# Sequence Stratigraphy, Tectonic Setting, and Gross Depositional Environments of the Palaeogene Pabdeh Group, in the Northern Emirates, United Arab Emirates

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**Extended abstract**

## Introduction

The present day structural and stratigraphic setting of the Northern Emirates is strongly related to the obduction of the Semail ophiolite, which led to onset of the Hajar Mountains and to the evolution of a foreland basin to the west of the uplifted area. The Cenozoic stratigraphy of the Northern Emirates (Pabdeh and Fars Groups), largely eroded/non-deposited in the hinterland, is well developed in the foreland basin, filling the accommodation space created in response to the lithospheric loading during obduction (Firpo, 2020). In parts, the Pabdeh Formation can reach thicknesses of greater then 3500m (Swire *et al*. 2022).

In the Northern Emirates, the Pabdeh Group is represented by a thick succession of fine clastics and argillaceous carbonates in a deep basinal facies, compared to its equivalent shallow water shelfal limestone and anhydrite of the Umm-er-Radhuma, Rus and Dammam in the central and western sectors of the Arabian Plate (van Dijk 2020).

In terms of hydrocarbon exploration, many wells have targeted the Pabdeh Group in the Northern Emirates. These have primarily been in the Pabdeh Basin to the west of the thrust front where a discovery was made at the Hamidiyah Field in Ajman in 1982.

Three wells were drilled in Ajman in 1982, 1983 and 1984. The most significant aspects of the oil production from these wells is that they have proven the presence and effectiveness of the petroleum system elements in the region with reservoir properties adequate to sustain production. The trapping mechanism was interpreted as a combination of structural and stratigraphic elements. Testing results showed that it has very rich gas with liquid yield approaching 300 barrels per MMCF of high-quality condensate.

The primary prospective reservoir in the foredeep area is the turbidites of the Pabdeh Group. The key to finding commercial accumulations in this play lies in identifying the areas of best reservoir development. However, to date this has been difficult due to the lack of 3D seismic data and lack of the wells drilled to sufficient depth. All previous exploration attempts have targeted structural traps, none of which were located in the primary sediment fairways. This study was kicked off to assess the hydrocarbon potential for the Pabdeh play in the Northern Emirates within the Western Foreland Basin.

As a direct result of this, it was possible to integrate and merge all available 3D and 2D seismic surveys in the Northern Emirates. This is the first unified 3D & 2D composite seismic dataset ever compiled for interpretation throughout the Pabdeh Basin and Northern Emirates. The 3D seismic datasets in the Northern Emirates are shown in Figure 1. This interpretation has been integrated with all the available well data and biostratigraphy to establish a more refined sequence stratigraphic framework, leading to the identification of the deep basin “systems tracts” and providing key insights into the internal sequence stratigraphy of the Pabdeh Group and on the distribution of potential reservoirs facies.

## Area of Study

The study area encompasses the Emirates of Ras Al Khaimah, Umm Al Quwain, Sharjah, Ajman, Dubai (northern sector) and the Omani side of the Musandam Peninsula which includes the Bukha, West Bukha and Tibat offshore fields. The area of interest is limited to the west by the maritime boundary with Iran, while to the east it is defined by the Northern Oman Mountains thrust front (Figure1, Figure 2).

From a structural perspective, the project focussed mainly on the foredeep of the Northern Oman Mountains in the Northern Emirates, which evolved throughout the Late Cretaceous and Tertiary times in response to regional shortening due to the obduction of the Semail Ophiolite and closure of Neo-Tethys (Ali *et al* 2018). The basin architecture reveals a large wedge of sediment with thickness increasing from NW to SE, reaching maximum values close to the present-day thrust front.

The foredeep hosts over 6 Km of sediments (Pabdeh and Aruma Groups), represented predominantly by fine grained clastics with high carbonate content, reflecting the nature of the sediment source during the basin’s evolution.

## Geological and Structural Setting

The geology of the area of interest is largely revealed by the excellent outcrops of the Hajar Mountains that characterise the eastern side of the UAE and it is supplemented by numerous well penetrations. In total 212 wells were drilled over a period of 60 years from 1958 until 2018, data from these wells was used in this study.

The Pabdeh basin was filled with a thick Late Paleocene- Oligocene sequence that was sourced from Late Cretaceous topographic reliefs. Development of the Pabdeh Foredeep basin took place after a Late Cretaceous compressional event. In the UAE-north Oman, the Eocene sequence shows a typical flysch type facies containing clasts of the Hawasina chert and reworked Mesozoic faunas derived from the Cretaceous units, Mauddud (~Sarvak) and Nahr Umr (~Kazhdumi) Formations (Searle, 1988).

Based on biostratigraphic data (Orang *et al.* 2018), the age of the oldest foredeep Pabdeh basin infill is Late Palaeocene. The age of the uppermost part of the Pabdeh Group extends into the Oligocene. It was first described from the foredeep basin developed at the same time in Iran. A detailed bio-, chrono- and lithostratigraphy for the Pabdeh Group is illustrated by Figure 3

