Graben Basin and the Eastern Rutbah Basin were not connected to the phosphate-rich MTB in the Iraqi Western Desert, underscoring the role of regional tectonics in controlling sedimentation and basin evolution.

CRediT authorship contribution statement

Ibrahim Q. Mohammed: Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology. **Ali H. Dohan:** Writing – original draft, Resources, Methodology, Investigation. **Anwar K. Mousa:** Writing – original draft, Validation, Software, Resources. **Fadhil A. Lawa:** Writing – original draft, Supervision, Resources,

Investigation, Data curation. **Sawsan H. Alhazaa:** Methodology, Investigation, Data curation. **Sherif Farouk:** Writing – review & editing, Writing – original draft, Supervision, Software. **Khaled Al-Kahtany:** Visualization, Validation, Software, Resources. **John H. Powell:** Writing – review & editing, Writing – original draft, Resources, Formal analysis.

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.

Acknowledgments

The authors thank the Chief Editor, Prof. Read Mapeo, Prof. Jamel Touir, and an anonymous reviewer for their valuable comments and suggestions, which significantly improved the manuscript. Ongoing Research Funding program, (ORF-Ctr-2025-5), King Saud University, Riyadh, Saudi Arabia. JHP publishes with the permission of the Director, British Geological Survey (NERC).

Data availability

Data will be made available on request.

References

- Abed, A.M., 2013. The eastern Mediterranean phosphorite giants: an interplay between tectonics and upwelling. *GeoArabia (Manama)* 18 (2), 67–94.
- Abed, A.M., Amireh, B.S., 1999. Sedimentology, geochemistry, economic potential, and paleogeography of an Upper Cretaceous phosphorite belt in the southwestern desert of Jordan. *Cretac. Res.* 20, 119–133.
- Ahmed, A.H., Aseri, A.A., Ai, K.A., 2022. Geological evolution of phosphorite deposits in NW Saudi Arabia as possible sources of trace elements and rare earth elements. *Ore Geol. Rev.* 144.
- Al-Bassam, K.S., 2017. Geology of the phosphorite deposits of Iraq. *Iraqi Bulletin of Geology and Mining Special Issue, Special (7)*, 25–50.
- Al-Bassam, K.S., Aba-Hussain, A.A., Mohammed, I.Q., Al-Rawi, Y.T., 2010. Petrographic classification of phosphate components of East Mediterranean phosphorite deposits. *Iraqi Bulletin of Geology and Mining* 6 (1), 59–79.
- Al-Jibouri, B.S.M., Gayara, A.D., 2015. Paleocene sequence development in the Iraqi Western Desert. *Iraqi Bulletin of Geology and Mining* 11 (3), 1–18.
- Al-Khalaf, S., Al-Mutwali, M., 2020. Biostratigraphy and sequence stratigraphy and depositional environment of Kolosh Formation in Dohuk Area, Northern Iraq. *Iraqi National Journal of Earth Science* 20 (2), 18–42.
- Al-Mutwali, M.M., 1992. Foraminifera, Stratigraphy, and Sedimentology of the Upper Cretaceous-Lower Tertiary Sediments in Selected Boreholes Around the Khlesia-Anah-Ramadi Area (Western Iraq). Unpublished Phd Thesis. Mosul University, p. 168.
- Al-Mutwali, M., Tamer-Agha, M., Y, M., Abawi, S.T., 2002. Facies distribution and paleogeography of lower tertiary deposits in Khleisia Anah-Ramadi area, western Iraq. *Iraqi National Journal of Earth Science* 2 (1), 14–27.
- Al-Naqib, K.M., 1967. Geology of the arabian peninsula: southwestern Iraq. *J. Afr. Earth Sci.* 560-G, 1–54. <https://doi.org/10.3133/pp560G>.
