Calcareous nannofossil zonation and sequence stratigraphy of the Jurassic System, onshore Kuwait

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ABSTRACT

This paper presents the calcareous nannofossil zonation of the Middle and Upper Jurassic of onshore Kuwait and formalizes current stratigraphic nomenclature. It also interprets the positions of the Jurassic Arabian Plate maximum flooding surfaces (MFS J10 to J110 of Sharland et al., 2001) and sequence boundaries in Kuwait, and correlates them to those in central Saudi Arabia outcrops. This study integrates data from about 400 core samples from 11 wells representing a nearly complete Middle to Upper Jurassic stratigraphic succession. Forty-two nannofossil species were identified using optical microscope techniques. The assemblage contains Tethyan nannofossil markers, which allow application of the Jurassic Tethyan nannofossil biozones. Six zones and five subzones, ranging in age from Middle Aalenian to Kimmeridgian, are established using first and last occurrence events of diagnostic calcareous nannofossil species. A chronostratigraphy of the studied formations is presented, using the revised formal stratigraphic nomenclature.

The Marrat Formation is barren of nannofossils. Based on previous studies it is dated as Late Sinemurian–Early Aalenian and contains Middle Toarcian MFS J10. The overlying Dhruma Formation is Middle or Late Aalenian (Zone NJT 8c) or older, to Late Bajocian (Subzone NJT 10a), and contains Lower Bajocian MFS J20. The overlying Sargelu Formation consists of the Late Bajocian (Subzone NJT 10b) Sargelu-Dhruma Transition, and mostly barren Sargelu Limestone in which we place Lower Bathonian MFS J30 near its base. The lower part of the overlying Najmah Formation consists of the Najmah Shale, which is subdivided into three subunits: (1) barren Najmah-Sargelu Transition, (2) Late Bathonian to Middle Callovian (lower Zone NJT 12) Lower Najmah Shale, and (3) Middle Callovian to Middle Oxfordian (upper Zone NJT 12 to NJT 13b) Upper Najmah Shale. Middle Callovian MFS J40 and Middle Oxfordian MFS J50 are positioned near the base and top of the Upper Najmah Shale. The upper part of the Najmah Formation is represented by the Late Oxfordian (Subzone NJT 13b) Najmah Limestone, and is overlain by the Kimmeridgian (Zone NJT 14) Jubaila Formation. Early Kimmeridgian MFS J60 and Late Kimmeridgian MFS J70 are positioned near the base and top of the Jubaila Formation. The positions of Late Jurassic MFS J80, J90 and J100 are not constrained by our biostratigraphic data and are positioned in the Gotnia Formation. The Upper Tithonian MFS J110 and the Jurassic/Cretaceous boundary are positioned in the Makhul Formation.

INTRODUCTION

During the Jurassic Period, the region of the State of Kuwait was located in a shallow-water, intra-shelf basin in the Arabian Plate, along the southwest margin of the Neo-Tethys Ocean (Sharland et al., 2001; Ziegler, 2001; Barrier and Vrielynck, 2008; Figures 1 and 2). The hydrocarbon exploration of the Jurassic System by Kuwait Oil Company (KOC) commenced with a deep well drilled in 1951 in Burgan Field, and oil was first discovered in the early 1980s (Al-Eidan et al., 2009), more than 40 years after the first oil discoveries in Cretaceous and Cenozoic (Tertiary) reservoirs. As part of KOC’s ongoing deep exploration program this study was undertaken to establish the Jurassic calcareous nannofossil zonation for Kuwait using the currently practiced lithostratigraphic scheme, and to place our results in the Arabian Plate sequence-stratigraphic framework.
This paper starts by introducing and formalizing the new and currently used informal lithostratigraphic nomenclature, lithostratigraphy, generalized lithofacies, and interpreted depositional settings of the Jurassic rock units in onshore Kuwait. These new and redefined units differ from those published by Yousif and Nouman (1997) and Al-Sahlan (2005), who designated a type section for Kuwait’s Jurassic formations in the Minagish-27 Well (Figure 1). From oldest to youngest, they used the names Marrat, Dhruma, Sargelu, Najmah, Gotnia and Hith formations. The Marrat, Dhruma, and Hith formations are defined in surface exposures in Saudi Arabia (Powers, 1968), whereas the Sargelu, Najmah, and Gotnia formations are defined in wells and outcrops in Iraq (van Bellen et al., 1959-2005).

Next, our paper establishes the Middle to Late Jurassic calcareous nannoplankton biostratigraphy of onshore Kuwait. In our study, 42 calcareous nannofossil species were identified from 400 core samples taken from 11 wells (Figure 1). The nannofossil markers include Kuwaiti markers (Kadar et al., 2011, 2013a, b; Al-Moraikhi et al., 2014), as well as the global Tethyan nannofossil events (Mattioli and Erba, 1999; Casellato, 2010). The type sections of the Jurassic Tethyan nannofossil zones are defined in the Umbria Marche and Lombardy basins in the Mediterranean Province, Italy (Figure 2) where the successions are continuous, well exposed, and provide ammonite zonal control (Mattioli and Erba, 1999; Channell et al., 2010).

The dataset presented in this paper allows us to date the Middle to Upper Jurassic stratigraphic succession in onshore Kuwait, and to compare our results with those of previous authors. Based on the interpretation of sedimentary features, lithofacies, depositional settings and age criteria, we interpret the positions of the Arabian Plate maximum flooding surfaces (MFS, Sharland et al., 2001), and propose their correlations to the current Jurassic sequence-stratigraphic models in central Saudi Arabia.
Figure 2: Map of paleogeography during the Jurassic Period, showing the location of the type section for Tethyan nannofossil zonation and the study area in Kuwait, on the southwest margin of the Neo-Tethys Ocean (modified after Barrier and Vrielynk, 2008).

MATERIAL AND METHODS

The section in Kuwait from the Lower Jurassic Marrat Formation to the lower part of the Upper Jurassic Gotnia Formation has been extensively drilled, logged, and cored. Only two significant intervals have not been seen and described in detail in core: the lower portion of the Marrat Formation, down to its contact with the Minjur Formation, and an approximately 200 ft (60 m) interval in the upper portion of the Upper Marrat unit and the basal portion of the Dhruma Formation.

Throughout this study, every effort has been made to tie the nannofossil data to the new lithostratigraphy. All samples are from cores, with depths recorded and, where available, annotated on detailed core descriptions. More than 7,000 ft (2,150 m) of core have been described in detail by the authors, supplemented by more than 3,000 high-resolution scanned images of core slabs. Three of the cores are restricted to the Gotnia and Hith formations. In 8 wells, the cored interval begins in the Gotnia and continues downward. In 27 wells, the cored interval begins in the Najmah Limestone and continues deeper, and in 17 wells, the cored interval extends down into the Dhruma Formation. The detailed core descriptions have been used to determine the depth shifts necessary to correlate them to open-hole well logs. Correlations between wells and to uncored wells are, in turn, based on the logs. An additional 17,000 ft (5,180 m) of core has been described in detail and 6,500 scanned images of core slabs acquired from the Marrat Formation. These data and the accompanying open-hole logs are the basis for the sedimentologic and lithostratigraphic discussion in this paper.