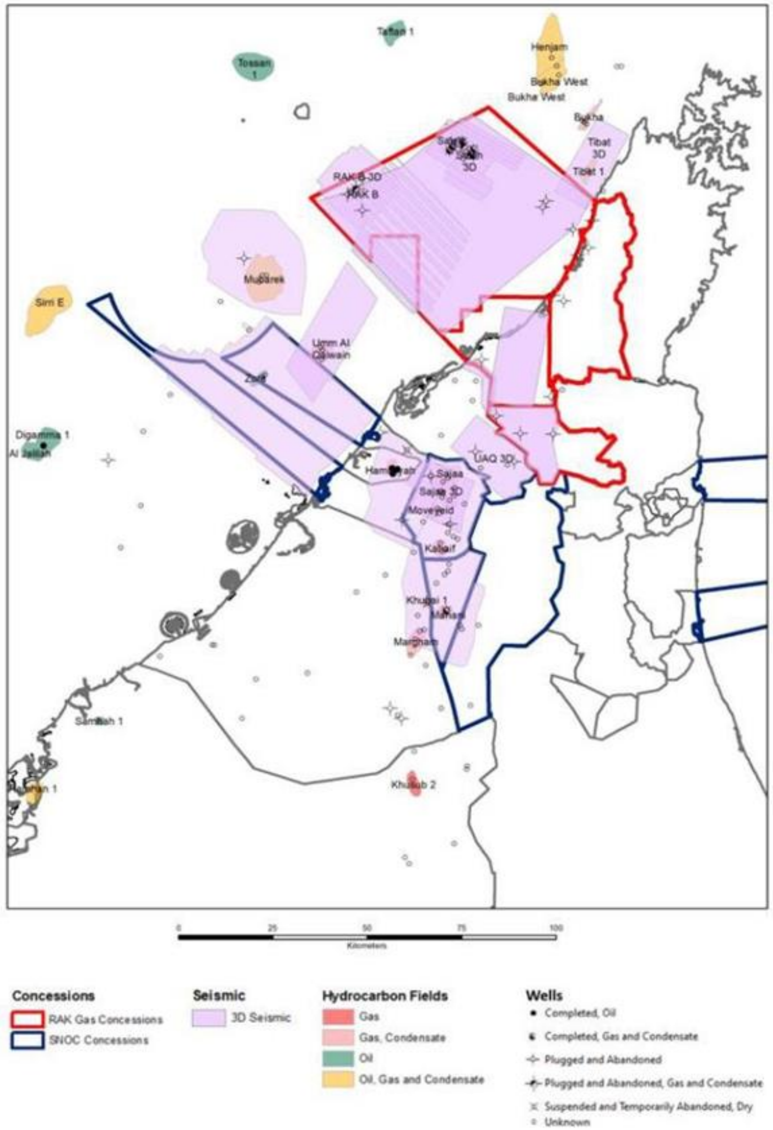


Figure 1. Map showing all 3D seismic datasets in the Northern Emirates

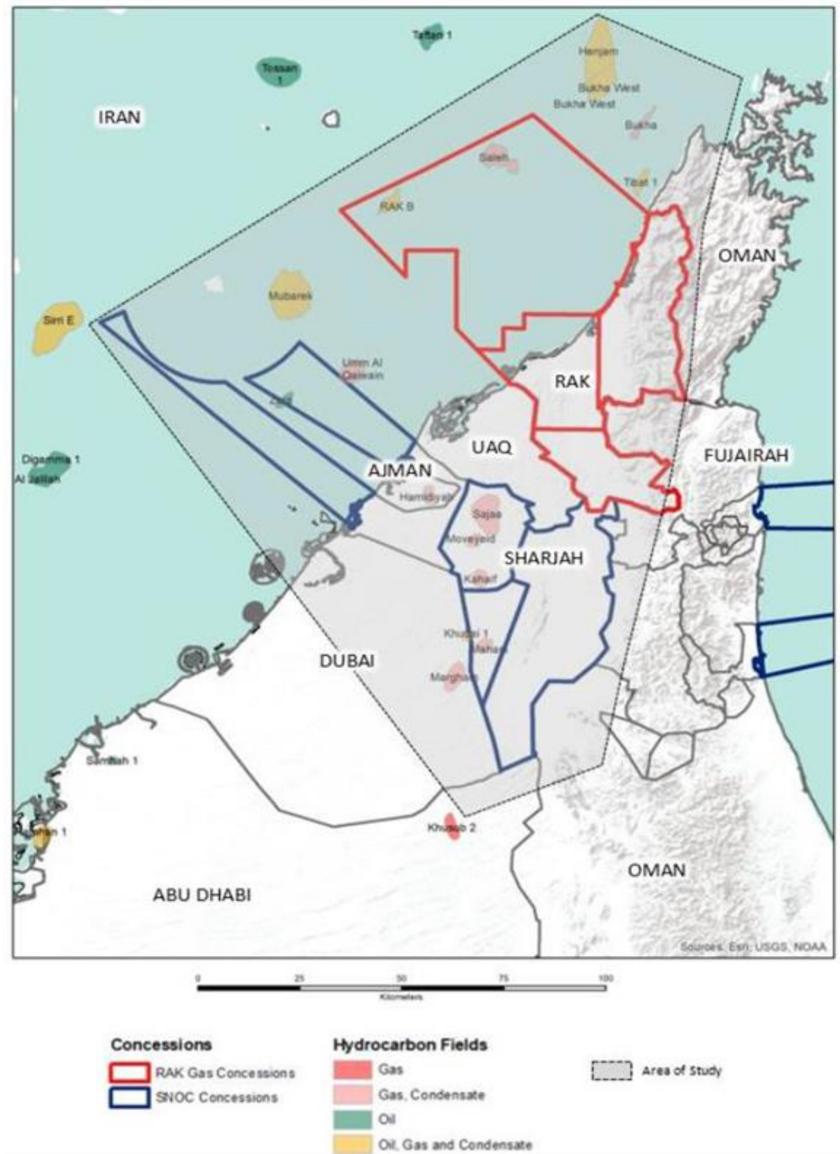


Figure 2. Area of Study

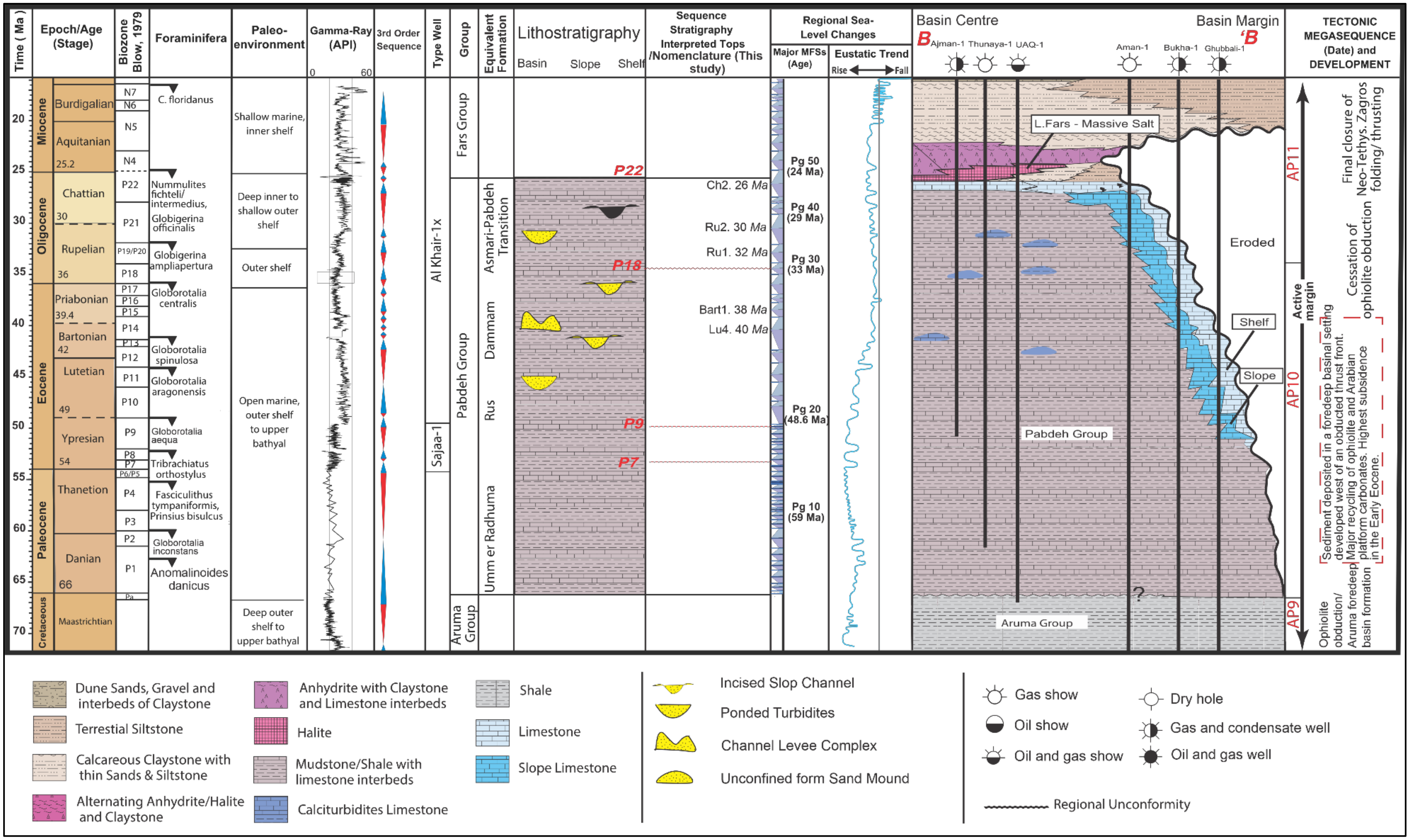

Figure 3. A Detailed Stratigraphy of the Pabdeh Group, UAE (compiled from Haq and Al-Qahtani 2005, Sharland *et al* 2004, Blow, 1969)

The structural setting of the Foreland Basin is summarised in Figure 4. Movement on the thrust front was associated with imbrication and duplex stacking of the Cretaceous Aruma Group, ophiolite, and sub-ophiolite units which terminated in the late Cretaceous, Campanian (Clowser *et al* 1983). Bulldozing at the thrust front had incorporated older foredeep strata within the thrust belt with the development of olistostromes above basal decollement faults. Unconformably overlying the wedge and onlapping on to it was a Latest Cretaceous, Maastrichtian aged interval deposited in shallow marine conditions ,Simsima Formation (Noweir 1998). There was then a hiatus before deposition of the Pabdeh took place in the early to mid-Palaeocene.

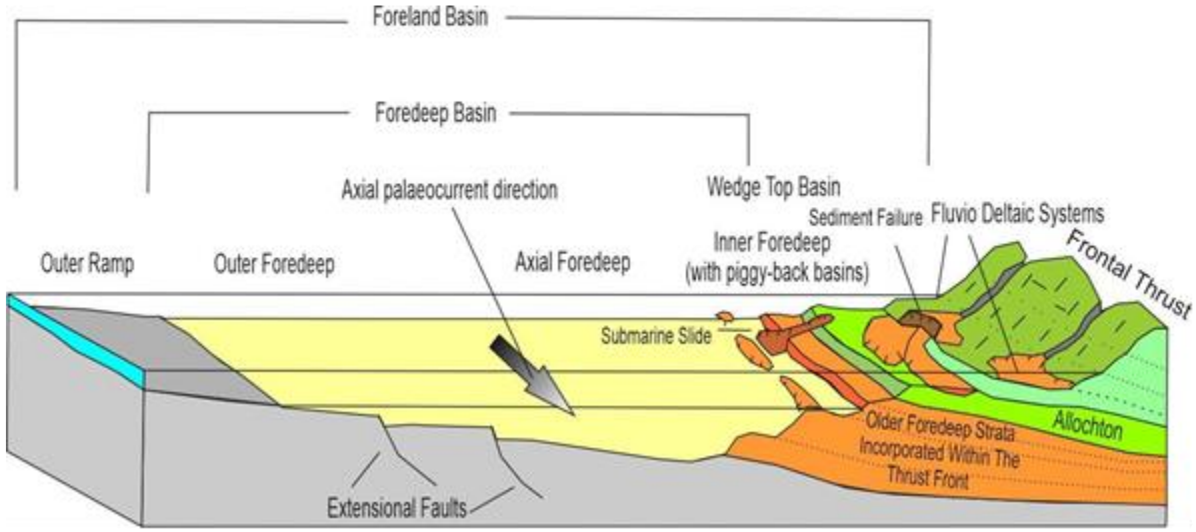


Figure 4- Structural Zones of the Foreland Basin (after Mutti *et al* 2002)

Uplift of the orogenic wedge led to down cutting and erosion and to the deposition of fringing fluvio- deltaic systems along the thrust front, further out these were deposited as mixed carbonate and clastic systems with deep marine fans being deposited along the basin floor, likely in an axial manner parallel to the thrust front.

Westwards, into the foreland was where the main axis and depo-centre of the Pabdeh Foredeep was located. The Inner foredeep basin extends from offshore Ras al Khaimah, though onshore Umm al Quwain, into onshore Sharjah, Ajman, and south into Dubai. A further compressional event in the Late Eocene to mid Miocene led to ductile folding of the Pabdeh strata and to the formation of piggy back basins. Syn-tectonic activity governed sedimentary channel systems that ran across the inner foredeep pooling up mainly reworked and eroded limestones and minor sandstones as ponded turbidites, here they were held up by developing syn- tectonic sub-vertical thrusts and backthrusts. As this sediment built up there was eventually spill over topographic highs or cut through especially if flows were high energy or high density.

During the Palaeocene to Lower Eocene, although there was little tectonic activity and subsidence was at a maximum due to crustal loading along the thrust front, the depo-centres developed parallel to this thrust front and this is when the thickest Pabdeh units was deposited. Evidence for a eustatic over print can be seen and periods of lowstand led to down cutting along the shelf to slope break with the development of channelized and also canyonised systems that then fed into the main foredeep basin as turbidite lobes. During these lowstands the turbidites were deposited basinwards as fans that are downlapped above by prograding sequences of the overlying highstand. In the outer foredeep compression gives way to an extensional regime and some extensional faults can be recognized as the foredeep gives way to the outer ramp where equivalent facies were deposited.

The Eocene section is deeper water deposited in mainly a bathyal to outer bathyal palaeoenvironment although shallower water deposits are seen on the shelf to the south and east. Intermittent calciturbidites are related to short term eustatic sea level falls and to incision events transporting through high energy flows of shelfal material into the deeper basin. While the Oliogocene Pabdeh foredeep represents mainly basinal infill which is also over printed by a general eustatic sea level drop through this period. Consequently, there is generally a coarsening up of the sediments during this time and a decrease in organic richness of deposited marls.

