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A Regional Sequence Stratigraphic Approach to Identifying Stratigraphic Traps in the Mesozoic

Christopher Gravestock, Alex Bromhead, Mike Simmons (Halliburton)
Frans van Buchem (KAUST) Roger Davies (Davies Geoconsulting)

ABSTRACT

The Mesozoic stratigraphy of the Middle East hosts multiple world-class and economically significant petroleum systems. Since the initial discovery of oil in an anticline structure in 1908 (Masjed-e-Suleyman, Iran), further exploration and production in the Middle East has been fundamentally focussed on large, low-risk structural traps. Across the Arabian Plate, the presence of large unexplored structural traps at similar scales are now becoming scarce. Therefore, continued explorational success in the Middle East must now focus on the identification of subtle stratigraphic traps, particularly within the hydrocarbon-rich Mesozoic succession. To identify, locate and evaluate potential subtle stratigraphic traps, sequence stratigraphic principles have been applied across the Mesozoic stratigraphy of the Arabian Plate. This regional approach which utilises a robust age-based framework reduces lithostratigraphic uncertainty across international boundaries and provides a predictive capability in the identification and magnitude of stratigraphic plays. Herein, we focus attention on three stratigraphic intervals in the Mesozoic succession, namely Triassic, Middle–Late Jurassic and the middle Cretaceous in which regional, sequence stratigraphic based correlations have detected stratigraphic trap potential. The three Mesozoic successions of interest are associated with the following stratigraphic traps:

- Triassic sub-crop traps associated with a base Jurassic regional unconformity and intra-Triassic unconformities. Further potential in the Triassic succession is related to onlap trap geometries associated with differential topography across the Arabian Plate.
- Middle–Late Jurassic pure stratigraphic trap geometries associated with progradation at basin margins and stratigraphic pinch-out plays situated either side of the Rimthan Arch related to late Oxfordian/early Kimmeridgian eustatic sea-level fall.
- Middle Cretaceous sub-crop traps underlying the regional mid-Turonian unconformity with further subtle stratigraphic trap potential associated with basin margin progradation and pinch-out geometries associated with onlap onto basin margins.

The application of a regional sequence stratigraphic approach highlights the remaining exploration potential and production opportunities associated with the hydrocarbon-rich Mesozoic succession.

EXTENDED ABSTRACT

Introduction

Applying a consistent sequence stratigraphic model across the Mesozoic strata of the Middle East provides a framework in which subtle stratigraphic geometries and architectures can be identified. In this work, we have consistently and systematically applied a globally calibrated sequence stratigraphic model which has evolved from a schema first developed and published in GeoArabia Special Publication 2 (Sharland et al., 2001) for the Arabian Plate. Since the first publication of this sequence stratigraphic schema, this framework has received further updates in Davies et al. (2002), Sharland et al. (2004), and Simmons et al. (2007) with continued refinement in Davies and Simmons (2018) as an example. The application of this biostratigraphically constrained age-based framework provides a regionally consistent interpretation of the Triassic, Middle –Late Jurassic and middle Cretaceous stratigraphy. This sequence stratigraphic framework provides a mechanism in which multiple and often disparate local and/or regional datasets can be consistently integrated providing geological insight within regional exploration workflows. The database used in this work is comprised of publicly available literature which include key subsurface data including well logs, outcrops, seismic lines, biostratigraphy, and sedimentological information from across the Arabian Plate. All of this data has been brought together within one globally consistent tectono-stratigraphic framework (see Head and Simmons 2021). The objective of this study is to highlight identified examples of subtle stratigraphic traps across the Middle East utilising a regional sequence stratigraphic approach. This approach has shed light on further potential and the continued prospectivity of the Mesozoic successions across a mature hydrocarbon province.

Triassic sub-crop and onlap plays

The Late Permian to Early Triassic succession of the Middle East contains some of the world's most important gas resource. Located within simple structural traps, the carbonates of the Upper Khuff Formation located in Saudi Arabia, Qatar and Abu Dhabi and its equivalent the Kangan Formation of Iran, are sealed by the regional shales of the Sudair Formation and its equivalents, including the Aghar Shale (Davies and Simmons, 2018). In contrast, the Middle–Late Triassic succession has produced relatively minor volumes of accumulated hydrocarbons despite the interval hosting multiple potential reservoirs, seal, and source rocks (Davies and Simmons, 2018).