The logs and cross-sections all use the same header and color-fill settings. The gamma-ray (GR) logs are displayed on a logarithmic scale in order to reveal cyclicity: from 1–500 API at low GR in grain-supported limestones, dolomites, and evaporites; or 5–500 API for high GR values in the organic-rich Najmah Shale units. The color is adjusted to vary from red in grain-supported fabrics to black in argillaceous fabrics. The GR log curves have not been normalized, so that there is variation in the colors. The neutron porosity (NPHI) is colored to vary from black at 0% to dark blue at 10% and higher. The bulk density (RHOB) is shaded red at densities above 2.80 gm/cc to show anhydrite.
LITHOSTRATIGRAPHY

Marrat Formation

Nomenclature and Authors: The Marrat Formation was named and defined in outcrop sections in Saudi Arabia (Steineke, 1937, unpublished Aramco report; Steineke et al., 1958; Powers et al., 1966; Powers, 1968). Yousif and Nouman (1997) first published the term “Marrat Formation” in Kuwait.

Reference Section: Minagish-27 Well between 13,515 ft (4,120 m) and 15,350 ft (4,679 m) (Figure 3).

Lithology and Thickness: The thickness of the Marrat Formation is on average ca. 2,000 ft (610 m) in Kuwait. In Minagish-27 Well, Yousif and Nouman (1997) included 1,540 ft (470 m) of strata in the formation and subdivided it into (top to bottom) A, B, C, D and E units (Figure 3). These subdivisions have been replaced by the Lower, Middle and Upper Marrat members, based on the presence of argillaceous sediments in the Lower and Upper members (Al-Eidan et al., 2009; Neog et al., 2010; Al-Moraikhi et al., 2014). The formation consists of interbedded limestone, dolomite, anhydrite, sandstone and shale.

Boundaries: The Marrat Formation conformably overlies the Triassic–Lower Jurassic Minjur Formation in Kuwait. A karsted unconformity is locally present between the Middle and Upper Marrat members in northern Kuwait. The boundary between the Marrat Formation and overlying Dhruma Formation has not been cored. On electrical logs it appears to be conformable (Figure 3), and the highest core in the Upper Marrat Member suggests a gradual upward deepening towards the Dhruma Formation.

Depositional Setting: Neog et al. (2010) characterized the depositional setting of the Lower Marrat Formation as a broad, shallow platform that was separated from the Neo-Tethys Ocean by a barrier system situated along the outer rim of the Arabian Plate. Calcareous nannofossils are absent in the Marrat Formation from 9 wells drilled in Dhabi, Magwa, Mutriba, North Minagish, Raudhatain, Rahiyah, Sabriyah and Umm Niqa in onshore fields (Figure 1). The absence of nannofossils and low diversity of benthic foraminiferal assemblages indicate that the formation was deposited in restricted marine conditions within sabkha-tidal flat to shallow neritic setting (Truskowski et al., 2015).

The Lower Marrat consists of several high-frequency sequences, which aggrade upward from open-marine to restricted lagoonal and peritidal lithofacies. Agglutinated benthonic foraminifera *Haurania deserta* and *Almijella amiji* are generally present in the Lower Marrat indicating a shallow neritic environment. Various benthonic foraminifera associations (*Siphovalvulina-Everticyclammina-Mesoendothyra*, acritarchs-Pseudocyclusaminina-Mesoendothyra-miliolids, *Glommospira*-spine spicules, and *Mesoendothyra-Siphovalvulina*-calcareous benthonic foraminifers) were recognized in the Middle Marrat indicating a shallow open-marine platform to moderately deeper intrashelf basin. The Upper Marrat Member displays more ramp-like geometries and generally more argillaceous lithofacies, from sabkha to middle shelf settings. The tidal flat and shallow lagoonal setting is indicated by the association of *Pseudocyclusaminina*, *Redmondoides*, *Timidonella* and few miliolids.

Dhruma Formation

Nomenclature and Authors: The Dhruma Formation was named and defined in outcrops in Saudi Arabia (Steineke, 1937, unpublished Aramco report; Steineke et al., 1958; Powers et al., 1966; Powers, 1968). Yousif and Nouman (1997) first published the term “Dhruma Formation” in Kuwait, and the current definition and name is little changed.

Reference Section: Minagish-27 Well between 13,377 ft (4,078 m) and 13,515 ft (4,120 m) (Figure 4). See also composite of wells B and F in Figure 5.

Lithology and Thickness: The Dhruma Formation in Minagish-27 Well is 138 ft (42 m) thick and consists of shale and calcareous shale with occasional argillaceous lime mudstone and wackestone interbeds. It ranges in thickness from ca. 60 ft (18 m) in northern Kuwait to 175 ft (53 m) in the south (Figure 6 and Enclosure I).
Figure 3: Log display of the Marrat Formation in Minagish-27 Well, comparing lithostratigraphic nomenclature of Yousif and Nouman (1997), and the one commonly practiced in Kuwait Oil Company (KOC) and adopted in this paper. See Figure 1 for location and Enclosure I for legend.
Boundaries: The base of the Dhruma Formation in Kuwait is placed where the interbedded shale and limestone beds of the Upper Marrat Member, are replaced by the basinal shales with high gamma-ray counts. The upper boundary with the Sargelu Formation is discussed below.

Depositional Setting: The calcareous shales and argillaceous limestones in the lower part of the Dhruma Formation are characterized by a moderate to higher abundance of calcareous nannofossils, which generally indicate a deep-marine setting. The upper part shows a shallowing upward trend to the limestones of the Sargelu Formation.

Sargelu Formation

Nomenclature and Authors: The Sargelu Formation was named for surface exposures in the Surdash Anticline, northeastern Iraq (Wetzel, 1948, unpublished report; Dunnington, 1958-2005; van Bellen et al., 1959-2005). Strata considered to be correlative with the Sargelu Formation of Iraq were penetrated in the Burgan-113 Well in Kuwait, which may explain the adoption of the formation name in Kuwait (van Bellen et al., 1959-2005). Yousif and Nouman (1997) first published the term “Sargelu Formation” in Kuwait.

Reference Section: In this paper the Sargelu Formation is redefined in Minagish-27 Well between 13,166 ft (4,014 m) and 13,377 ft (4,077 m) (Figure 4). See also composite of wells B and F in Figure 5.