**Palaeogene. The Pabdeh Foredeep Basin**

Following ophiolite obduction, passive margin sedimentation was re-established in the Maastrichtian with the deposition of widespread shallow-marine gastropod and rudist-rich limestones of the Simsima Formation (Searle *et al*., 2014). A period of erosion at the start of the Cenozoic is attributed to isostatic rebound (Noweir *et al*., 1998) before the onset of the development of a second foreland basin, the Pabdeh Basin, along the western side of the northern Oman Mountains and Musandam Peninsula and northwards into Iran. Very stable conditions are shown by the fossiliferous shallow- water carbonates deposited throughout this period lasting ca. 40Myr along the entire Oman Mountains (Searle *et al*., 2014). Ductile folding of the Pabdeh Group implies continuing crustal shortening after ophiolite obduction during sedimentation of the Late Oligocene – Early Miocene Asmari Group. Well sections in the UAE record a second major flexural foreland basin, the Palaeocene–Eocene Pabdeh Basin that developed ahead of the thrust front. Balanced and restored cross- sections show that a minimum of 15 km of westward translation occurred along the Hagab Thrust (Searle, 1988; Dunne *et al*., 1990). Offshore Ras al Khaimah and the Omani Musandam, seismic data image several major east-dipping, west-verging thrust faults that cut through Upper Cretaceous Fiqa Formation and Palaeogene Pabdeh Formation rocks in the footwall (Figure 5). Thrust tip lines terminate beneath the Upper Miocene Lower Fars Formation and are abruptly truncated at the base of the Mishan Formation (Upper Miocene) marls (Ricateau and Riche, 1980). These structural relationships confirm that the culmination of the Musandam shelf carbonates and movement along the Hagab Thrust was a mid-Cenozoic event spanning Oligocene–Early Miocene. Several exploration wells drilled offshore Omani Musandam reached the top shelf carbonates (Henjam, Bukha, Ghubbali, Salama wells).

Seismic and well data show that the Henjam and Bukha wells were on the stable folded foreland beneath the Hagab Thrust, whereas the top-shelf carbonates in the Ghubbali and Salama wells are much shallower, because they drilled into the toe of the Hagab Thrust. The Hagab Thrust therefore, must lie between the sites of the Bukha and Ghubbali wells, offshore Musandam and extends southwards down into the UAE (Figure 6).

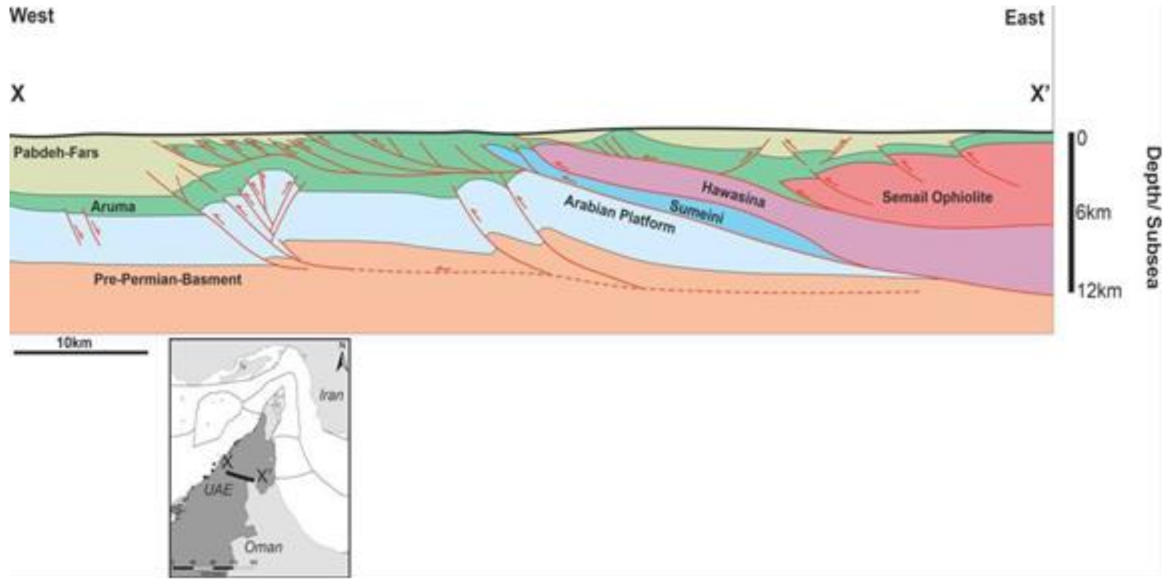


Figure 5. Northern Emirates Regional Structural Setting (after Dunne *et al* 1990)

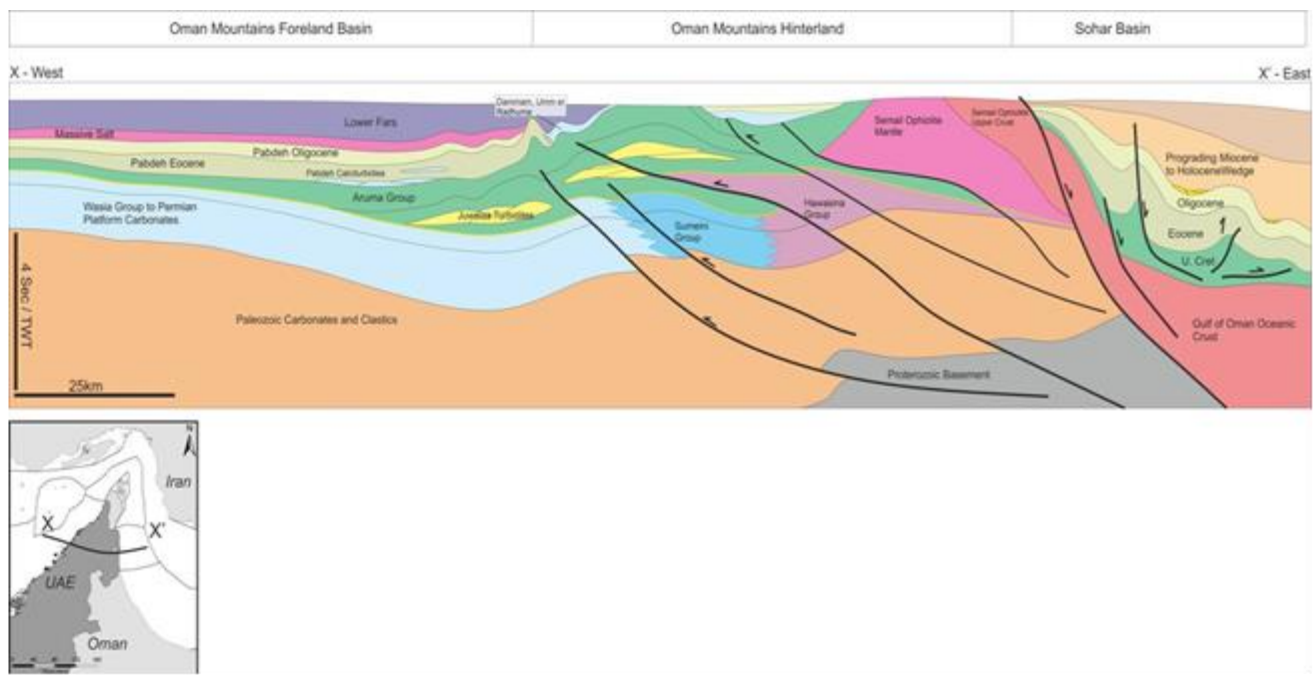


Figure 6. Structural Cross Section Northern Emirates

**Chronostratigraphy**

There are a 46 historical wells in the area of interest that have accompanying biostratigraphic reports. Due to the high carbonate content of the geological section, age dating mainly relies on microforaminifera supplemented by calcareous nannofossils. Fossil assemblages are normally diverse as well as abundant and preservation is often good especially with regards to recoveries from the Pabdeh section. This has allowed a high resolution biostratigraphic breakdown to be achieved.

Historical reports often use the biozonation compiled by Blow (1969). These for the Oligocene to Palaeocene aged Pabdeh are equivalent to biozones from P22 to P2. The equivalent Calcareous Nannofossil biozones range from NP25 to NP4. Modern biostratigraphy is less available in the dataset, although some recent results are available from a stratigraphic hub well (Aman-1) in the near offshore area of Ras Al Khaimah. The well is key in that it was drilled on the axis of the paleo foredeep basin and therefore has one of the thickest penetrations of the Pabdeh Group.

New biostratigraphy from the Al Khair -1 and Oryx-1 well have identified a condensed basal Palaeocene section that suggests this is interpreted to be part of the 66.5 Ma SB is present. This indicates the base of the Pabdeh Group formations.

Lower Pabdeh Sequences, Palaeocene to basal Lower Eocene, 66.5 Ma SB, 55 Ma SB and 54 Ma SB

- Group – Pabdeh
- Umm er Radhuma is the shallow marine subsurface equivalent
- Age - Paleocene and Basal Lower Eocene, Danian, Thanetian, base Ypresian, Planktonic Zones P1-P7. In the study area, microfossils have been recovered from the Lower Pabdeh. The lithological components indicate a direct derivation from the Oman Mountain front areas in the east and northeast areas of the Pabdeh Foredeep Basin. It is around 390m thick within the subsurface reference section (Brooz -1X well).

*Name*. The Umm er Radhuma formation (equivalent) was named by Henry & Brown (1935) in an unpublished Aramco report, for the Umm er Radhuma the type section is from a well that was drilled in Saudi Arabia (Hewaidy, 1994).

*Subsurface reference section or type well*. Lower Palaeocene and Upper Palaeocene: Brooz-1 well, drilled onshore Ras Al Khaimah, United Arab Emirates. Basal Lower Eocene: Al Khair-1X well, drilled onshore Umm al Quwain, United Arab Emirates.

*Lithology***.** Lower Palaeocene: Limestones grading to and interbedded with mudstones. The limestones are highly argillaceous finally becoming very calcareous mudstones. The limestones are occasionally sandy and fossiliferous with minor glauconite. Upper Palaeocene. Conglomeratic detrital horizons, composed of chert fragments and quartz grains Interbedded with mudstones and limestones. The mudstones are light to olive grey, sandy, pyritic and calcareous. Basal Lower Eocene: This interval consists of very light grey to light grey, lower part becoming pinkish grey to light brownish grey, calcareous mudstones which locally grade into limestones. These are found with minor, light brownish grey, hard, microcrystalline limestones, crystalline calcite, and medium dark grey, waxy shales.

*Distribution.* In the study area of Northern Emirates Pabdeh Basin, the subsurface equivalent of the Umm er Radhuma Formation have been penetrated in almost all the drilled wells.