Following the break-up of Pangea in the late Paleozoic, the Arabian Plate during the Triassic occupied a sub-equatorial to equatorial setting on the southern passive margin of the Neo-

Tethys (van Oosterhout & Pöppelreiter, 2014). The Triassic was largely a period of tectonic quiescence, although subsidence rates were variable both stratigraphically and geographically which led to the presence of intra-shelf basins (Faqira et al., 2009; Aqrawi et al., 2010; Korngreen & Benjamini, 2011; Bialik et al., 2012). During the Early Triassic, the Palmyride rifts developed on the western part of the Arabian Plate (Walley, 2001; Brew et al., 2001). By the Late Triassic, this rifting and related uplift intensified as a precursor to the onset rifting in the Mediterranean in the Early Jurassic (Bialik et al., 2012; Berra and Angiolini, 2014). As a consequence of these events, two major stratigraphic breaks are present from the latest Carnian to late Norian and at the Triassic/Jurassic boundary. Deposition on the Arabian Plate during the Triassic was dominated by shallow-marine carbonate and evaporite deposition, although there are periods of siliciclastic deposition that can be widespread across the plate (Davies & Simmons, 2018; Davies et al., 2019). These periods of siliciclastic deposition relate to tectonic uplift of the hinterland, eustatic lowering and a humid climate.

The Triassic succession of the Arabian Plate is complex with countries having their own lithostratigraphic scheme and in some cases, several competing schemes (e.g. Al-Husseini & Mattner, 2007; Horbury, 2018; Lunn et al., 2019). Nonetheless, the Triassic stratigraphy exhibits strong cyclicity within the succession enabling Sharland *et al.* (2001) to apply a plate-wide third-order maximum flooding surface-based sequence stratigraphic interpretation. This interpretation was updated by Davies and Simmons (2018, 2020) reflecting new understanding from biostratigraphic and sedimentological studies.

The application of a robust age-based sequence stratigraphic framework helps to resolve lithostratigraphic inconsistencies across international boundaries and aids the identification of subtle stratigraphic architectures and geometries. During the Triassic, there was some intra-plate differential topography such as the subtle positive feature of the Qatar Arch and this structuration led to multiple trapping geometries such as sub-crop traps associated with the juxtaposition of the Middle–Late Triassic Jilh Formation unconformably below the Middle Jurassic Dhruma Formation (Figure 6 of Stewart et al., 2016). However, risks associated with this play include the presence of a working topseal. A further trapping geometry located on the flanks of the Qatar Arch relates to the onlap of the Late Triassic–Early Jurassic Minjur Formation and its equivalents (Figure 6 of Stewart et al., 2016). Both of these stratigraphic plays are regionally extensive and have been identified in the Rub al Khali Basin, through Qatar and into Iranian territory (Figure 1). The geological history of the Qatar Arch stems back to the Precambrian and there is a notable absence of the Precambrian Hormuz Salt on the crest of the Qatar Arch. This suggests that uplift originated from the earlier Precambrian Najd rifting and the Qatar Arch is a feature that was reactivated on several occasions in geological time. (Edgell, 1996: Talbot and Alavi, 1996; Al-Husseini, 2000; Konert et al., 2001; Stewart et al., 2016).