Lithology and Thickness: In the present study the Sargelu Formation is formally subdivided into the argillaceous “Sargelu-Dhruma Transition”, and the overlying “Sargelu Limestone”. In Minagish-27 Well, the top of the Sargelu-Dhroma Transition is placed at 13,275 ft (4,046 m). The thickness of the Sargelu Formation increases from an average of 65 ft (19.8 m) in northern Kuwait to a maximum of 195 ft (59 m) in the southern region of the country. The thickness of the Sargelu-Dhruma Transition averages about 30 ft (9 m) in the north and increases to ca. 90 ft (27 m) in the south (Figure 6 and Enclosure I).

Boundaries: The base of the Sargelu Formation is placed at the change from predominantly limestone with subordinate shale interbeds, to predominantly calcareous shale with subordinate limestone interbeds as originally defined by Yousif and Nouman (1997). The upper boundary with the Najmah Formation is discussed below.

Depositional Setting: The Sargelu Formation is generally an aggradational succession. The Sargelu-Dhroma Transition consists of intensely burrowed, interbedded argillaceous limestones and skeletal wackestones, with a declining number of calcareous nannofossils. The setting of the Sargelu-Dhroma Transition is interpreted as an outer-ramp, slope and basin margin. The Sargelu Limestone only has thin shale interbeds that shallow upward into packstones containing cortoids, coated grains and skeletal fragments. Flora is absent in the limestone. The setting of the Sargelu Limestone is interpreted as an open marine shelf.

Najmah Formation

Nomenclature and Authors: The type section for the Najmah Formation is in the Najmah-29 Well, drilled in the late 1930s on the Najmah-Quayarah Anticline southeast of Mosul in northern Iraq (Dunnington, 1953, unpublished report; van Bellen et al., 1959-2005). Yousif and Nouman (1997) first published the term “Najmah Formation” in Kuwait, and subdivided it into units 1 to 4.

Reference Section: In the current lithostratigraphic practice, the Najmah Formation is defined in Minagish-27 Well between 12,955 ft (3,948 m) and 13,166 ft (4,014 m) (Figure 4). See also composite of wells B and F in Figure 5.

Lithology and Thickness: The Najmah Formation is divided into the Najmah Shale (13,017–13,166 ft, 3,967–4,013 m) and overlying Najmah Limestone (12,955–13,017 ft, 3,948–3,967 m). In turn, the Najmah Shale is divided into: (1) Najmah-Sargelu Transition (13,152–13,166 ft, 4,008.5–4,013 m); (2) Lower Najmah Shale (13,118–13,152 ft, 3,998–4,008.5 m); and (3) Upper Najmah Shale (13,017–13,118 ft, 3,967–3,998 m; Figure 4). The latter three units are distinguished by the differences in limestone
Figure 4: Log display of the Dhruma, Sargelu, Najmah, Jubaila and basal Gotnia formations in Minagish-27 Well, comparing lithostratigraphic nomenclature of Yousif and Nouman (1997) and the one commonly practiced in Kuwait Oil Company (KOC) and adopted in this paper. See Figure 1 for location and Enclosure 1 for legend.
lithofacies of strata that are interbedded with fissile, organic-rich, argillaceous lime mudstones. Their boundaries are clearly recognized on electrical logs and can be correlated throughout Kuwait (Figures 4 to 6 and Enclosure I). The Najmah Formation varies in thickness from about 140 ft (42.7 m) in the north to 220 ft (67.0 m) in the south.

**Najmah-Sargelu Transition, Najmah Formation**

This unit was previously assigned to the Sargelu Formation by Yousif and Nouman (1997). It contains two distinct types of limestone beds that are interbedded with organic-rich argillaceous lime mudstones. One of these limestone lithofacies is a mud-dominated packstone containing cortoids, coated grains, and other skeletal fragments. The other is a skeletal-microbial wackestone which commonly contains juvenile ammonites. The Najmah-Sargelu Transition is relatively constant in thickness, varying from about 14 to 24 ft (4.3 to 7.3 m).

**Lower Najmah Shale, Najmah Formation**

This unit was previously assigned to the Sargelu Formation by Yousif and Nouman (1997; Figure 4). It consists of skeletal-microbial wackestones interbedded with organic-rich argillaceous lime mudstones. The skeletal-microbial wackestones are similar to the ones that occur in the underlying Najmah-Sargelu Transition, consisting of a distinctive association of filamentous microbial mounds, minute articulated bivalves, and juvenile ammonites. The Lower Najmah Shale is about 20–25 ft (6.0–7.6 m) thick in the north, and thickens southward to a maximum of 84 ft (25.6 m) (Figures 4 to 6 and Enclosure I).

In southern Kuwait, the Lower Najmah Shale contains a wedge-like package of thick-bedded strata characterized by somewhat lower GR counts than the limestone beds in the rest of the Lower Najmah Shale and the underlying Najmah-Sargelu Transition (Figure 6 and Enclosure I). These strata have been referred to informally as the “grain flow” or “turbidite” unit (Al-Moraikhi et al., 2014); we refer to this package as the “Lower Wedge”. It is thickest in southeast Kuwait and thins to the northwest.

**Upper Najmah Shale, Najmah Formation**

This unit corresponds to the lower part of Najmah Unit 2, and units 3 and 4 of Yousif and Nouman (1997, Figure 4). In most wells in Kuwait it consists of dark, microlaminated, organic-rich argillaceous lime mudstones (Figures 5 and 6, Enclosure I). It is also informally referred to as the “kerogen” unit. It lacks both types of beds seen in the underlying Najmah units. It is more basinal in character, lacking burrowing and containing dense accumulations of the pelagic bivalve *Bositra* sp. Its thickness averages about 45–60 ft (13.7–18.3 m) in the north and increases to a maximum of 180 ft (54.9 m) in the Umm Gudair area (Figure 6 and Enclosure I).

In southern Kuwait, the Upper Najmah Shale also contains a wedge-like package of thick-bedded strata characterized by low-GR (“grain flow” or “turbidite” unit of Al-Moraikhi et al., 2014); we refer to this package as the “Upper Wedge” (Figure 6 and Enclosure I). It corresponds to Najmah Unit 3 of Yousif and Nouman (1997) in Minagish-27 Well. The Upper Wedge thickens where the Lower Wedge thins. It also thins to the northwest.

**Najmah Limestone Member, Najmah Formation**

The Najmah Limestone corresponds to the upper part of Unit 2 of Yousif and Nouman (1997) in Minagish-27 Well (Figure 4). Its thickness ranges between 40 and 60 ft (12.2–18.3 m) (Figures 5 and 6, Enclosure I). A condensed interval with abundant ammonites and other fossils occurs at the base of the Najmah Limestone. The lower part usually contains a few interbeds of organic-rich argillaceous lime mudstone that are burrowed by ichnofauna of the *Zoophycos* ichnofacies. This burrowing extends a few feet down into the Upper Najmah Shale and is associated with common slumping and brecciation.