- Al-Sammari, A., Al-Jubouri, F., Khshaba, A., Al-Rabaii, M., Sahara, A., Beruti, A., Beko, T., 1994. Geological Studies of Akkas Field. Iraq Oil Exploration Company unpublished report, Baghdad, Iraq, p. 256.
- Ali, A.A., 1985. Facies Analysis of Umm Er Radhuma Formation in Selected Area from Western Desert, Iraq. Unpublished M.Sc. thesis, University of Baghdad, Iraq, p. 190.
- Andrews, J.J., 1992. Cretaceous and Paleogene lithostratigraphy in the subsurface of Jordan, *Subsurface Geology Bulletin* 5. Geology Directorate, Subsurface Geology Division, Ministry of Energy and Mineral Resources, Amman.
- Aqrabi, A.A., Goff, J.C., Horbury, A.D., Sadooni, F.N., 2010. The Petroleum Geology of Iraq, 424. Scientific Press. *Beaconsfield*.
- Arnott, R.W.C., 2010. Stratigraphic architecture of a deep-water slope channel-levee complex: the Upper Cretaceous Tres Pasos Formation, southern Chile. *Sedimentology* 57 (4), 979–1008.
- Baceta, J.I., Pujalte, V., Serra-Kiel, J., Robador, A., Orue-Etxebarria, X., 2004. El Maastrichtense final, Paleoceno e Ilerdiense inferior de la Cordillera Pirenaica. *Geología de España* 308–313.
- Baoumy, H., Farouk, S., 2022. The geochemical and economic significance of REE in the Upper Cretaceous-Eocene Tethyan phosphorites. *J. Afr. Earth Sci.* 194, 104635.
- Bamerni, A., Al-Qayim, B., Rund Ali Hammoudi, F.F., 2021. High-resolution biostratigraphic analysis of the Cretaceous-Paleogene Boundary in the Kurdistan Region (NW Iraq). *Stratigraphy* 18 (4), 251–268. <https://doi.org/10.29041/strat.18.4.02>.

- Brito, L., Bessette, C., Dashti, S., Liel, A.B., Wham, B., 2024. Influence of stratigraphic variability and layering on liquefiable soils near and away from structures. *GeoCongress 2024*, 383–393.
- Burchette, T.P., Wright, V.P., 1992. Carbonate ramp depositional systems. *Sediment. Geol.* 79 (1–4), 3–57.
- Catuneanu, O., 2017. Sequence stratigraphy: guidelines for a standard methodology. *Stratigraphy & Timescales* 2, 1–57. <https://doi.org/10.1016/bs.sats.2017.07.003>.
- Catuneanu, O., Zecchin, M., 2013. High-resolution sequence stratigraphy of clastic shelves II: controls on sequence development. *Mar. Petrol. Geol.* 39 (1), 26–38.
- Catuneanu, O., Galloway, W.E., Kendall, C.G.St.C., Miall, A.D., Posamentier, H.W., Strasser, A. and Tucker, M.E., 2011. Sequence stratigraphy: methodology and nomenclature. *Newsl. Stratigr.*, v. 44/3, p. 173–245.
- Ctyroky, P., Karim, S.A., 1971. Stratigraphical paleontology of Umm-Radhuma Formation in Akashat Phosphate deposit-Gaara area, W. Iraq. *J. Geol. Soc. Iraq* 4, 59–72.
- Dashtgard, S.E., Löwemark, L., Wang, P.L., Setiaji, R.A., Vaucher, R., 2021. Geochemical evidence of tropical cyclone controls on shallow-marine sedimentation (Pliocene, Taiwan). *Geology* 49 (5), 566–570.
- Dunham, R.J., 1962. Classification of carbonate rocks according to depositional texture. In: Ham, W.E. (Ed.), *Classification of Carbonate Rocks*, 1. American Association of Petroleum Geologists Memoir, pp. 108–121.
- El Bami, R., Raji, O., Ouabid, M., Elghali, A., Khadiri Yazami, O., Bodinier, J.L., 2021. Phosphate rocks: a review of sedimentary and igneous occurrences in Morocco. *Minerals* 11 (10), 1137.