*Contact relationships.* This formation is the lowermost unit of the Pabdeh group and overlies the Upper Cretaceous Aruma group with disconformable contact. The base of the Pabdeh Group sequence downlaps the erosional surface of the Aruma Group to the east. It is bedding parallel in general to the west, with clear indication of downlap onto the underlying Aruma Group while gradually forming a condensed interval further westward.

*Biostratigraphy.* Lower Palaeocene of Zone P2 ,Upper Palaeocene of Zones P3-P6 and Late Palaeocene to Early Eocene of Zone P7 intervals are assigned age intervals to this formation based on the extracted downhole occurrences of planktonic foraminifera (*Globoratalia inconstans* P2 Zone, *Globoratalia velascoensis* P6-P3 Zone and *Globorotalia velascoensis* P7 Zone ) (Clowser, *et al.*, 1983).

*Palaeoenvironment.* At the top of this unit there are thick turbiditic deposits. The presence of planktonic foraminifera to the base of the interval shows that all of the deposits are of open marine origin. The presence of rare but indigenous benthonic foraminifera indicate deposition within a deeper outer shelf to upper bathyal palaeoenvironment.

*Sequence Stratigraphy.* Relates to the Sequence Boundary recognised at the base of Palaeocene, Danian (66.5 Ma SB) and two recognised In the Upper Palaeocene, Thanetian 55 Ma SB and 54 Ma SB.

*Hydrocarbon Prospectivity.* Palaeocene dark shales are of potential source rock quality and are mature in the axis of the foredeep basin with TOC% between 1-3. With a relatively low average geothermal gradient of 25°C/KM for the basin and average depositional rates of over 200 metres / 10Ma there is also potential for the generation of biogenic gas. While potential calciturbidite reservoir is present in the Palaeocene section depth of burial means that porosities and permeabilities are very low.

**Formation: Lower Eocene Pabdeh 50 Ma SB**

- Group – Pabdeh
- Rus Formation subsurface equivalent
- Age - Lower Eocene, Ypresian, Planktonic Zones P8-P9

The stratigraphic equivalent to the Lower Eocene Pabdeh is the Lower Eocene Rus Formation that generally overlies the Paleocene Umm er Radhuma Formation and underlies the Middle to Upper Dammam Formation.

It is present in the subsurface with different depths and thicknesses throughout the study area. This section has been penetrated in the subsurface of the study area with several wells and it is 1183 m thick at the subsurface reference section.

The relationship between the stratigraphical units seen in the Northern UAE versus those identified in the Western UAE are illustrated by Figure 7.

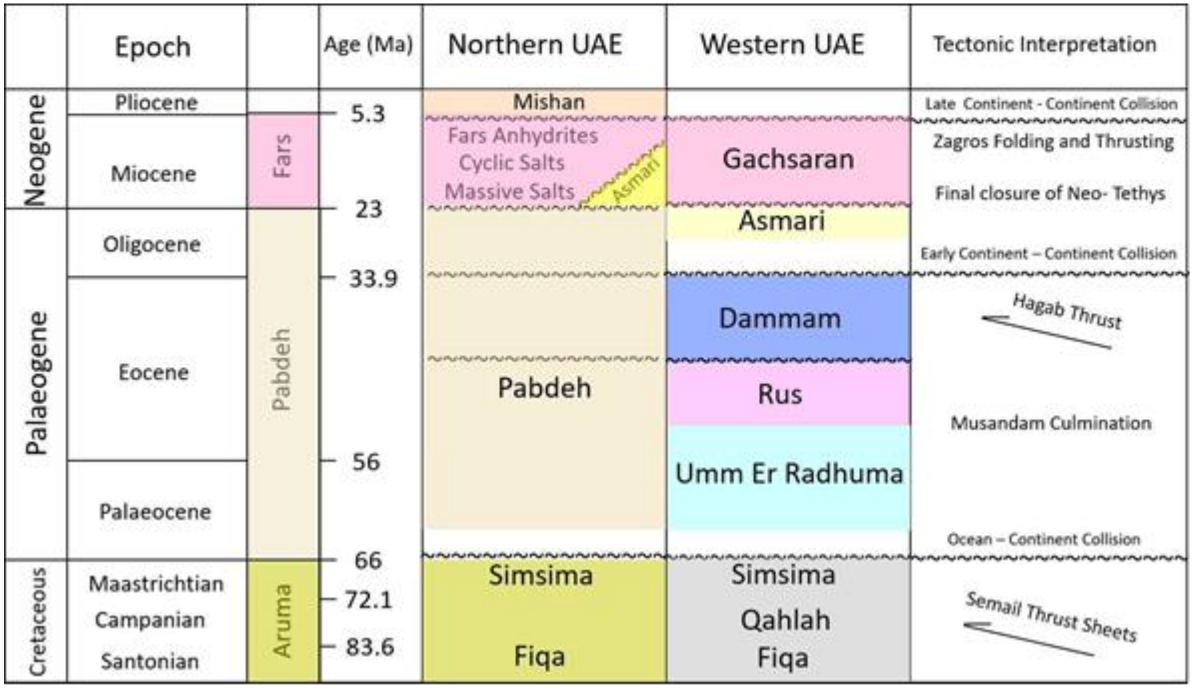


Figure 7 - Tertiary and Late Cretaceous Stratigraphy, U.A.E.

*Name.* The Rus Formation was first named from the rocks of the Umm er Ru'us (26°1904" N, 50°07'51" E.), which outcrop in a small hill in Saudi Arabia (the Dammam Dome). Bramkamp (1946, cited in Powers *et al.* 1966) first applied the name Rus Formation as a direct replacement for the term "Chalky Zone" which had been informally used for Lower Eocene beds above the Umm er Radhuma and below the Dammam Formation.

*Subsurface reference section or type well.* Al Khair-1X well, drilled onshore Umm al Qaiwain, United Arab Emirates.

*Lithology.* Various mudstones, generally moderately calcareous to calcareous, dominate this interval. The upper part is light to medium grey, firm to hard, moderately silty with occasional fine sand and finely pyritic. The mudstones are very light to medium grey becoming locally light brownish grey, generally as found at the top of the interval, but rarely sandy, and grading locally to argillaceous limestones. The lower part is mainly white to very light grey, slightly argillaceous limestones become more common, with minor, medium dark grey, waxy shales occurring at the base of this interval.

*Distribution.* The Lower Eocene Pabdeh is seen across the Pabdeh foredeep basin in the Northern Emirates and can be up to 1000 metres thick. Many wells have penetrated the Rus Formation equivalent in the Arabian Peninsula. It also outcrops in Saudi Arabia, Bahrain, Oman and the eastern margin of the Northern Emirates Pabdeh Basin. There are also some minor outcrops of Pabdeh of Eocene to Palaeocene age in Ras Al Khaimah (Mills *et al*. 2023)

*Contact relationships.* Upper and lower boundaries are conformable as well as transitional laterally into the Dammam and Umm er Radhuma sediments.

*Biostratigraphy.* This lower Pabdeh section was dated as Lower Eocene (Planktonic Zones P8-P9) according to samples collected and investigated in the Biostratigraphy and Palaeoenvironments report of Al Khair-1X well, drilled onshore Umm al Qaiwain, United Arab Emirates. (Clowser, 1986). The occurrence of *Globorotalia aequa* indicates that Lower Eocene sediments have been encountered further evidence is provided by the presence of *Globigerina appressocamerata* and *G. soldadoensis.*

*Palaeoenvironment.* Rich assemblages of planktonic foraminifera occur throughout this interval. Deposition took place in an open marine, deep outer shelf to upper bathyal palaeoenvironment.

*Sequence Stratigraphy.* Relates to the sequence boundary recognised at the base of the lower Eocene, Ypresian (50 Ma SB).

*Hydrocarbon Prospectivity*. Lower Eocene argillaceous limestones are of potential source rock potential with TOC of 1-2%. While thin sands occur in this interval they have as yet unproven reservoir potential. Fractured limestones provide a potential reservoir in this interval.

**Formation: Middle Eocene Pabdeh, 42.5 Ma SB**

- Group – Pabdeh
- Dammam Formation subsurface equivalent
- Age - Middle Eocene, Lutetian to Bartonian, Planktonic Zones P10-P14

*Name.* The name Dammam Formation was introduced by Bramkamp (1941) in an unpublished Aramco report from a type section located along the Dhahran Al’Alah road in eastern Saudi Arabia, at latitude 26o 19'26"N, and longitude 50o 4'5"E, beginning at the point where this road intersects the margin of the Dammam Dome (Powers, Ramirez and Redmond, 1966) however, in Oman it is referred to as a part the Seeb Limestone Formation and in the Northern Emirates the Pabdeh Formation (Jones and Racey, 1994).

*Surface reference section or type well.* Al Khair-1X well, drilled onshore Ras Al Khaimah, United Arab Emirates. Also this is the oil producing zone in the Ajman-1 well.

*Lithology*. Middle Eocene Pabdeh consists of locally pyritic, moderately silty, calcareous mudstones, as described from the overlying section. The mudstones of the lower part are very light grey to light grey firm, moderately silty, calcareous and contain rare pyrite they are locally slightly glauconitic or carbonaceous. The mudstones grade in places to brownish grey and pinkish grey, sandy and locally argillaceous dolomitic limestones and dolomites. Conglomerates are present and these grades locally to dolomitic sandstones consisting of very fine to coarse grained lithic sand with often a dolomitic cement. Calciturbidites occur in this interval they are mainly fine to coarse-grained sandstones, poorly to well sorted, moderately rounded to sub- rounded, composed of cherts, igneous rock fragments and limestone grains/clasts with subordinate quartz grains. Limestone clasts can contain ooids, pellets, shell fragments and large benthic foraminiferas (*alveolinas* and nummulites). Intercalations of claystones and limestones/marls are subordinate.

*Distribution.* The Dammam Formation is widely exposed throughout large areas of southern Iraq, Kuwait, Saudi Arabia, Qatar, UAE and Oman. In the Northern Emirates, the Dammam Formation subsurface equivalent is the Middle Eocene Pabdeh Formation. (Jones and Racey 1994).

*Contact relationships.* Nature of Upper Contact: The upper contact of the Middle Eocene Pabdeh section is often erosional this leads to an overlying truncated Upper Eocene Pabdeh. The erosional contact is related to compressional tectonics and the onset of folding of the Pabdeh section.