The basal limestones commonly contain microbial dendrolite growth forms and are intensely burrowed by *Thalassinoides* at common hardgrounds, forming a labyrinth of burrows. Upward, these lithofacies are replaced by peloidal and microbial packstones, with common encrusted and burrowed surfaces. These are overlain by packstone beds and oncoidal zones burrowed by *Diplocraterion, Thalassinoides*, and *Teichichnus*. In the highest beds, the lithofacies are commonly grain-dominated packstones with coated grains and contain *Ophiomorpha* and *Diplocraterion* burrows.
Figure 5: Composite logs and core description of Middle and Late Jurassic stratigraphic section sampled for this study. Nannofossil sample locations and abundances are shown on the right. Stratigraphic nomenclature and Jurassic Tethyan zonation as defined in this paper are shown on the left. See Enclosure I for legend.
Figure 6: North-south cross-section, showing lithologic variation in Najmah Formation in Kuwait. Note the thick upper wedge that thins northward and is absent north of Minagish-27 Well. The lower wedge (not visible in this section; see Enclosure I) can be seen in the Lower Najmah Shale in SE Kuwait and thins to the NW. See Figure 1 for well location and spacing. See Enclosure I for legend.
Jurassic stratigraphy, onshore Kuwait

Figure 6: North-south cross-section, showing lithologic variation in Najmah Formation in Kuwait. Note the thick upper wedge that thins northward and is absent north of Minagish-27 Well. The lower wedge (not visible in this section; see Enclosure I) can be seen in the Lower Najmah Shale in SE Kuwait and thins to the NW. See Figure 1 for well location and spacing. See Enclosure I for legend.
Boundaries: The boundary of the Najmah Formation with the underlying Sargelu Formation is transitional, with thin organic-rich (kerogenous) beds appearing in the uppermost Sargelu Formation and increasing upward. The boundary is normally placed at the highest grain-supported beds.

Al-Moraikhi et al. (2014) recorded in four wells a characteristic, non-truncated, negative carbon-isotope excursion spanning the Sargelu Formation, Najmah-Sargelu Transition and lower part of the Lower Najmah Shale. They suggested that this interval does not contain a major unconformity. Based on their biostratigraphic and carbon-isotope data they inferred a substantial unconformity at the base of the Upper Wedge, corresponding to a hiatus of Early Callovian–Middle Oxfordian or younger age.

The Najmah Limestone lies conformably on the Najmah Shale. The Najmah Formation (top Najmah Limestone) is unconformably overlain by a thin unit of shale, calcareous shale, and peloidal limestone beds of the Jubaila Formation. The contact has been described in at least eight cores, and in all cases is interpreted as an unconformity with minor karsting and evidence for exposure. Variations in thickness of the Najmah Limestone in North Kuwait are attributed to erosion at this unconformity.

Depositional Setting: Calcareous nannofossils are generally absent in the Najmah-Sargelu Transition. This unit consists of interbedded ORAM (microlaminated organic-rich argillaceous lime mudstone) and skeletal microbial wackestones but also has mud-dominated packstone beds with cortoids, coated grains, and various skeletal fragments. These are interpreted as having been transported downslope from an outer-shelf or ramp setting. The microbial skeletal wackestones appear to represent an oxygen-minimum zone setting along the basin margin.

Nannofossils with a low diversity re-appear in the Lower Najmah Shale. This unit contains beds with a distinctive association of filamentous microbial wackestones, minute articulated bivalves, and juvenile ammonites, interbedded with ORAM. These beds appear to have accumulated in-situ in a base-of-slope setting along the basin margin and have been referred to informally as the “ammonite nursery”. The Lower Wedge was deposited as a probable lowstand package within the Lower Najmah Shale. These resedimented grain-flow beds are part of an overall retrogradational succession and were likely sourced from farther south along the Burgan Arch.

The Upper Najmah Shale is more basinal in character, lacking burrowing and containing dense accumulations of the pelagic bivalve Bositra sp. Common to abundant calcareous nannofossil assemblages were identified within this unit. It is clearly basinal, consisting of predominantly ORAM with a few pure lime mudstone beds that may represent very distal subaqueous flows. Likewise, the Upper Wedge was deposited as a lowstand unit within the Upper Najmah Shale.

The Najmah Limestone is characterized by the absence-to-abundance of nanoflora. The basal beds overlie a condensed zone representative of outer shelf to upper slope. The succession of litho- and ichnofacies indicate shallowing upward and probably progradation to inner shelf or lower shoreface depositional settings.

Jubaila Formation

Nomenclature and Authors: The type section of the Jubaila Formation is defined in the cover rocks of Saudi Arabia (Powers et al., 1966; Powers, 1968; Énay et al., 1987). This formation name is introduced here for the first time in Kuwait. It corresponds to the lower part of Najmah Unit 1 of Yousif and Nouman (1997), and below the 4th Anhydrite of the Gotnia Formation in Minagish-27 Well (Figure 4).

Type Section: Well F, between core depths 14,617.5 and 14,625.5 ft (4,455–4,458 m) (Figure 5). In Minagish-27 Well the Jubaila Formation is encountered between 12,929 and 12,955 ft (3,941–3,948 m) (Figure 4).

Lithology and Thickness: The Jubaila Formation consists predominantly of argillaceous limestone, dolomitic limestone and calcareous shale. The sediments are generally dark, reddish brown to nearly black in color. In Well F, the Jubaila Formation is only 8 ft (2.4 m) thick but it thickens southwestward to ca. 40 ft (12.2 m) in Well I (Figures 4 to 6 and Enclosure I).
Boundary: For lower boundary see Najmah Formation. The Jubaila Formation is unconformably overlain by the Gotnia Formation.

Depositional Setting: In North Kuwait, the Jubaila Formation consists of generally argillaceous, laminated to thin-bedded peloidal and thrombolitic mudstones, wackestones, and mud-dominated packstones deposited in peritidal to shallow subtidal environments. As the formation thickens southward and westward, it becomes more argillaceous and less microbial, as well as becoming burrowed. The environments toward the south and west are probably representative of inner ramp/shelf depositional settings. Abundant calcareous nanofossils were recognized in the argillaceous mudstone in wells D, E, F, I and K. Cocospheres (complete spheres of coccoliths) were also identified within the Jubaila Formation, indicating a low-energy, open-marine, depositional environment.