- El-Azabi, M.H., Farouk, S., 2011. High-resolution sequence stratigraphy of the Maastrichtian-Ypresian succession along the eastern scarp face of Kharga Oasis, southern Western Desert, Egypt. *Sedimentology* 58 (3), 579–617.
- Embry, A.F., Klovan, J.E., 1971. A late Devonian reef tract on northeastern Banks Island, NWT. *Bull. Can. Petrol. Geol.* 19 (4), 730–781.
- Farouk, S., 2016. Paleocene stratigraphy in Egypt. *J. Afr. Earth Sci.* 113, 126–152.
- Farouk, S., Faris, M., 2013. Calcareous nannofossil and foraminiferal bio-events of the Danian-Selandian transition of the Quseir area, northwestern Red Sea margin, Egypt. *Micropaleontology* 59 (2–3), 201–222.
- Farouk, S., Marzouk, A.M., Ahmad, F., 2014. The Cretaceous/Paleogene boundary in Jordan. *J. Asian Earth Sci.* 94, 113–125.
- Farouk, S., El-Sorogy, A., 2015. Danian/Selandian unconformity in the central and southern Western Desert of Egypt. *J. Afr. Earth Sci.* 103, 42–53.
- Flügel, E., 2010. *Microfacies of Carbonate Rocks: Analysis, Interpretation and Application*. Springer-Verlag, Berlin.
- Föllmi, K.B., 2016. The role of phosphorite in the global phosphorus cycle. *Earth Sci. Rev.* 158, 1–22.
- Föllmi, K.B., Garrison, R.E., Ramirez, P.C., Zambrano-Ortiz, F., William, J.L., Benedikt, L., 1992. Cyclic phosphate-rich successions in the Upper Cretaceous of Colombia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 93 (3–4), 151–182.
- Fouad, S.F., 2006. Fault geometry and depth of detachment in Anah Graben, West Iraq. *Iraqi Bulletin of Geology and Mining* 2 (1), 13–29.
- Gil-Gil, J., Bretones, A., Boix, C., García-Hidalgo, J.F., 2024. Evolution of Coniacian facies and environments in the Iberian basin: a longshore current controlling siliciclastic sand distribution on a carbonate platform. *J. Afr. Earth Sci.* 205. <https://doi.org/10.1007/s10347-024-00681-2>. Article 104910.
- Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.E., 2012. *The Geologic Time Scale*. Boston, USA.
- Haak, A.B., Schlager, W., 1989. Compositional variations in calciturbidites due to sea-level fluctuations, late Quaternary, Bahamas. *Geol. Rundsch.* 78, 477–486.
- Hammoudi, R., 2011. High-resolution biostratigraphy of the K/T boundary in the Higran Section, Shaqlawa Area, Northern Iraq. *Iraqi National Journal of Earth Science* 11 (1), 23–48.
- Haq, B.U., 2014. Cretaceous eustasy revisited. *J. Afr. Earth Sci.* 113, 44–58. <https://doi.org/10.1016/j.jglp.2014.01.002>.
- Haq, B.U., Hardenbol, J., Vail, P.R., 1987. Mesozoic and Cenozoic Chronostratigraphy and Cycles of sea-level Change, 42. SEPM Special Publication, pp. 71–108.
- Hardenbol, J., Thierry, J., Farley, M.B., Jacquin, T., De Graciansky, P.C., Vail, P.R., 1998. Mesozoic and Cenozoic Sequence Chronostratigraphic Framework of European Basins.
- Hottinger, L., 2014. Paleogene larger Rotaliid Foraminifera from the Western and Central Neotethys. Springer, Berlin, pp. 191–p.
- Jassim, S.Z., Buday, T., Jassim, S.Z., Goff, J.C., 2006. *Geology of Iraq*. DOLIN, sro, distributed by Geological Society of London.