*Biostratigraphy*. The occurrence of *Globorotalia spinulosa* indicates that Middle Eocene sediments are present indicating a P14 Biozone. The presence of the P13 Zone is indicated by *Globigerapsis kugleri* while Zone P12 is indicated by *Globorotalia matthewsae*. The presence of *Globorotalia aragonensis* indicates Zone P11 and *Globorotalia lensiformis* Zone P10.

*Palaeoenvironment*: Rich and diverse assemblages of planktonic foraminifera were recorded throughout this interval indicative of deposition under open marine conditions in a deep outer shelf to upper bathyal environment. Intermittent incursions of turbiditic sediments from a shallower shelf represent low stand down cutting events and channelization and the deposition of related fans.

*Sequence Stratigraphy: 42.5 Ma SB*. the top of this unit is a major sequence boundary and downcutting event across the Pabdeh Fore Deep basin and is based on the biostratigraphy and zonal identification.

*Hydrocarbon Prospectivity***.** Both proven hydrocarbon reservoirs and source rocks occur in this interval. The Ajman Hamadiyah Oilfield has produced oil from the P14 Zone from two wells (Ajman-1 and Ajman-2). Hydrocarbon source rocks are also identified in the Middle Eocene. Dark shales with a TOC of 1-4% are recorded in the Ajman-1 well and in the Brooz-1.

**Formation: Upper Eocene Pabdeh Sequence 38 Ma SB and 36 Ma SB (Bartonian)**

- Group – Pabdeh
- Dammam Formation subsurface equivalent
- Age - Upper Eocene, Priabonian, Planktonic Zones P17-P15

*Name.* The name Dammam Formation was introduced by Bramkamp (1941).

*Surface reference section or type well.* The type well is Aman-1 in offshore Block A.

*Lithology:* A series of moderately to highly calcareous mudstones, occur throughout this interval, becoming moderately silty and locally highly pyritic below. Minor amounts of moderately dolomitic mudstones together with traces of pale yellowish brown, hard, finely sucrosic dolomites were recorded at the lower part. A detailed correlation for the Pabdeh Formation is shown in Figure 5.

*Distribution.* The Dammam Formation is widely exposed throughout large areas of southern Iraq, Kuwait, Saudi Arabia, Qatar, UAE and Oman. In the Northern Emirates, the Dammam Formation subsurface equivalent is the Upper Eocene Pabdeh Formation (Jones and Racey 1994).

*Contact relationships*. The upper most Eocene is represented by an unconformity related to compressional tectonic folding in the Pabdeh basin. The nature of the Eocene section is seen by the stratigraphical correlation. Details of the Pabdeh Stratigraphy including sequence boundaries are also illustrated by Figure 8.

*Biostratigraphy*. The top of the Eocene section is based on the presence of *Globorotalia centralis* which is indicative of the Foram Biozone P17. The Zone P16 is based on the presence of *Cribrohantkenina inflata* while the presence of *Porticulasphaera semiinvoluta* represents the Zone P15.

*Palaeoenvironment.* Rich and diverse planktonic foraminiferal assemblages are recorded throughout this interval. Deposition took place in an open marine, outer shelf to upper bathyal environment.

*Sequence stratigraphy*. The top of this unit is recognized by the 36 Ma sequence boundary and an unconformity. The Upper Eocene is often truncated in the Pabdeh Basin at this sequence boundary.

*Hydrocarbon Prospectivity*. Some potential pay has been identified in this level represented by fine grained sandstones, these intervals are often quite thin.

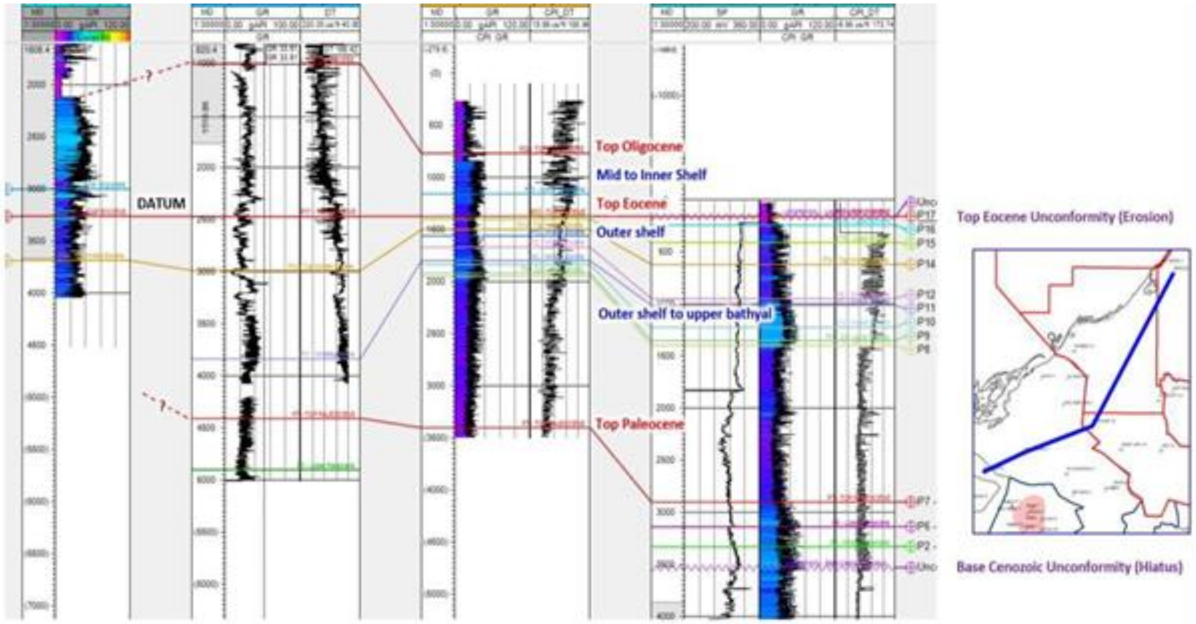


Figure 8. Stratigraphic Correlation 4 wells Ajman to Ras Al Khaimah

**Formation: Oligocene Pabdeh, Rupelian and Chattian, 33 Ma SB and 26.5 Ma SB**

- Group – Pabdeh
- Oligocene Pabdeh is equivalent to the Asmari
- Age Oligocene Rupelian and Chattian, Foraminifera Zones: P22 to P19

*Name.* The Oligocene Pabdeh is equivalent in part to the Asmari Formation. In the eastern Pabdeh Basin the Oligocene Pabdeh is often transitional to the Asmari Formation that overlies it, towards the west it is overlain by Fars Group evaporites.

*Surface reference section or type well.* The type well for the Oligocene Pabdeh is in the onshore well Al Khair- 1X.

*Lithology.* Lower Oligocene: This interval is composed of less calcareous light to medium grey mudstones.

Upper Oligocene: consists of locally sandy mudstones and occasional lithic sands. The mudstones are olive grey and brownish olive grey, locally subfissile, slightly to moderately calcareous and locally pyritic.

Asmari – Pabdeh Transition: this interval consists of slightly to highly silty, variably coloured mudstones, medium dark grey to dark grey, olive grey, greenish olive grey, brownish grey and brownish olive. They are firm to hard, occasionally calcareous, with thin calcite veins, finely pyritic, with scattered bivalve debris and common fine to coarse, often sub-rounded quartz and lithic grains. Where very sandy, these mudstones grade into fine grained argillaceous sandstones. There are local concentrations of fine to occasionally coarse, unconsolidated sands, consisting of lithic, mineral and reworked bioclastic fragments, angular to rounded, which become less common and coarser downhole. These may represent highly argillaceous sandstones from which the soft matrix has been washed out.

*Distribution.* The Oligocene Pabdeh Formation is seen across the Pabdeh Foredeep Basin.

*Contact relationships.* An unconformity and sequence boundary (36 Ma SB) marks the base of the Oligocene Pabdeh while its top is marked by the 24.5 Ma SB.

The upper contact of the Oligocene Pabdeh marks the end of Pabdeh deposition in the foredeep basin and it is unconformable. Compressional folding and thrust faulting in the latest Oligocene to middle Miocene caused uplift and erosion and the development of an angular unconformity. The unconformity can cause deep truncation of older strata. This event is related to the collision between the Arabian and the Eurasian plates and is culminated by continent-continent collision. The compressional event explains the representative facies seen in the Miocene. Over the generated structural highs and along their flanks a mixed mainly clastic unit consisting of interbedded mudstones, siltstones, limestones, cherts and coarse sands were deposited as the Asmari Formation.

In the confined basin evaporitic facies of the Fars Formation was deposited away from developing compressional highs. This means that in the present-day offshore area Fars Anhydrites directly overlie the Oligocene Pabdeh while over the compressional highs then the Asmari facies directly overlies Oligocene Pabdeh (Orang *et al.* 2018; Ricateau and Richie, 1980; Searle *et al.*, 2014). This facies association for the base Fars (the Fars Massive Salts) is illustrated by the gross depositional environment (GDE) map for this interval.

*Biostratigraphy.* The presence of the planktonic foraminifera *Globigerina praebulloides* and *Globigerina officinalis* are indicative of a Late Oligocene age and the zones P22 and P21. The presence lower in the section of *Globorotalia increbescens* is indicative of Zone P20 and P19.

*Palaeoenvironment.* The planktonic assemblages vary from poor to rich through this interval and are of limited diversity suggesting deposition in a mid-shelf environment for the Upper Oligocene. The lower Oligocene was deposited in a slightly deeper outer shelf palaeo-environment. The Oligocene marks an infilling of the Pabdeh Foredeep Basin prior to deposition of evaporites of the Fars Group. It also relates to a relative eustatic sea level fall.

*Sequence Stratigraphy*. Sequence boundaries mark the base (36 Ma SB) and the top of the Oligocene Pabdeh (24.5 Ma SB) a third sequence boundary is recognized at 26.5 Ma.

*Hydrocarbon Prospectivity*. There is some reasonable sand development within the Oligocene Pabdeh, these are often ophiolite derived and have an exotic mineralogy, gas shows were identified in the Oligocene Pabdeh of the Al Khair-1X well.