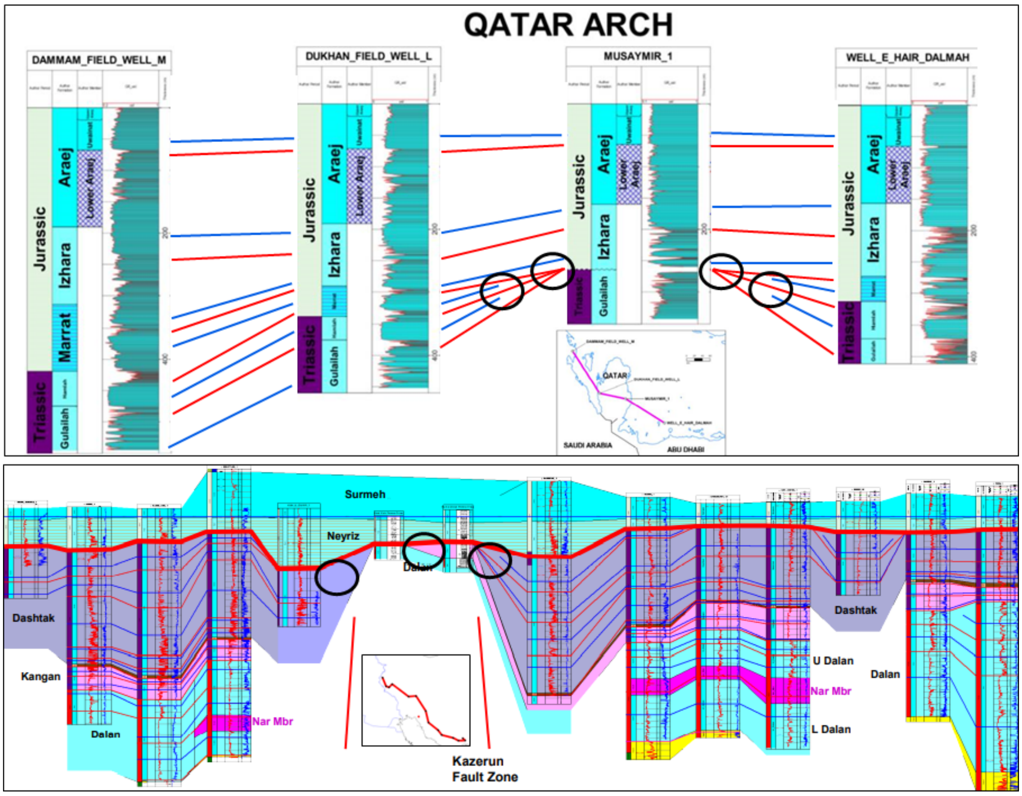

Figure 1 – Regional correlations from multiple locations in the Arabian Plate which highlight the geometries and architectures of the Triassic stratigraphy. The black circles indicate the location of identified sub-crop and onlap stratigraphic traps.

A major shift in the tectonic regime toward the end of the Triassic to Early Jurassic led to a regional angular unconformity that affected much of the Arabian Plate. Toward the north of the Arabian Plate, rifting in the eastern Mediterranean related to Gondwana break-up caused uplift to the Arabian Shield, erosion and tilting (Sharland et al., 2001, 2004). In the southern portion of the Arabian Plate, in Oman, uplift resulting from the precursor rifting and movement of India from Arabia contributed to this unconformity with progressive marine onlap of the Mafraq Formation (Hughes-Clarke, 1988; Grabowski and Norton, 1995). This major angular unconformity, in places, has varying degrees of erosion into the underlying stratigraphy. In Kuh-e-Dinar (southwest Iran), Jurassic stratigraphy rests unconformably above the Late Permian Dalan Formation (Szabo and Kheradpir, 1978), highlighted in Figure 1. However, there is an alternative interpretation in that Kuh-e-Dinar was a relict positive feature throughout the Triassic with the re-establishment of Early Jurassic regional carbonate platforms, the Neyriz and Marrat formations with a basal shale seal overlying the angular unconformity, providing the necessary elements to generate sub-crops plays across the Arabian Plate (Figure 1). Similar geometries are located in the northern plate where the basal Jurassic unconformity differentially truncates the underlying Late Triassic carbonates, shales and evaporites of the Sargelu Formation (Lunn et al., 2019). There is potential for these sub-crop plays to be extensive, however to date, none of these plays have been successfully drilled (Davies and Simmons, 2018). This unconformity is less prospective where sand-prone deposits of the Early Jurassic Upper Minjur Member directly overlie the sandstones of the Late Triassic Lower Minjur Member (Stewart et al., 2016; Issautier et al., 2019).