- Jassim, S.Z., Karim, S.A., Basi, M., Al-Mubarak, M.A., Munir, J., 1984. Final Report on the Regional Geological Survey of Iraq, Vol. 3, Stratigraphy. Manuscript Report. Geological Survey of Iraq.
- Kalifi, A., Messaoud, J.H., Baby, G., Ibrahim, K., Powell, J.H., van Buchem, F., 2025. Tectono-stratigraphic evolution of the Late Cretaceous-Eocene of Jordan and implications for the Arabian Plate convergent margin phase. *Mar. Petrol. Geol.* 181, 107525. <https://doi.org/10.1016/j.marpetgeo.2025.107525>.
- Karim, S.A., Al-Kubaysi, K.N., 2020. Biostratigraphy and environmental reconstruction of the Akashat formation (Paleocene phosphatic sequence), Western Desert, Iraq. *Iraqi Bulletin of Geology and Mining* 16 (2), 1–20.
- Karim, S.A., Al-Kubaysi, S., 2020a. Biostratigraphy of the Late Cretaceous-early Paleocene succession in selected wells, Jambur Oil Field, Kirkuk, Northern Iraq. *Iraqi Geological Journal* 55 (2C), 221–238.
- Klitzsch, E., Wycisk, P., 1987. Geology of the sedimentary basins of northern Sudan and bordering areas. *Berliner Geowissenschaftliche Abhandlungen, Reihe A* 75, 97–136.
- Kominz, M.A., Browning, J.V., Miller, K.G., Sugarman, P.J., Mizintseva, S., Scotese, C.R., 2008. Late Cretaceous to Miocene sea-level estimates from the New Jersey and Delaware coastal plain coreholes: an error analysis. *Basin Res.* 20 (2), 211–226.
- Lawa, F.A., Al-Karadakh, A.I., Ismail, K.M., 2017. An interfingering of the Upper Cretaceous rocks from Chwarta-Mawat Region, NE Iraq. *Iraqi Bulletin of Geology and Mining* 13 (1), 15–26.
- Lawa, F.A., Qadir, H.A., 2023. New biostratigraphic ideas about the Cretaceous/Paleogene boundary from selected sections in Kurdistan-Mesopotamian foreland basin, Northern Iraq. *Iraqi National Journal of Earth Science* 23 (2), 124–156.
- Li, L., Keller, G., 1998. Maastrichtian diversification of planktonic Foraminifera at El Kef and Elles, Tunisia. *Ecologiae Geologicae Helveticae* 91, 75–102.
- MacEachern, J.A., Pemberton, S.G., 1992. *Ichnological Aspects of Cretaceous Shoreface Successions and Shoreface Variability in the Western Interior Seaway of North America*. Special Publications of SEPM.
- Meissner, C.R., Riddler, Jr.G.P., Van Eck, M., Aspinall, N.C., Farasani, A.M., Dini, S.M., 1989. Preliminary Geologic Map of Turayf Quadrangle, Sheet 31C, and Part of the an Nabk Quadrangle, Sheet 31B, Kingdom of Saudi Arabia. Report Prepared by the U.S. Geological Survey in cooperation with the Deputy Ministry for Mineral Resources, Saudi Arabia, USGS Saudi Arabian Mission.
- Messaoud, J.H., Kalifi, A., Alibrahim, A., Ibrahim, K., Chirakal, T., Ardilla-Sanchez, M., Leila, W.A., Ben Chabaane, N., Grélaud, C., Powell, J.H., van Buchem, F., 2025. Chronostratigraphy of the mixed Upper Cretaceous deposits at the northern margin of the Arabian Plate (Jordan). *Newsl. Stratigr.* 58, 161–201. <https://doi.org/10.1127/nos/2025/0858>.
- Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Pekar, S.F., 2005. The Phanerozoic record of global sea-level change. *Science* 310 (5752), 1293–1298.