Dark grey to brown slightly calcareous claystones in the Lower Oligocene can have TOC's up to 1.5% and Hydrogen Indices up to 300 but often they are immature with vitrinite reflectance (%R0) <0.5. They can have some hydrocarbon source rock potential if buried deeper.

Sandstones described as lithic which are very fine to fine grained and occasionally glauconitic with rounded grains and of moderate sorting can be of reservoir quality. They are more common in the Upper Oligocene and were deposited as the Pabdeh foredeep basin infilled and shallowed. Migration routes from mature source rock can be along deep-rooted compressional faults. Gas was recovered from this unit in a test on the Oryx-1 well.

Palaeofacies distribution (Gross Depositional Environment)

Having defined the area of interest (AOI) for this study which covers the whole of the Pabdeh Foredeep Basin then a series of gross depositional environment (GDE) maps were generated for the Pabdeh Group. Seismic mapping of maximum flooding events (surfaces) across the basin calibrated to biostratigraphic data in wells and integrated with well log data that allowed the refinement of these events was used for the generation of four GDE maps. The maximum flooding surfaces and derived GDE maps represent four snapshots in time that outline the development of the Pabdeh foredeep basin.

The maps are based on well data but are supplemented by geological outcrop descriptions which are limited for the Pabdeh section. A structural restoration project undertaken by SNOC has allowed the original position of some of the allochthonous fault blocks to be determined and these are also shown on the maps. The maps also show the area along the thrust front where the Pabdeh sediments are either eroded or are not present the relationship between this and the extent of the Semail Ophiolite is also illustrated. The predicted coastline is also shown on these maps.

A detailed stratigraphy for the Pabdeh Group illustrating the position of Sequence Boundaries is shown in Figure 9.

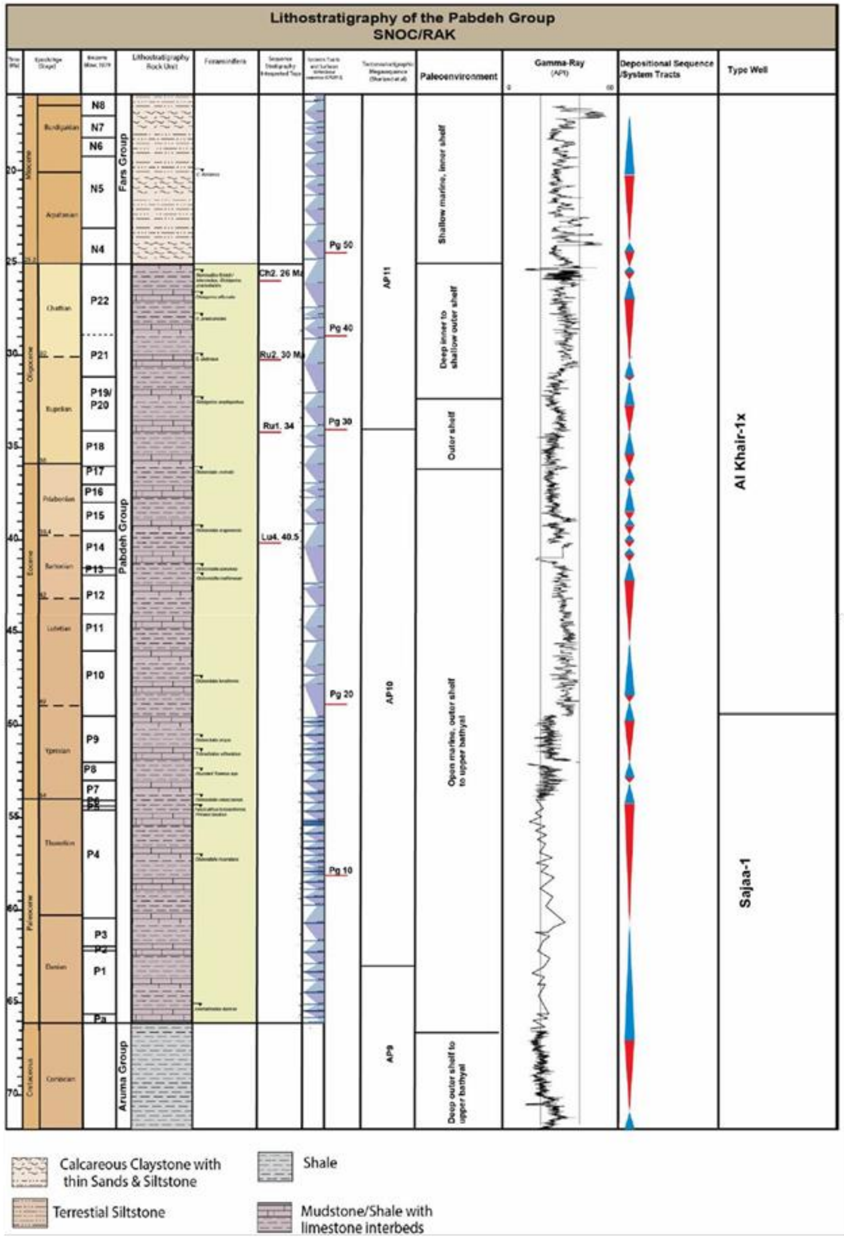


Figure 9. A Detailed Stratigraphy of the Pabdeh Group

Gross Depositional Environment (GDE) Lower Eocene to Palaeocene (Biozone P8-P2; SB 66.5 Ma to SB 50 Ma)

This GDE maps represents the Palaeocene to Lower Eocene interval rather than a MFS and its top is a sequence boundary. It is representative of the base of the Pabdeh sequence. Two palaeofacies are identified. The main basinal depositional axis is represented by calcareous mudstones and minor shales and limestone. Some coarser units contain exotic igneous clasts and minor cherts. Deposition was in an outer shelf to upper bathyal environment. The facies to the south and west of the basin axis are represented by Nummulitic wackestones, packstones and minor grainstones deposited in an inner shelf environment. The GDE map is illustrated in Figure 10.

Gross Depositional Environment (GDE), Middle Eocene, Lutetian, (SB 50 Ma to SB 42.5 Ma (Near Biozone P9 to P12)

This GDE map represents an interval within the Middle Eocene, Lutetian and its base is a Sequence Boundary (42.5Ma). It is representative of the lower part of the Pabdeh sequence. Two palaeofacies are identified. The main basinal depositional axis is represented by calcareous mudstones, shales and argillaceous limestones with thin interbeds of calcareous turbidites. Deposition was in an outer shelf to upper bathyal environment. The facies to the south and west of the basin axis is represented by bioclastic limestones with shale and marl that were deposited in an inner shelf environment. The GDE map is illustrated in Figure 11.

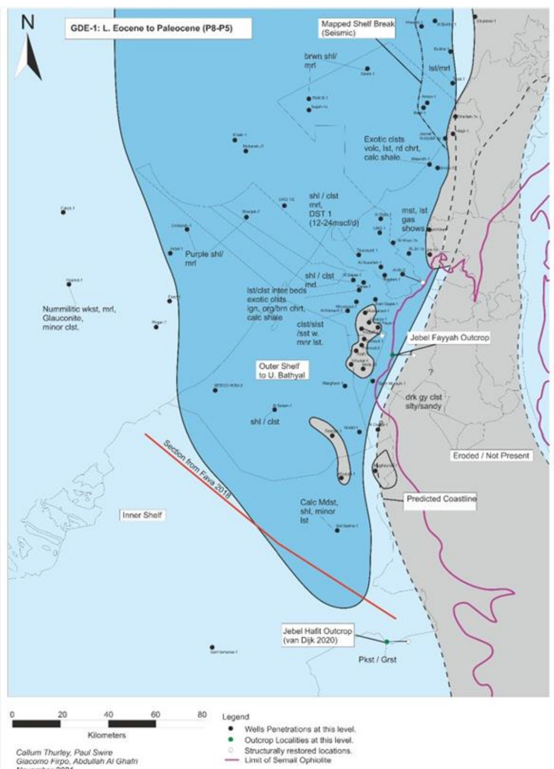

Figure 10 – GDE1; Lower Eocene to Palaeocene (Biozones P8-P5; SB 66.5 Ma to SB 50 Ma)

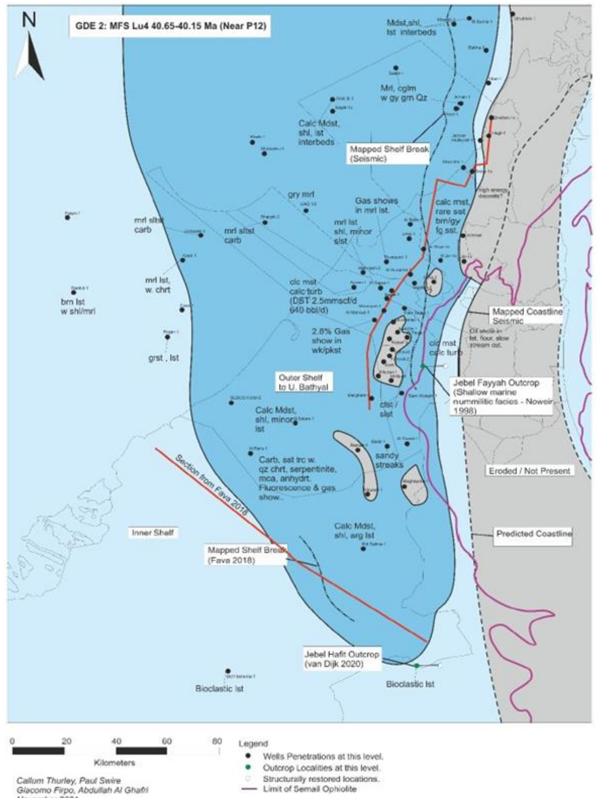


Figure 11 - GDE 2; Middle Eocene, Lutetian (SB 50 Ma to SB 42.5 Ma, near Biozone P9 to P12)

Gross Depositional Environment (GDE) Early Oligocene, Rupelian 1, (Near Biozone P18 – P20; SB 36 Ma - SB 33 Ma)

This GDE map represents an MFS within the lowest Oligocene, Rupelian and its base is a Sequence Boundary. It is representative of the middle part of the Pabdeh sequence. Two palaeofacies are identified. The main basinal depositional axis is represented by calcareous mudstones, shales and argillaceous limestones with thin interbeds of calcareous turbidites and thin conglomerates with exotic clasts of ophiolite. Deposition was in an outer shelf to upper bathyal environment. The facies to the south and west of the basin axis is represented by Nummultic limestones with silty shale and marl that were deposited in an inner shelf environment. The GDE map is illustrated in Figure 12.