Gotnia Formation

Nomenclature and Authors: The Gotnia Formation was originally defined as the Gotnia Anhydrite Formation (Dunnington, 1953, unpublished report; van Bellen et al., 1959-2005), with its type section in the Awasil-5 Well in central Iraq. The Gotnia Formation was correlated to the unnamed salt-and-anhydrite section penetrated in Burgan-113 Well, probably explaining assignment of the name Gotnia Formation to the Kuwait section (Lababidi and Hamdan, 1985; Ali, 1995; Yousif and Nouman, 1997).

Ali (1995) and Yousif and Nouman (1997) used different numbering systems for the cycles of salt and anhydrite (Figure 7). Ali (1995) assigned the name 1st Anhydrite to the anhydrite and limestone section between the 1st and 2nd Salts, while Yousif and Nouman (1997) assigned the name 1st Anhydrite to the Hith Formation and did not number the anhydrite and limestone section below the 4th Salt.

Reference Section: The Gotnia Formation is defined between 11,532 ft (3,515 m) and 12,929 ft (3,941 m) in Minagish-27 Well (Figure 7).

Lithology and Thickness: The Gotnia Formation is 1,397 ft (426 m) thick in Minagish-27 Well, where the full section from 1st Salt to 4th Anhydrite is represented (Figure 7). The formation thins northward to Well F, where the Gotnia is 528 ft (161 m) thick. The maximum thickness was encountered in southern Kuwait in the area of Minagish Field (Enclosure II). Maps and cross-sections published by Ali (1995) and Yousif and Nouman (1997) clearly show dramatic thinning toward northern Kuwait.

Boundaries: In a representative stratigraphic succession the basal 4th Anhydrite of the Gotnia Formation unconformably overlies the Jubaila Formation. The unconformity is recognized throughout Kuwait, and especially in the north (Enclosure II). Yousif and Nouman (1997, their figure 11) show that between Minagish Field and more northerly Dhah Field (Figure 1), the Gotnia 4th Salt and 3rd Salt are absent due to onlap. In Dhah Field Well F (their Well DA-A), they show the 2nd Salt rests directly on the Jubaila Formation. In core, however, a thin tongue of the 3rd Salt and underlying 3rd Anhydrite are present.

Depositional Setting: The Gotnia Formation was deposited in the restricted evaporitic Gotnia Basin. The basin was bounded to the south by the NE-trending Rimthan Arch, approximately situated along the Kuwait-Saudi Arabian border, and to the east by the Burgan Arch (see figure 13 of Yousif and Nouman, 1997). Evaporite lithofacies described in core are all interpreted as sabkha, tidal flats, or very shallow subtidal. The limestones and dolomites in the Gotnia anhydrite units are laminated to thin-bedded peloidal and microbial mudstones to packstones. Occasionally, the anhydrites preserve the geometry of stromatolites as well, indicating deposition under more restricted conditions. These peritidal to subtidal settings suggest that rapid deposition of halite kept up with subsidence.

Hith Formation

Nomenclature and Authors: The Hith Formation is exposed in a large solution cavity named Dahal Hit, situated south of Ar Riyad, the capital of Saudi Arabia (Steineke, 1935, unpublished Aramco report; Steineke et al., 1958; Powers et al., 1966, Powers, 1968; see review in Wolpert et al., 2015).
In Kuwait, Ali (1995) did not discuss the Hith Formation. Yousif and Nouman (1997) retained it as a separate formation and named it the 1st Anhydrite, thus confusing its nomenclature with that of Ali (1995) (Figure 7; see above discussion).

Reference Section: The Hith Formation is defined between 11,199 ft (3,413 m) and 11,532 ft (3,515 m) in Minagish-27 Well (Figure 7 and Enclosure II).

Lithology and Thickness: As seen in core and interpreted from logs, the Hith Formation consists of interbedded massive to nodular anhydrite and peloidal to stromatolitic microbial limestones and dolomites; salt beds are generally absent. In Minagish-27 Well, the Hith Formation is 334 ft (102 m) thick. It thins northward to Well F, where it is 213 ft (65 m) thick. Yousif and Nouman (1997, their figure 14) show the thickness of the Hith Formation in the Rugei Well, which was drilled in an isolated location in SW Kuwait (Figure 1), to exceed 1,100 ft (335 m). We note that this thickness is about three to five times greater than elsewhere in Kuwait and controlled by just one well, a result that requires confirmation.

Boundaries: The lower boundary of the Hith Formation with the Gotnia Formation is abrupt and conformable. The upper contact, with the Makhul Formation, is interpreted as an unconformity. A profound facies change occurs from the shallow, restricted carbonate-evaporite cycles of the Hith to the Makhul Formation deep, open-marine, basinal argillaceous mudstones punctuated by thin, possibly distal turbidites.

Depositional Setting: Lithofacies described in core are very similar to those seen in core in the Gotnia evaporite units, representing deposition in sabkha, tidal flat, and shallow subtidal environments. These limestone and dolomite lithofacies are also generally microbial, with peloidal, thrombolitic, and stromatolitic growth forms, some of them clearly deposited in restricted brines and containing molds of gypsum crystals. The Hith becomes more carbonate-dominated upward.

**Makhul Formation**

Nomenclature and Authors: The Makhul Formation has its type locality in Makul-1 Well near the southern margin of the foothills region of northern Iraq (Dunnington, 1955, 1957). The Makhul Formation is defined between 11,199 ft (3,413 m) and 11,532 ft (3,515 m) in Minagish-27 Well (Figure 7 and Enclosure II).

![Figure 7: Log display of the Gotnia and Hith formations in Minagish-27 Well, showing numbering scheme for the anhydrite units (Ali, 1995), as commonly practiced in Kuwait Oil Company (KOC). Position of MFS J80, J90 and J100 after Sharland et al. (2001). See Figure 1 for location and Enclosure I for legend.](http://pubs.geoscienceworld.org/geoarabia/article-pdf/20/4/125/5448249/kadar.pdf)
unpublished report; van Bellen et al., 1959-2005). The Makhul Formation in Kuwait has no formally published type section or reference sections that show the defining wireline log characteristics and lithological variability of this formation.

Reference Section: Internal KOC reports (e.g. Crittenden, 2012, unpublished KOC report) have suggested that the Minagish-8 Well (10,640–11,465 ft; 825 ft thick) could serve as a reference section for the Makhul Formation. However, the Makhul Formation has not been cored in this well. Accordingly, additional reference wells that have been cored and contain biostratigraphical data (Minagish-5 or Mutriba-2) could be chosen.

Lithology and Thickness: The Makhul Formation in onshore Kuwait is predominantly a dark grey, argillaceous carbonate mudstone (Al-Eidan et al., 2000) (see Enclosure II for description). In the offshore area of Kuwait, Al-Fares et al. (1998) reported that the Makhul Formation comprises dense, grey to dark grey limestones and interbedded dark grey shales. In northern Kuwait the thickness of the formation varies: in Raudhatain Field (ca. 570 ft), Riquah Field (> 1,215 ft), Northwest Raudhatain Field (ca. 780 ft) and Minagish Field (650 ft) (see Figure 1 for locations).