More subtle, low-angle sub-crop plays may exist beneath intra-Triassic unconformities with the potential for this play being identified in the Triassic stratigraphy in the Ghawar area of Saudi Arabia. This play has also been identified in outcrop sections and along the flanks of the Qatar Arch in the Rub al Khali Basin (Stewart et al., 2016) where differential preservation beneath the base Minjur Formation unconformity has resulted in a very low angle truncation of the underlying Jilh Formation. However, there are major risks associated with this play such as topseal effectiveness, especially where the unconformity is overlain by the sand-dominated formations such as the Minjur Formation. An approach to reduce topseal risk is to perform a seismic characterisation analysis which can distinguish between shale-prone as opposed to more sand-prone deposits to reduce risk and highlight potential exploration success.

There are also other important considerations regarding the prospectivity of these Triassic stratigraphic trap examples. The Triassic succession in the Middle East is not a major interval of organic-rich source rock deposition (Davies and Simmons, 2018) as compared to the underlying and overlying successions. The charge for most of the Early Triassic plays is derived from the Silurian Qusaiba Formation and its equivalents, however there is evidence to suggest the Early Triassic Kangan Formation is producing hydrocarbons in parts of Iran (Ahanjan et al., 2017) sealed by the shales of the Sudair Formation and its equivalents. The Triassic succession does contain some locally important source rock horizons including the Early-earliest Middle Triassic Amanus Shale and the Middle Triassic Kurra Chine Dolomite in the northern portion of the Arabian Plate (Abboud et al., 2005). There is also potential for organic-rich facies to develop in mini-basins in Iraq (Aqrawi et al., 2010) and in the Palmyrides of Syria (Vulama, 2011) charging younger Middle–Late Triassic plays. Further exploration risk factors include the probability of grainstones as the primary reservoir facies, gas souring by thermochemical sulphate reduction related to the presence of anhydrites in the subsurface and seal effectiveness as discussed previously.

Jurassic basin margin progradation and pinch-out plays

The Jurassic succession in the Middle East is one of the world's most economically significant petroleum systems containing multiple world-class source rocks and reservoirs beneath a regional significant evaporitic topseal. Yet, in a regional context, the depositional systems are not fully understood. A recent review of the Middle–Late Jurassic of the eastern

Arabian Plate has challenged some of the long-held understandings on deposition system relationships, stratigraphic architectures, and geometries due to the inconsistent application of lithostratigraphic nomenclature across country borders. These inconsistencies have held back understanding of the full exploration and production potential of the Jurassic petroleum system.

A consistent sequence stratigraphic model was constructed and re-evaluated based upon regional correlation transects spanning 2000 km in length, across eight countries, and containing key subsurface wells constrained by age-diagnostic biostratigraphic information provided by the Jurassic Escarpment outcrops in Saudi Arabia (Al-Mojel, 2017). Additional subsurface biostratigraphic control is provided by a reference well (Minagish-27) in Kuwait originally published by Kadar et al. (2015) and recently reviewed by de Cabrera et al. (2019). This methodology has provided new insight in subsurface stratigraphic architectures and offers alternative models for depositional misunderstandings whilst illuminating new subtle stratigraphic play concepts to maximise the exploration and production potential of the Middle–Late Jurassic.