Gross Depositional Environment Upper Oligocene Chattian 1, SB 26.5 Ma to SB 24.5 Ma (Near Biozone P21 - P22)

This GDE map represents an MFS within the Upper Oligocene, Chattian and its base is a Sequence Boundary. It is representative of the upper part of the Pabdeh sequence. Two palaeofacies are identified. The main basinal depositional axis is represented by calcareous mudstones, pelletal wackestones and minor dolomites. Deposition was in an outer shelf to upper bathyal environment. The facies to the south and west of the basin axis are represented by bioclastic limestones and grey dolomites deposited in an inner shelf environment. The GDE map is illustrated in Figure 13.

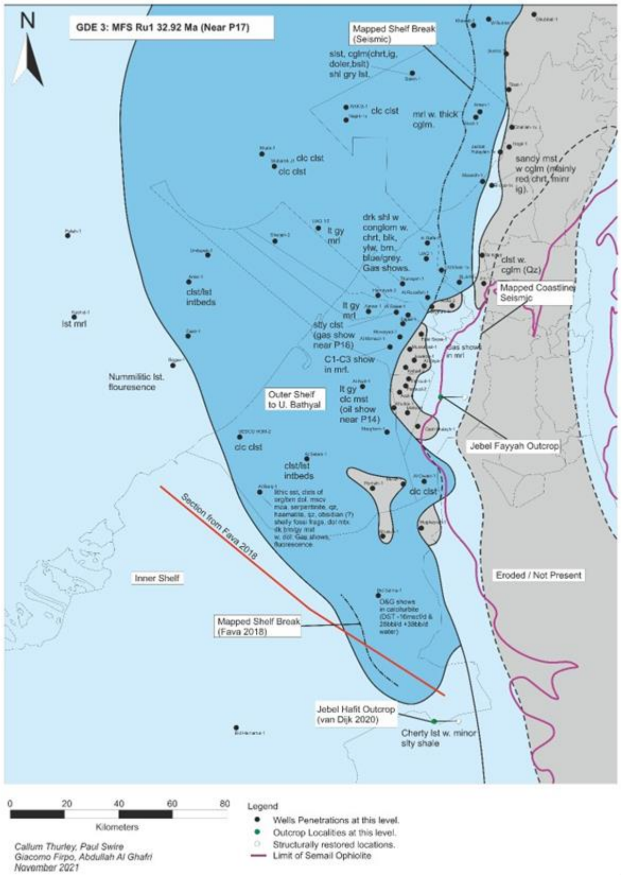


Figure 12 – Early Oligocene, Rupelian 1 (SB 36 Ma to SB 33 Ma, Biozones P18 to P20)

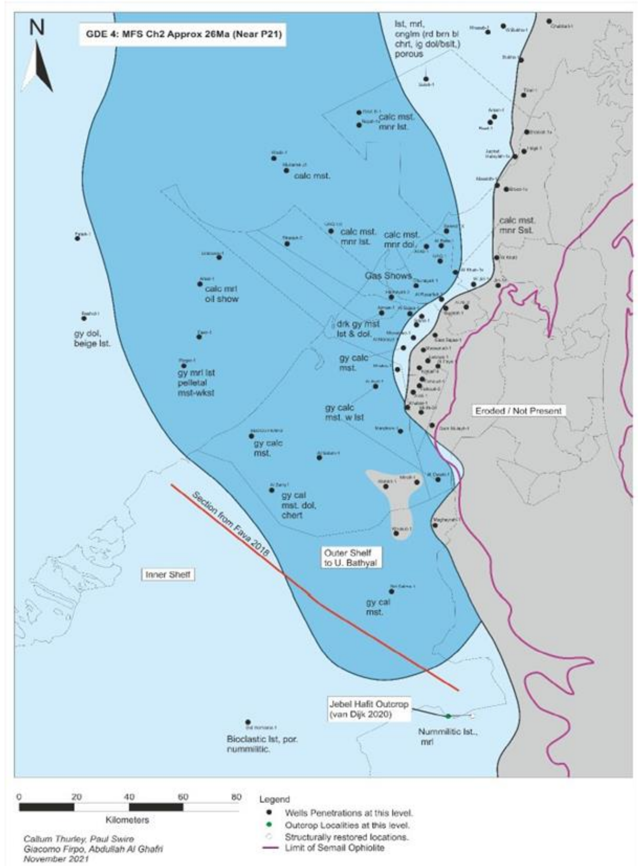

Figure 13 – GDE; Upper Oligocene, Chattian 1, SB 26.5 Ma to SB 24.5 Ma (Near Biozone P21-P22)

**Sequence Stratigraphy**

In this study, we used all the available data in the West Coast UAE foreland basin including 3D seismic data sets 2D seismic lines and the available well data (Figure 1). Seismic composite lines were selected to tie the key wells. These were then analysed to identify the major sequence boundaries. This was done by identifying the discordant relationship of the reflectors, these include down lapping and onlapping events as well as obvious unconformities (Figure 14). The unconformities or their correlative conformities have been then tied to the well data using the well velocity data. Once identified on the well logs the potential sequence intervals were tied to the biostratigraphy to give an age range of the sediments deposited within the "sequence". Analysis of the gamma ray logs was then carried out to identify retrograde and prograding para sequence stacking patterns to identify potential systems tracts and condensed intervals (high gamma spikes). By definition (J C Van Wagoner *et al* 1988) each sequence has an unconformity at the base. So, each sequence has an unconformity at the base and the top (the unconformity of the over lying sequence), which defines the sequence. Within the sequence succession there was a high gamma event defined that is correlated to the condensed interval (a major down lap surface on the seismic in the basinal setting). This interval is also represented by a faunal abundance in the biostratigraphy. It is this event that has been recognised by other workers and correlated to the Maximum flooding Surface (MFS), which have in turn has been used to name the sequence (Sharland *et al* 2004). In this study all the seismic data is confined to the basin and slope settings as the near shore deposits have been eroded, therefore the MFS cannot be identified. In the basin the MFS equivalent is located within the condensed interval (CI).

In this study SNOC/RAK Gas have adopted the AAPG Memoir 26 “sequence”. Which is “a succession of sediments bounded by unconformities and their correlative conformities” (J C Van Wagoner *et al*, 1988).

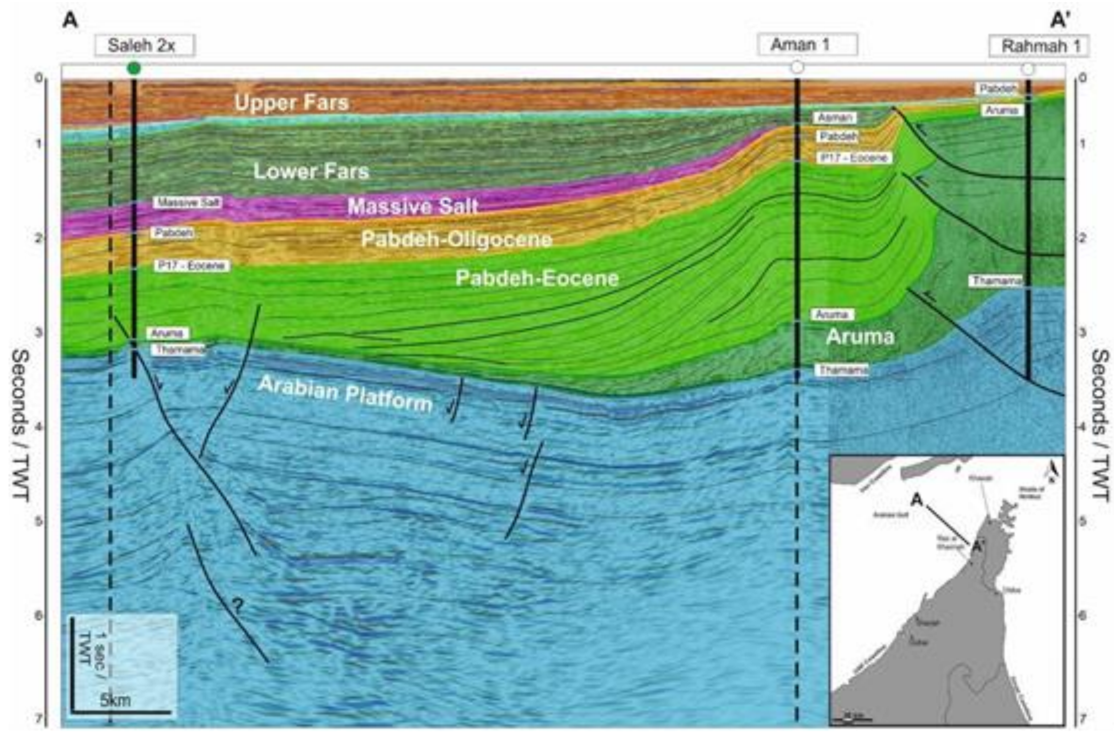


Figure 14. Seismic dip line Ras Al Khaimah illustrating down lap of the lower Pabdeh units

The Sequences identified during this study have been named according to the biostratigraphic age range shown below:

| | | |
|---|---|---|
| • Early Miocene, | Aquitanian. | Sequence Boundary 24.5 Ma |
| • Late Oligocene, | Chattian. | Sequence Boundary 26.5 Ma |
| • Early Oligocene, | Rupelian 2. | Sequence Boundary 33 Ma |
| • Early Oligocene, | Rupelian 1. | Sequence Boundary 36 Ma |
| • Upper Eocene, | Priabonian. | Sequence Boundary 38 Ma |
| • Middle Eocene, | Bartonian. | Sequence Boundary 42.5 Ma |
| • Lower Eocene, | Ypresian 2 | Sequence Boundary 50 Ma |
| • Lower Eocene, | Ypresian 1 | Sequence Boundary 54 Ma |
| • Late Paleocene, | Thanetian. | Sequence Boundary 55 Ma |
| • Early Paleocene, | Danian | Sequence Boundary 66.5 Ma |

Although deposition of the Pabdeh Group in the western foredeep basin was tectonically driven by subsidence in front of the advancing thrust front, there is apparently a eustatic sea level over print. The Eocene section is deeper water deposited in mainly a bathyal to outer bathyal palaeoenvironment although shallower water deposits are seen on the inner foredeep shelf.