Boundaries: For lower contact see the Hith Formation discussed above. The contact of the Makhul Formation with the overlying Minagish Formation appears to be diachronous.

Depositional Setting: The Makhul Formation represents a significant deepening upward setting from the Hith Formation. The biofacies of the formation are characterized as a radiolarite facies (Crittenden, 2012, unpublished KOC report), which consists of calcitized radiolaria, calcispheres and calcitized sponge spicules, rare Bositra? buchi and Saccomma spp., rare nannofossils, and rare small agglutinated Textularia spp., Ammobaculites spp. and possible cyclamminids. Miliolids, lentimucilinds, algae, bivalve and echinoderm fragments were identified as allochthonous shallower marine taxa.

Two biozones occur in the formation. The lower biozone is characterized by the virtual absence of in-situ fauna/flora, dominated by sponge spicules and radiolaria, which represents an open-marine, low-energy, partly euxinic intrashelf basin. The upper biozone is marked by a diverse, but sparse in number, in-situ bentonic and planktonic fauna/flora, which represents a more open-shelf setting. The Makhul Formation gradually shoals upward to the Minagish Oolite.

MIDDLE TO UPPER JURASSIC CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY

Since the comprehensive zonation made by Barnard and Hay (1974), calcareous nannofossils have become a major tool for subdividing Jurassic marine sediments. The global nannofossil biostratigraphic zonation for the Mesozoic has its roots in the work of Thierstein (1971, 1973, 1976) who established a nannofossil zonation from successions exposed in Europe, USA and Australia as well as Deep Sea Drilling Project sites drilled by Glomar Challenger. More elaborate biostratigraphic schemes for Middle and Late Jurassic were then proposed by many workers (e.g. Roth, 1973, 1983; Perch-Nielsen, 1985). In the last 20 years the Jurassic nannofossil zonation has undergone further developments and revisions (Bralower et al., 1989; de Kaenel et al., 1996; Bown et al., 1998; Bown and Cooper, 1998; Mattioli and Erba, 1999; Casellato, 2010).

In summary, two synthetic biostratigraphic schemes exist for the Jurassic, namely: (1) The Boreal nannofossil zones (Bown and Cooper, 1998), which are mainly based on NW European sections. (2) The Tethyan Jurassic nannofossils zones (designated NJT) (Mattioli and Erba, 1999; Casellato, 2010), which are based on sections in Northern and Central Italy. The Tethyan Lower and Middle Jurassic nannofossil zonation (biozones NJT 1–11 of Mattioli and Erba, 1999) have been extended into the Upper Jurassic and lowermost Cretaceous (biozones NJT 12–17 and NKT) by Casellato (2010). The majority of index species occurring in the Tethyan Middle Jurassic to Late Jurassic nannofossil zones are also present in the onshore Kuwait area. In this study, Zones NJT 8c–11 of Mattioli and Erba (1999), Zones NJT 12–14 of Casellato (2010) and the Tethyan Cretaceous Coccolith Zone CC 1 of Bergen (1994) were applied with minor modifications (Figures 8 and 9). Remarks on the nannofossil events, zones, and subzones identified herein are discussed in the following section in ascending stratigraphic order.
Remarks on Nannofossil Zones and Subzones

Six nannofossil zones and five subzones were identified in this study and cover most of the Middle Aalenian–Kimmeridgian interval (Figures 8 and 9). One Berriasian nannofossil zone, CC 1 was identified in Minagish Field (Millenium, 2013, unpublished report) and added in Figure 10 in order to indicate the Jurassic/Cretaceous boundary in onshore Kuwait.

| Ma     | Series | Stage | Sub-Stage | Zone | Event          | Zone/Subzone | Event          |
|--------|--------|-------|-----------|------|----------------|---------------|----------------|
| 145.0  |        |       |           | CC-1 | N. steimannii minor* |               | N. steimannii minor* |
| 152.1  |        |       |           |      | N. wintereri*   | NJT 15 - 17   |                |
| 157.3  |        |       |           | NJT 13b | N. gl.minor*, U. gr.granulosa* |               |                |
| 161.5  |        |       |           | NJT 13a | N. infans*   | NJT 17       |                |
| 165.1  |        |       |           | NJT 13 | M. chiastus*, H. noeliae*, P. senaria*, P. beckmanii* |               |                |
| 166.1  |        |       |           | NJT 12 | C. mexicana minor* |               |                |
| 168.3  |        |       |           | NJT 11 | A. helvetica*  |               |                |
| 170.3  |        |       |           | NJT 9 | A. helvetica + |               |                |
|        |        |       |           | NJT 8c | W. contracta + |               |                |
|        |        |       |           | NJT 8a | W. manivitae*  |               |                |

Figure 8: Middle to Late Jurassic calcareous nannofossil zones for Kuwait as used in this study. The Tethyan Zones NJT 8–11 of Mattioli and Erba (1999) and Zones NJT 12–17 of Casellato (2010) were applied here with minor modifications. Time scale after Gradstein et al. (2012) and International Commission on Stratigraphy (2015).
Subzone NJT 8c: Middle Aalenian to Late Aalenian

Definition: Interval from the first occurrence of Cyclagelosphaera margerelii to the first occurrence of Watznaueria britannica.

Authors: Mattioli and Erba (1999)

Assemblage: The FO of Watznaueria britannica occurs 3 feet above the base of the deepest cored section of the Dhruma Formation in Well B. The abundant occurrence of W. contracta, W. fossacincta, Schizosphaerella punctulata, Carinolithus superbus, Discorhabdus criotus, D. striatus, Ethmorhabdus galicus and Lotharingius crucicentralis characterizes this interval in North Kuwait.

| Ma   | Series | Stage | Sub-Stage | Zone         | Subzone Zone | Selected Calcareous Nannofossil |
|------|--------|-------|-----------|--------------|--------------|--------------------------------|
| 170  | Jurassic| Bathonian | L         | NJT 11       | NJT 11       |                                  |
|      |        | Bajocian | L         | NJT 10b      | NJT 10b      | S. punctulata                   |
|      |        |         | E         | NJT 10a      | NJT 10a      | D. superbus                     |
| 160  | Jurassic| Callovian | L         | NJT 12       | NJT 12       | C. margareta                    |
|      |        |         | E         | NJT 13       | NJT 13       | W. britannica                   |
| 155  | Jurassic| Kimmeridgian | L         | NJT 14       | NJT 14       | A. helvetica                    |
|      |        |         | E         | NJT 15       | NJT 15       | W. manivitae                    |
|      |        |         |           |              |              | W. barnesae                     |
| 145  | Jurassic| Tithonian | L         | NJT 15 - 17  | NJT 15 - 17  | C. mexicana minor               |

Figure 9: Ranges of selected calcareous nannofossils in the Kuwait area. Time scale after Gradstein et al. (2012) and International Commission on Stratigraphy (2015).
Zone NJT 9: Latest Aalenian to Early Bajocian

Definition: Interval from the first occurrence of *Watznaueria britannica* to the first occurrence of *Watznaueria manivitae*.