One stratigraphic misunderstanding that exists on the Arabian Plate is the development and sedimentary infill of the Late Jurassic Gotnia Basin and its relationship with the Rimthan Arch. Several authors attribute the creation and sedimentary infill patterns of the Gotnia Basin to be largely controlled by tectonics (e.g. Jassim and Buday, 2006; de Cabrera et al., 2019). An alternative model by Gravestock et al. (2020) proposes a dominant role of eustatic sea-level change in combination with the ability of the carbonate factory to create topographic relief as the explanation for the establishment of time equivalent carbonate platforms and adjacent intra-shelf basins. In this interpretation, shallow-water carbonates of the Rimthan Arch were able to keep pace with rising sea-level whilst the Gotnia Basin became a sediment starved intra-shelf basin and developed organic-rich facies. Inherited accommodation space generated from the collapse of the Marrat/Alan carbonate platforms during the Early Jurassic related to rifting in the eastern Mediterranean (Sharland et al., 2001) were important secondary influences. This re-evaluated understanding of the creation of the Gotnia Basin, subsequent sedimentary infill and relationship with the Rimthan Arch has important consequences with respect to the petroleum habitat and this new derived insight has illuminated several subtle stratigraphic trap opportunities that may exist in the Gotnia and Hanifa basins. These stratigraphic opportunities include prograding and interbedded Highstand System Tract (HST) grainy carbonates of the Hanifa Formation reservoirs in the margins of the Hanifa Basin. Similarly, in the Gotnia Basin, progradational geometries of the Hanifa Formation are observed in a seismic stratigraphic interpretation from Wharton (2017) close to the Saudi Arabia-Kuwait border showing the transition from Rimthan Arch to the Gotnia Basin. Other stratigraphic opportunities relate to a lowering of sea-level around the Oxfordian/Kimmeridgian boundary which exposed the Rimthan Arch and surrounding platforms forcing the carbonate factory to prograde basinward where lowstands were deposited in both basins. In the Hanifa Basin, stratigraphic pinch-outs onto the basin margin are sealed by overlying Transgressive System Tract (TST) marls and organic-rich carbonates whilst in the centre of the basin, deeper-water carbonates interbedded within the source rock and evaporites of the Diyab Formation may prove to be an interesting exploration opportunity.

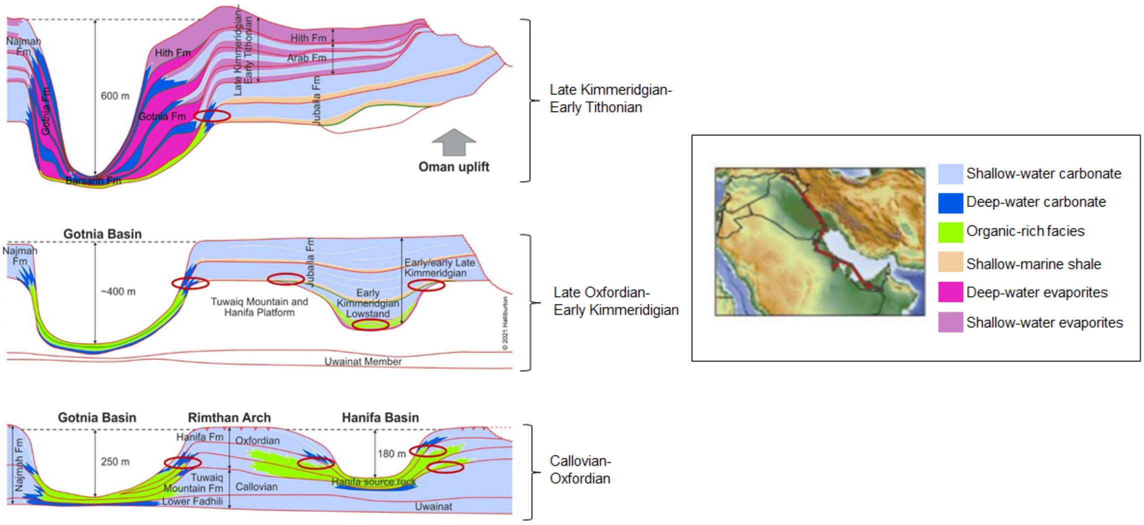

Figure 2 – A cross section through the eastern Arabian Plate for the Middle–Late Jurassic interval highlighting the evolution of the Gotnia and Hanifa basins separated by the Rimthan Arch. Red circles highlight the stratigraphic trap potential within both basins.

In the Gotnia Basin, time equivalent stratigraphy relates to the grainy reservoir facies of the Najmah Limestone that prograded into the basin. Up-dip, these grainy carbonates have the potential to form pinch-out traps against the Rimthan Arch. This conceptual play is likely to be charged by the underlying organic facies of the Naokelekan Formation and sealed by overlying TST marly facies and organic-rich carbonates. A further additional play relates to the potential for carbonates interbedded with prograding evaporite lenses on the margins of the Gotnia Basin, a play which has tested hydrocarbons in structural traps (Moustafa et al., 2015; Ghneej et al., 2015, 2018) but may have additional stratigraphic potential.