- Mohammed, I.Q., 1993. Mineralogy, Petrology, and Depositional Environments of Clay and Siliceous Rocks in the Maastrichtian-Danian Sequence in Western Iraq. University of Baghdad, p. 171. Unpublished Ph.D. Thesis.
- Mohammed, I.Q., Farouk, S., Mousa, A.K., Lawa, F.A., 2022. Lithofacies types, mineralogical assemblages, and depositional model of the Maastrichtian-Danian successions in the Western Desert of Iraq and eastern Jordan. *J. Afr. Earth Sci.* 186, 104397.
- Mohammed, I.Q., Sarin, T., Singh, P., Lawa, F.A., Farouk, S., Al-Kahtany, K., Banerjee, S., 2025. The influence of depositional conditions on chemical and mineralogical composition of glauconite: case study from the Late Cretaceous Dokan Basin in Kurdistan region of Iraq. *Appl. Clay Sci.* 263, 107639.
- Mousa, A.K., Al-Dulaimi, S.I., Mohammed, I.Q., 2020. Biostratigraphy of the Late Cretaceous/Early Paleocene successions at KH 5/6 and KH 5/8 core interval, Western Desert of Iraq. *The Iraqi Geological Journal* 104–125.
- Mousa, A.K., Al-Dulaimi, S.I., Mohammed, I.Q., Lawa, F.A., 2023. Stratigraphic analysis and depositional environment of the newly recorded Umm Er Rhadhuma Formation (Paleocene) from the borehole K.H12/7, South Anah City, Western Iraq. *Iraqi Geological Journal* 56 (1C), 94–109.
- Nakkady, S.E., 1950. A new foraminiferal fauna from the Esna shales and Upper Cretaceous chalk of Egypt. *J. Paleontol.* 24, 675–692.
- Notholt, A.J.G., 1985. Phosphorite resources in the Mediterranean (Tethyan) phosphogenic province: a progress report. *Sciences Géologiques, bulletins et mémoires* 77 (1), 9–17.
- Pandey, M., Pant, N.C., Arora, D., Gupta, R., 2021. A review of Antarctic ice sheet fluctuations records during Cenozoic and its cause and effect relation with the climatic conditions. *Polar Science* 30, 100720.
- Playton, T.E., Kerans, C., Janson, X., 2010. Carbonate slope aprons: a new depositional model for the Devonian reef complexes of the Canning Basin, Western Australia. *J. Sediment. Res.* 80 (10), 881–903.
- Powell, J., 1989. Stratigraphy and sedimentation of the Phanerozoic rocks in central and south Jordan, Bulletin 11. Geology Directorate, Natural Resources Authority (Ministry of Energy and Mineral Resources), Part B: Kurnub, Ajlun and Belqa Groups 161, 12 figures, 17 tables, Amman.
- Powell, J.H., Moh'd, B.K., 2011. Evolution of Cretaceous to Eocene alluvial and carbonate platform sequences in central and south Jordan. *GeoArabia-Middle East Petroleum Geosciences* 16 (4), 29–82.
- Pratt, B., Raviolo, M., Botdonaro, O., 2012. Carbonate platform dominated by peloidal sands: lower Ordovician La Silla Formation of the eastern Precordillera, San Juan, Argentina. *Sedimentology* 59, 843–866. <https://doi.org/10.1111/j.1365-3091.2011.01282.x>.
- Pufahl, P.K., Grimm, K.A., Abed, A.M., Sadaqah, R.M.Y., 2003. Upper Cretaceous (Campanian) phosphorites in Jordan: implications for the formation of a south Tethyan phosphorite giant. *Sediment. Geol.* 161 (3–4), 175–205.
- Rahaghi, A., 1978. Paleogene biostratigraphy of some parts of Iran. Publications of the National Iranian Oil Company, Geological Laboratories 7, 1–165.