Authors: Bown et al. (1988) emended by Mattioli and Erba (1999)

Remarks: Nannofossil recoveries in this interval are good and its diversity is moderate. Important species occurring in the zone are *Watznaueria britannica, W. contracta, W. fossacincta* (rare), *W. manivitae, Schizosphaerella punctulata, Carinolithus superbus* and *C. magherelii*. This interval has been identified in the Dhruma Formation in Well B.

Zone NJT 10: late Early Bajocian to Late Bajocian

Definition: Interval from the first occurrence of *Watznaueria manivitae* to the first occurrence of *Watznaueria barnesae*.

Authors: Mattioli and Erba (1999)

Remarks: This zone is subdivided into two subzones based on the LO of *Carinolithus superbus*.

Subzone NJT 10a: late Early Bajocian to early Late Bajocian

Definition: Interval from the first occurrence of *Watznaueria manivitae* to the last occurrence of *Carinolithus superbus*.

Authors: Mattioli and Erba (1999)

Remarks: Nannofossil recoveries of this interval are good and its diversity is moderate. Three nannofossil events are observed within the subzone; these are: (1) abundant nannofossil *Schizosphaerella punctulata*, which characterizes the subzone in onshore Kuwait; (2) the LO of *Diductius constans* was recorded in the lower part of this zone; and (3) influx of *Watznaueria manivitae*. Important species occurring in the zone are: *Biscutum novum, Carinolithus magharensis, Carinolithus superbus, Cyclocargelosphaera margarelii, Diductius constans, Discorhabdus criotus, D. striatus, Schizosphaerella punctulata, Watznaueria britannica, W. contracta, W. fossacincta* and *W. manivitae*. In the studied wells, the last occurrence of *Carinolithus superbus* is recorded in the Dhruma Formation in wells B and H.

Subzone NJT 10b: Late Bajocian

Definition: Ranges from the last occurrence of *Carinolithus superbus* to the FO of *Watznaueria barnesae*.

Authors: Mattioli and Erba (1999)

Remarks: Nannofossil recovery in the subzone is good and its diversity is moderate. The abundant co-occurrence of *W. britannica* and *W. manivitae* characterizes this interval in North Kuwait. There are four nannofossil events recorded within this interval: (1) a peak abundance of *Discorhabdus striatus*, an event that characterizes basal Late Bajocian nannofossil assemblages (de Kaenel et al., 1996), at the upper part of this interval; (2) abundant *Biscutum novum* occurs in the lower part of this zone; (3) LO *Discorhabdus criotus*; and (4) LO *Carinolithus magharensis* that can be used as an additional marker of this subzone. In the studied wells, the last occurrence of *Carinolithus magharensis* is recorded in the Dhruma Formation in wells A, B, C, G and H.

Zone NJT 11: Early Bathonian to Middle Bathonian

Definition: Covers the interval from first occurrence of *Watznaueria barnesae* to first occurrence of *Cyclagelosphaera wiedmannii*. In this study, the LO of *Carinolithus magharensis* can be used as an additional marker to identify the base of this zone and the FO of *Ansulasphaera helvetica* is used as an additional marker to identify the top of this zone.

Authors: Defined here, modified from Mattioli and Erba (1999)

Remarks: Nannofossil recoveries in this interval are few or barren as represented by most of the samples from the Sargelu Limestone, overlying the Sargelu-Dhruma Transition.

Zone NJT 12: Late Bathonian to Late Callovian

Definition: Ranges from first to last occurrences of *Cyclagelosphaera wiedmannii*. In this study the FO and LO of *Ansulasphaera helvetica* are used as additional markers.

Authors: Defined here, modified from Casselato (2010)
| Jurassic Stratigraphy, Onshore Kuwait |

| Stage | Series | Zone | Event | Sub-Stage | Zone Event |
|-------|--------|------|-------|-----------|------------|
| Tithonian | Lower Jurassic | Tithonian | L. crucicentralis + | | |
| | | | N. steimannii minor + | | |
| | | | S. bigoti maximum | | |
| | | | A. helvetica + | | |
| | | | A. helvetica* | | |
| | | | W. barnesae*, C. magharensis + | | |
| | | | W. manivitae* | | |
| | | | W. britannica* | | |
| | | | S. punctulata*, D. striatus*, W. contracta + | | |
| | | | C. superbus + | | |
| | | | C. margerelii* | | |
| | | | C. mexicana minor* | | |
| | | | W. manivitae (A), W. britannica (A) | | |
| | | | L. hauffii + | | |
| | | | C. deflandrei* | | |

Figure 10: Chronostratigraphic correlation of the Middle to Late Jurassic strata. See Figure 1 for locations.
Remarks: The FO of *A. helvetica* is slightly below the FO of *C. wiedmannii* (Mattioli and Erba, 1999) at the base of Zone NJT 12 (Bown and Cooper, 1998), and the LO of *A. helvetica* is slightly below the LO of *C. wiedmannii* (Casellato, 2010). Therefore, the age of the Zone NJT 12 of this study is slightly younger than the age of the Zone NJT 12 of Casellato (2010) (Figure 8). The nanno assemblage of the Zone NJT 12 comprises the most resistant species of genus *Watznaueria* such as *W. barnesae*, *W. britannica*, *W. fossacincta*, *W. manivitae* and *Cyclagelosphaera margerelii* as represented by nanno assemblages in the Lower and Upper Najmah Shales in Well K.

### Zone NJT 13: Oxfordian

**Definition:** Interval from last occurrence of *A. helvetica* to the beginning of the acme of genus *Watznaueria*.

**Authors:** Defined here, modified from Casellato (2010)

**Remarks:** The first occurrence of *C. deflandrei* is recorded within this interval and is used as an additional marker to subdivide the NJT 13 Zone into two subzones, e.g., the NJT 13a and NJT 13b Subzones.

### Subzone NJT 13a: Early Oxfordian

**Definition:** Interval from last occurrence of *A. helvetica* to first occurrence of *C. deflandrei*.

**Authors:** Defined here, modified from Casellato (2010)

**Assemblage:** The FO of *C. deflandrei* occurs slightly above the LO of *L. sigilatus* (Casellato, 2010). The middle part of this subzone is rich in *Watznaueria* spp., dominated by *Watznaueria britannica*, *W. manivitae*, and *Cyclagelosphaera margerelii*. *Watznaueria barnesae* is less common. This base of this interval occurs at the Upper Najmah Shale in Well K.