Middle Cretaceous sub-crop and basin margin progradation plays

The middle Cretaceous succession of the Arabian Plate is a prolific conventional petroleum system containing, along with its equivalents, one of the most important Middle Eastern reservoirs, the Mishrif Formation. The Mishrif Formation is a high-quality carbonate reservoir which is dominantly produced from structural closures within giant and super-giant fields across the Arabian Plate such as the Rumaila Field in Iraq. Further stratigraphic trap potential associated with the Mishrif Formation is principally related to depositional facies changes at shelf margins, where porous, grainy carbonates transition into tight, more micritic carbonates and sub-crop traps beneath the regional mid-Turonian unconformity. Yet, successful exploration of the sub-crop play concept beneath the mid-Turonian unconformity is geologically complex and will require detailed understanding of facies changes and the morphology of the depositional system. The application of a regionally consistent sequence stratigraphic model for the middle Cretaceous provides a framework that enables facies changes and morphology of the depositional system to be characterised at a high temporal resolution at the Arabian Plate-scale. Regional correlations that apply this consistent sequence stratigraphic framework are invaluable in understanding the distribution of source, reservoir and seal.

Throughout the middle Cretaceous there are important plate-scale depositional and tectonostratigraphic trends that occurred on the Arabian Plate. The Albian succession is largely siliciclastic dominated with deposition occurring on a broad muddy ramp. Major delta systems such as the Burgan Delta of Kuwait transported siliciclastics sourced from the Arabian Shield across the Arabian Plate and into deeper water. During the Late Albian, these siliciclastic systems were suppressed which led to the re-establishment of a broad carbonate ramp, the Mauddud Formation and its regional equivalents, across much of the Arabian Plate. Throughout the Cenomanian, the carbonate ramp differentiated facilitating the development of intra-shelf basins. These intra-shelf basins include the Shilaif-Natih (UAE-Oman), which developed via differential carbonate aggradation (Razin et al., 2017) and the Najaf Basin (Iraq) that developed due to suppression of the carbonate ramp related to siliciclastic input (Davies et al., 2019). The initiation of subduction in the Neo-Tethys and ophiolite obduction along the eastern plate margin during the Turonian generated a major erosional unconformity. The magnitude of this unconformity diminishes away from the active margin and therefore preservation beneath this unconformity is variable generating a complex sub-crop expression in the subsurface.

The Albian–Turonian succession contains prolific carbonate reservoirs that develop with rudist-rich grainstone and biostrome facies which preferentially develop along the margins of intra-shelf basins. These reservoirs typically occur within progradational packages associated with the HST when carbonate production exceeds accommodation space forcing grainy carbonates basinward. The movement of this progradation package form stratigraphic pinch-out geometries with more mud-dominated micritic carbonates and siliciclastic shales forming both lateral and intra-formational seals. Exploration potential in this play exists where there is sufficient charge from organic-rich intervals within the middle Cretaceous or from proven source rocks within older stratigraphy.

As discussed earlier, preservation beneath the Turonian erosional unconformity is variable and this has been identified in the sub-crop stratigraphy across the southern and central part of the Arabian Plate (Figure 3). Exploration potential in the sub-crop is high where karstified, rudist-rich carbonates are juxtaposed against the unconformity with the regional shale of the Coniacian Laffan Formation providing the effective seal overlying the unconformity (Al-Zaabi et al., 2010; Franco et al., 2018).