- Razmjooei, M.J., Thibault, N., Kani, A., Mahanipour, A., Boussaha, M., Korte, C., 2014. Coniacian-Maastrichtian calcareous nannofossil biostratigraphy and carbon-isotope stratigraphy in the Zagros Basin (Iran): consequences for the correlation of Late Cretaceous Stage Boundaries between the Tethyan and Boreal realms. *Newsl. Stratigr.* 47 (2), 183–209.
- Riddler, G.P., Van Eck, M., Farasani, A.M., 1989. The phosphorite deposits of the Sirhan-Turayf region, northern Saudi Arabia. *J. Afr. Earth Sci.* 2 (3), 558–563. <https://doi.org/10.1017/CBO9780511564458.007>.
- Rodríguez-Tovar, F.J., Puga-Bernabéu, Á., Buatois, L.A., 2008. Large burrow systems in marine Miocene deposits of the Betic Cordillera (Southeast Spain). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 268 (1–2), 19–25.
- Saleh, A.S., Tamar-Agha, M.Y., 2016. Petrology, mineralogy, and diagenesis of the Rus and Jil Formations (Eocene) in Najif and Samawa areas, Southern Iraq. *Iraqi J. Sci.* 57 (2C), 1504–1520.
- Sarmad, A., Buckman, S., Aswad, K.J., Jones, B.G., Ismail, S.A., Nutman, A.P., 2013. The tectonic evolution of a Neotethyan (Eocene–Oligocene) island-arc (W alash and N

- aopurdan groups) in the Kurdistan region of the Northeast Iraq Zagros Suture Zone. *Isl. Arc* 22 (1), 104–125.
- Sarmad, A., Ismail, A., Nutman, A.P., Bennett, V.C., Jones, B.G., Buckman, S., 2016. The intra-oceanic Cretaceous (~ 108 Ma) Kata–Rash arc fragment in the Kurdistan segment of Iraqi Zagros suture zone. Implications for Neotethys evolution and closure. *Lithos* 260, 154–163.
- Schlager, W., 2005. Carbonate Sedimentology and Sequence Stratigraphy. *SEPM Society for Sedimentary Geology*, Tulsa, Oklahoma, p. 200. Society for Sedimentary Geology.
- Schmidt, D.N., Thomas, E., Authier, E., Saunders, D., Ridgwell, A., 2018. Strategies in times of crisis—insights into the benthic foraminiferal record of the Palaeocene–Eocene Thermal Maximum. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* 376 (2130), 20170328.
- Schmitz, R.J., Schultz, M.D., Lewsey, M.G., O'Malley, R.C., Ulrich, M.A., Libiger, O., Ecker, J.R., 2011. Transgenerational epigenetic instability is a source of novel methylation variants. *Science* 334 (6054), 369–373.
- Serra-Kiel, J., Vicedo, V., Baceta Caballero, J.I., Bernaola Bilbao, G., Robador Moreno, A., 2020. Paleocene larger Foraminifera from the pyrenean Basin with a recalibration of the Paleocene shallow benthic zones. *Geol. Acta* 18, 20–70. <https://doi.org/10.1344/GeologicaActa2020.18.8>.
- Sharbazeri, K.M., Dronadgh, I.G., Mahmood, Q.A., 2009. Biostratigraphy of the Cretaceous/Tertiary boundary in the Siran Valley (Sulaimani Region, Kurdistan, NE Iraq). *Geol. Carpathica* 60, 381–396.
- Sharland, P.R., Casey, D.M., Davies, R.B., Simmons, M.D., Sutcliffe, O.E., Hardenbol, J., 2004. Arabian plate sequence stratigraphy - revisions to SP2. *GeoArabia (Manama)* 9 (1), 199–214.
- Sharland, P.R., Ratmond, A., Casey, D.M., Daris, R.B., Hall, S.H., Hewerd, A.P., Horbury, A.D., Simmons, M.D., 2001. Arabian plate sequence stratigraphy. *GeoArabia Special Publication*.