Intermittent turbiditic sediments and calciturbidites can be related to short term eustatic sea level falls and to incision events transporting high energy channels shelfal material out into the deeper basin. While the Oligocene Pabdeh foredeep represents mainly basinal infill this is also over printed by a general eustatic sea level drop through this period. Consequently, there is generally a coarsening up of the sediments during this time and a decrease in organic richness of deposited marls.

Third order Sequences of the Pabdeh Formation

The fauna and lithological character indicate shallowing with time, where the environment progressively changed from deep basin to outer shelf to marginal marine. In the Sajaa-1 well (Figure 2) the Pabdeh group was divided into two main units on the basis of lithology and log character; an upper unit from 145 metres to 1310 metres of clay and claystone and a lower unit from 1310 metres to 2015 metres of interbedded limestone and clay. The top of the Pabdeh Group is picked on the basis of lithology and first appearance of the planktonic foraminifera *Globigerina praebulloides*. The lower contact with the underlying upper Cretaceous is sharp and unconformable. The base of the Pabdeh group sequence onlaps the erosional surface of the Aruma Group to the east, and the reflectors become more conformable away from the thrust front to the west. A hiatus in deposition is indicated from the biostratigraphy. The syn-tectonic deposition of the Pabdeh Group is marked by onlapping reflectors on top of the flanks of anticlines, while the reflectors appear as downlap on the base of the synclines (Figure 14). The top of the Pabdeh Group is in an angular unconformity with the Fars Group over the anticlines; elsewhere, the group appears disconformable with overlying sequences.

Sequence-stratigraphic concepts are used in this study to identify genetically related strata and their bounding unconformities, or their correlative conformities, in seismic, well-log, core samples and outcrop data.

Sequence boundaries are deemed the most significant surfaces, they are defined as unconformities or their correlative conformities. Sequence boundaries are formed due to a relative fall in sea level. Across the Pabdeh foredeep the best location for observing sequence development is over the near offshore RAK well Aman-1.

Structurally the well is located just west of the compressional edge of the near offshore area before it passes westwards into an area that was more affected by subsidence and passive fill. For the Pabdeh it was drilled in the palaeo-axis of the foredeep basin and therefore it preserves some of the greatest thicknesses of this group of sediments. During later Pabdeh deposition (in the Oligocene) the fore deep basin had mainly infilled and the slope – shelf break had prograded westwards so that during later lowstand slope incision and channel infill can also be recognized in the proximity of the Aman-1 well. Some recent biostratigraphic work on the Aman- 1 well has helped in sequence definition Figure 15.

Palaeocene, Eocene, and Oligocene Pabdeh is preserved in the Aman-1 well (Figure 1) and the sequence boundaries identified are also shown in the correlation on Figure 11. Although a number of maximum flooding surfaces have been identified and mapped across the inner, axial and outer foredeep basins it is a slope feeder channel system that has been age dated as Middle Eocene (Foram Zones P14 -P9; SB 1.38 Ma) that has been identified as a major event in the development of the basin. Channelization related to canyon downcutting during a low stand can be identified on seismic. This is across offshore Ras Al Khaimah and shows the shelf slope break with a series of dendritic and anastomosing slope feeder channels and areas of slope bypass on the Eocene shelf to slope break, down dip of this in the axial foredeep possible basin floor fans developed at this time (Swire *et al* 2022).

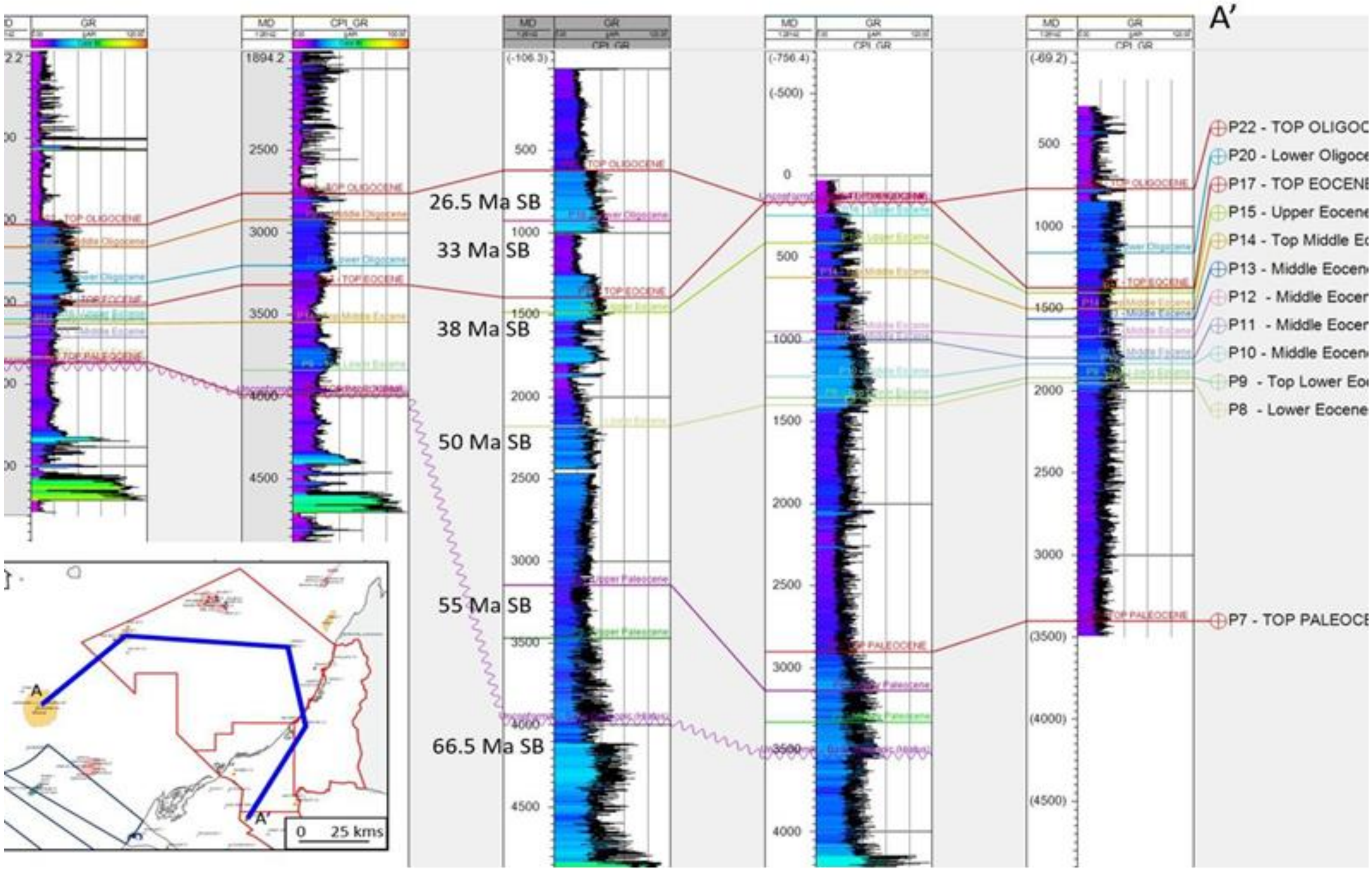

Figure 15. Sequence correlation (six wells) from offshore Sharjah to Onshore Ras Al Khaimah (A to A')

## Conclusions

The Pabdeh Group of sediments and carbonates is confirmed by modern and historical biostratigraphic data to be of Palaeocene, Danian to Upper Oligocene, Chattian age. The foredeep basin developed ahead of the obducted thrust front due to loading with its inception in the Late Cretaceous. The base of the Pabdeh is marked by a hiatus estimated to be 6 million years.

The Pabdeh basin can be split into an inner foredeep and an outer axial foredeep basin, the thickness of the Pabdeh in the axial foredeep can be in excess of 3.5 kms. The inner foredeep sediments lying on the wedge in front of the thrust can be shallow marine but in a transect these increases in water depths markedly away from the thrust front. While down warping of the basin was greatest in the Lower Eocene, deposition was marked by mainly argillaceous limestones. In the inner foredeep basin these then transition to calcareous marls in the outer foredeep. This was a relatively tectonically quiet period. This all changed in the Middle Eocene, an E-W tectonic event related to the Arabian Plate oblique compression against the Eurasian Plate led to tight broadly N-S trending folds to develop that detached towards the base of the Pabdeh and Aruma Groups. Ductile folding was associated with a major sequence boundary and a eustatic sea level fall that led to severe downcutting along the thrust front and a series of high energy events represented by thick sandstones, conglomerates and calci- turbidites. These formed as a series of deltas along the thrust front with related channels and canyons in the inner foredeep basin and also along the shelf to basin slope where slope fans were also deposited. These coarser sediments were also swept out into the main axis of the foredeep basin where basin floor fans were also deposited. With active compressional folding at this time syn-kinematic sedimentation in the inner foredeep and developing structures (compressional folding and thrusting) led to further downcutting events and for the deposition in deeper waters of ponded turbidites.

The top of the Middle Eocene is marked by an unconformity. Continuing but less severe structuration continued into the Late Eocene with a similar development of calcareous marls and this time interbedded thinner clastic units. These were deposited due to repeated high energy events related to further syn-kinematic deposition and another sequence boundary. The Late Eocene is not fully developed and its top again is marked by an unconformity.

Oligocene Pabdeh deposition took place during a relative period of structural quiescence and is represented by mainly calcareous marls which in the inner foredeep are interbedded with occasional thin sandstone units. The general pattern is of a shallowing upwards sequence as the foredeep basin was eventually filled. The top of the Pabdeh transitions into the Asmari facies in the inner foredeep and into the lower Fars elsewhere, this happens before a major tectonic event in the Middle Miocene. This event was related to final closure of the Tethys Ocean and led to a period of renewed compressional thrust faulting and severe truncation at a major unconformity at this time.

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