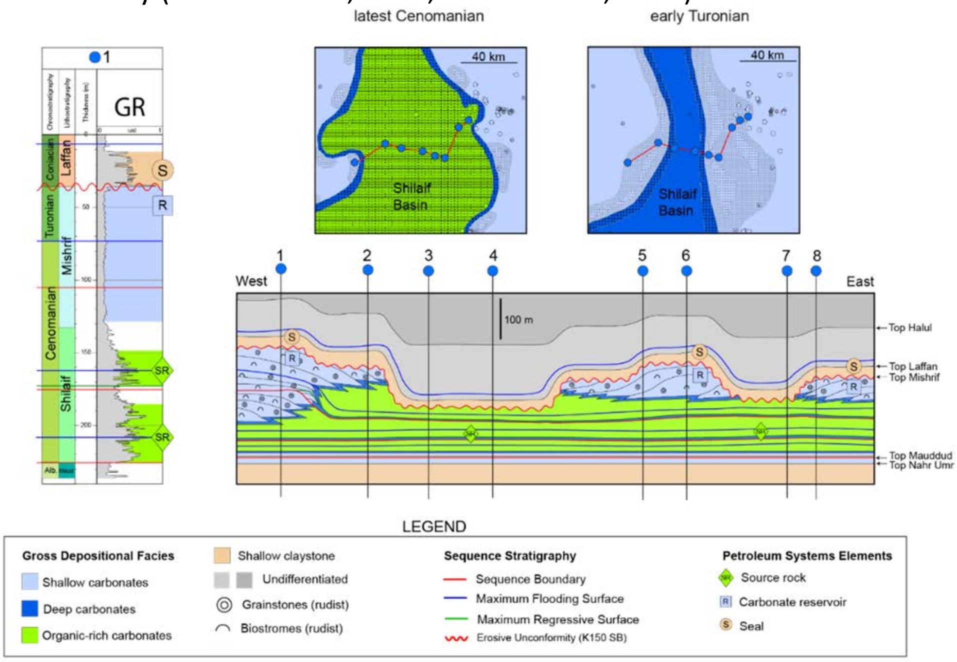

Figure 3 – A schematic well corelation through the northern section of the Shilaif Basin in offshore UAE (modified from Franco et al., 2018). This illustrates the potential for Mishrif reservoir sub-crop traps where rudist-rich grainy carbonates are juxtaposed against the mid-Turonian unconformity. This play is sealed by the overlying regional shale seal of the Coniacian Laffan Formation. The schematic cross section also highlights the variability in erosion and sub-crop preservation beneath the erosional unconformity.

By mapping the preservation limits of the Cenomanian–Turonian Mishrif Formation reservoir and its equivalents beneath the mid-Turonian unconformity, the distribution of the sub-crop potential across the Arabian Plate can be delineated. This methodology and subsequent results (Figure 4). have revealed seven important trends summarized below (after Bromhead et al., 2022):

Trend 1 – The Mishrif of south-eastern Iraq represented by high reservoir quality carbonates in patch reefs and shoals. This trend is associated with giant and supergiant fields which account for ~30% of Iraq’s reserves (Mahdi et al., 2013).

Trend 2 – Within the Mishrif Formation equivalent Sarvak Formation in the Dezful Embayment of south-west Iran, where the reservoir quality of the platform interior facies is enhanced by fracturing with the Cenozoic fold and thrust belt. Reservoir quality is also enhanced by karstification related to sea-level fall and Turonian uplift (Malekzadeh et al., 2020).

Trend 3 – The Mishrif Formation of the eastern UAE platform and adjacent areas of offshore Iran (Burchette, 1993) where excellent reservoir porosity exists in shelf margin shoals and isolated build-ups which have nucleated upon salt domes (e.g. Sirri fields and Umm al Dalkh Field). Reservoir quality is further enhanced by karstification beneath the mid-Turonian unconformity.

Trend 4 – The Natih Formation of northern Oman where reservoir quality within the Natih-A is enhanced by karstification beneath the mid-Turonian unconformity (van Buchem et al., 2002).

Trend 5 – The Mishrif Formation of offshore Qatar where differential erosion on the flanks of the Qatar Arch has generated a sub-crop profile with karstification of platform top carbonates (Deville de Periere et al., 2017; Botton-Dumay et al., 2002).

Trend 6 – The Mishrif Formation of southern Kuwait and the Partitioned Neutral Zone (PNZ) where differential erosion beneath the mid-Turonian unconformity has been illustrated along the Safaniyah-Nowrooz-Hendijan Arch by Al-Laboun (1987) and along the flanks of the Burgan Arch by Davies et al. (2002)

Trend 7 – The Rub al Khali Basin of Saudi Arabia where the screening methodology predicts high quality reservoir and potential for karstification. This area represents significant exploration opportunities away from known fields in a frontier area.