- Simmons, M.D., Sharland, P.R., Casey, D.M., Davies, R.B., Sutcliffe, O.E., 2007. Arabian plate sequence stratigraphy: potential implications for global chronostratigraphy. *GeoArabia (Manama)* 12 (4), 101–130.
- Sissakian, V.K., Fouad, S.F.A., 2015. Geological Map of Iraq, Scale 1:1,000,000, 4th Edition, 2012. *Iraqi Bulletin of Geology and Mining* 11 (1), 9–16.
- Sissakian, V.K., Mohammed, B.S., 2007. Stratigraphy. *Iraqi Bulletin of Geology and Mining Special Issue*, pp. 51–124.
- Soudry, D., Glenn, C.R., Nathan, Y., Segal, I., VonderHaar, D., 2006. Evolution of Tethyan phosphogenesis along the northern edges of the Arabian–African shield during the Cretaceous–Eocene as deduced from temporal variations of Ca and Nd isotopes. *Earth Planet Sci. Lett.* 243 (3–4), 576–588.
- Stassen, P., Thomas, E., Speijer, R.P., 2012. Integrated stratigraphy of the Paleocene–Eocene thermal maximum in the New Jersey Coastal Plain: toward understanding the effects of global warming in a shelf environment. *Paleoceanography* 27 (4).
- Trappe, J., 2001. A nomenclature system for granular phosphate rocks according to depositional texture. *Sediment. Geol.* 145 (1–2), 135–150.
- Ulmer-Scholle, D.S., Scholle, P.A., Schieber, J., Raine, R.J., 2014. A Color Guide to the Petrography of Sandstones, Siltstones, Shales, and Associated Rocks, 109. American Association of Petroleum Geologists, Tulsa, OK, USA.
- Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S., Hardenbol, J., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H. W., Ross, C.A., Van Wagoner, J.C. (Eds.), *Sea-Level Changes: an Integrated Approach*. Society of Economic Paleontologists and Mineralogists, Tulsa, Oklahoma, pp. 39–45. *SEPM Special Publication No. 42*.
- Wade, B.S., Pearson, P.N., Berggren, W.A., Pälike, H., 2011. Review and revision of Cenozoic tropical planktonic foraminiferal biostratigraphy and calibration to the geomagnetic polarity and astronomical time scale. *Earth Sci. Rev.* 104 (1–3), 111–142.
- Vaughan, T.W., Cole, W.S., 1941. Preliminary Report on the Cretaceous and Tertiary Larger Foraminifera of Trinidad British West Indies. *Geological Society of America Special Papers* 29-30, 1–137.
- Wade, B.S., O'Neill, J.F., Phujareanchaiwon, C., Ali, I., Lyle, M., Witkowski, J., 2020. Evolution of deep-sea sediments across the Paleocene–Eocene and Eocene–Oligocene boundaries. *Earth Sci. Rev.* 211, 103403.
- Westerhold, T., Röhl, U., Donner, B., McCarren, H.K., Zachos, J.C., 2011. A complete high-resolution Paleocene benthic stable isotope record for the central Pacific (ODP Site 1209). *Paleoceanography* 26 (2).
- Wignall, P.B., 1994. Mudstone lithofacies in the Kimmeridge Clay Formation, Wessex Basin, Southern England: implications for the origin and controls of the distribution of mudstones. *J. Sediment. Res.* 64 (4).
- Zhang, Y., Li, X., Wang, J., Liu, Y., 2023. Sedimentary characteristics and genesis of the Lower Cambrian phosphate-bearing strata in the Yangtze Platform, South China. *J. Afr. Earth Sci.* 205. <https://doi.org/10.1016/j.jseas.2023.105123>. Article 104920.
- Zuffa, G.G., Nilsen, T.H., Winkler, G.R., 1980. Rock-fragment petrography of the Upper Cretaceous Chugach terrane, southern Alaska (No. 80-713). US Geological Survey.