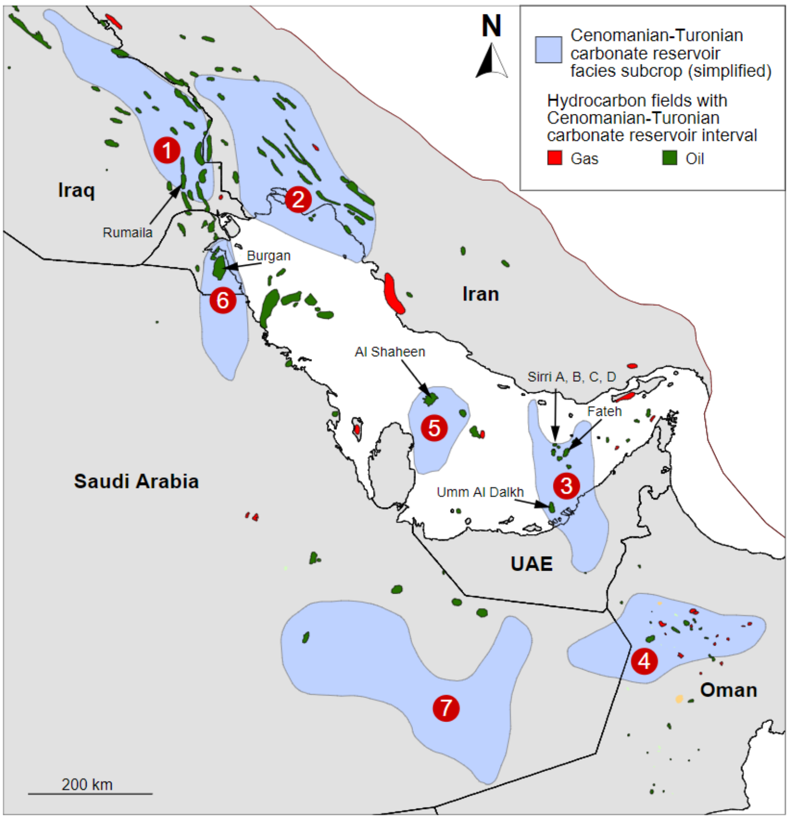

Figure 4 – Map showing the simplified distribution of potential carbonate reservoirs within the Cenomanian–Turonian sub-crop beneath the regional mid-Turonian unconformity (after Bromhead et al., 2022). This is overlain by hydrocarbon fields that have an associate carbonate reservoir of Cenomanian–Turonian age. This screening result reconciles with prolific reservoir trends (labelled), many of which have a sub-crop component.

Further stratigraphic trap potential may also exist in the Turonian lowstand siliciclastics of the Tuwayil Formation in south-western Abu Dhabi and may form stratigraphic pinch-out traps where sands onlap against the margins of the Shilaif Basin (Figure 7 and 8 of Azzam, 1995). The Tuwayil Formation is a proven reservoir at the Dhafra Field with reservoir porosities ranging between 10-20% (Azzam and Taher, 1993) and charged by the underlying Shilaif Formation (Azzam, 1995).

Conclusions

A thorough re-evaluation of the Mesozoic stratigraphy across the Arabian Plate has important consequences for the sedimentary fill, architectures, and geometries in several petroliferous basins. The consistent application of a regional-scale, robust age-based sequence stratigraphic framework has derived new insights in the prediction and distribution of source, reservoir, and seal facies, and the presence of stratigraphic traps. By conducting thorough literature reviews and integrating published datasets across international boundaries into a sequence stratigraphic framework, we have been able to identify several progradational, sub-crop and onlap subsurface geometries within the Mesozoic succession. There are however distinct geometries related to depositional architectures, platform morphology and tectonic events in each of the intervals examined in this paper which have been identified by the application of an Arabian Plate-scale sequence stratigraphic model. This re-evaluation and thorough assessment of three Mesozoic intervals in the Middle East has provided new insight and highlighted the continued exploration and production opportunities where the presence of undrilled structural traps is now limited.

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