### Subzone NJT 13b: Middle Oxfordian to Late Oxfordian

**Definition:** Interval from first occurrence of *C. deflandrei* to first occurrence of acme genus *Watznaueria*.

**Authors:** Defined here, modified from Casellato (2010)

**Remarks:** Nannofossil recovery in this interval is few to common and the assemblages are made up of *Watznaueria barnesae*, *W. britannica*, *W. manivitae*, *Cyclagelosphaera deflandrei* and *C. margerelii*. This interval has been identified in the Upper Najmah Shale in wells B, C, G and I as well as in the Najmah Limestone in wells A, D, F, H and J.

### Zone NJT 14: Kimmeridgian to early Early Tithonian

**Definition:** Interval from first occurrence of acme genus *Watznaueria* to first occurrence of *Conusphaera mexicana minor*.

**Authors:** Defined here, modified from Casellato (2010)

**Remarks:** The assemblages are characterized by dominant *Watznaueria* particularly *Watznaueria britannica* and *W. manivitae* as well as *Cyclagelosphaera deflandrei* and *C. margerelii*. *Watznaueria barnesae* is less common. This assemblage that has been identified in the Jubaila Formation in wells E, F, G, I and K is similar to the Kimmeridgian nanno assemblages which are characterized by dominant *Watznaueria* which have been reported by Bown et al. (1998) and can be correlated with the Kimmeridgian *Cyclagelosphaera margerelii* Zone of Haq (1983). The overlying Gotnia-Hith Formations is barren of nannoflora. However, the top markers *Conusphaera mexicana minor* and *Conusphaera mexicana mexicana* were recorded in the Makhul Formation, which stratigraphically lies above the Hith Formation at the Ratqa Field (Varol Research, 1998, unpublished report).

### Zone CC1: Early Berriasian

**Definition:** Interval from first occurrence of *Nannoconus kamptneri* and *N. steinmannii* to first occurrence of *Retecapsa angustiforata*.

**Author:** Bergen (1994)

**Remarks:** The first occurrences of *Nannoconus kamptneri minor* and *N. steinmannii minor* have been widely used as a marker for placing the Tithonian-Berriasian and the Jurassic-Cretaceous boundary at the base of magneto zone M18r (Channell et al., 2010). The lower boundary of this zone was identified within the Makhul Formation in Minagish Field (Millennia, 2013, unpublished report).
STUDIED SECTIONS

Well A

A total 22 samples were analyzed from Well A spanning the Sargelu-Dhruma Transition to Gotnia Formation, and ages from late Early Bajocian to Kimmeridgian (Figures 1 and 10, Table 1).

Nannofossil recovery in the Sargelu-Dhruma Transition is good with moderate diversity. The assemblages comprise Carinolithus magharensis, Cyclocargelosphaera margerelii, Discorhabdus criotus, D. striatus, Watznaueria britannica, W. contracta and W. manivitae suggesting an age of Late Bajocian, Zone NJT 10b of Mattioli and Erba (1999).

Samples from the Sargelu Limestone are barren of nannofossils and the age is indeterminate. There is a 44-ft core gap between the Sargelu Formation and the Upper Najmah Shale unit.

The Upper Najmah Shale to the Najmah Limestone contains rare to common, long-ranging taxa Watznaueria britannica, W. manivitae and Cyclagelosphaera margerelii, but Anusulaehphaer a helvetica, Cyclagelosphaera deflandrei and other species markers are absent. On this basis only an age ranging from Bathonian to Oxfordian, corresponding to Zones NJT 11 of Mattioli and Erba (1999) to NJT 13 of Casselato (2010) can be interpreted.

Table 1: Distribution and species diversities of nannofossils in Well A.

| Series            | Stage / Substage | Nanno Zone | MFS      | Formation  | Core Depth (Feet) | Abundance |
|-------------------|------------------|------------|----------|------------|-------------------|-----------|
| Jurassic          | Indeterminate    | Barren     |          | Gotnia     | 15,683.00 B       |           |
|                   | Kimmeridgian     |            |          |            | 15,689.00 B       |           |
|                   | Jubaila          |            |          |            | 15,693.00 F       |           |
|                   |                  |            |          |            | 15,693.30 R       |           |
|                   | Najmah           |            |          | Limestone  | 15,699.30 F       |           |
|                   |                  |            |          |            | 15,706.00 F       |           |
|                   |                  |            |          |            | 15,734.00 A       |           |
|                   |                  |            |          |            | 15,742.00 C       |           |
|                   |                  |            |          |            | 15,750.00 C       |           |
|                   |                  |            |          |            | 15,758.00 C       |           |
|                   |                  |            |          |            | 15,766.00 C       |           |
|                   |                  |            |          |            | 15,774.00 B       |           |
|                   |                  |            |          |            | 15,781.00 R       |           |
|                   |                  |            |          |            | 15,789.00 R       |           |
|                   |                  |            |          |            | 15,796.00 R       |           |
| Jurassic          | Indeterminate    | Barren     |          | Gotnia     | 15,838.00 B       |           |
|                   |                  |            |          |            | 15,846.00 B       |           |
|                   |                  |            |          |            | 15,854.00 B       |           |
|                   | Late             | Barren     | 130      | Sargelu    | 15,862.00 C       |           |
|                   | Bajocian         |            |          |            | 15,878.00 A       |           |
|                   |                  |            |          |            | 15,886.00 A       |           |
|                   |                  |            |          |            | 15,890.00 A       |           |

CORE GAP

Distribution chart: A = abundant (more than 10 specimens in one FOV), C = common (more than 1 specimen and less than 10 specimens in one FOV, F = few (more than 1 and less than 10 in 10 FOV), R = rare (one or several specimens respectively, were recorded outside the standard 300 specimens count). These symbols are in lower case when specimens are thought to be reworked or contaminated. Abundance: A = abundant, C = common, F = few, R = rare. Time scale after the International Commission on Stratigraphy (2015) and Gradstein et al. (2012).
Nannofossil recovery in the Jubaila Formation is few and its diversity is low. Assemblages are dominated by *Watznaueria britannica*, *W. manivitae*, *W. barnesae* and *Cyclagelosphaera margerelii*, suggesting a Kimmeridgian age, possibly Zone NJT 14 of Casellato (2010).

**Well B**

Sampling of Well B yielded a total of 46 samples (Figures 1 and 10, Table 2) from the Dhruma Formation to the Upper Najmah Shale, ranging from Middle or Late Aalenian to Late Oxfordian. The Dhruma Formation is dated as Middle or Late Aalenian to early Late Bajocian, equivalent to Subzone 8c, Zone 9, Subzone NJT 10a and lower Subzone NJT 10b of Mattioli and Erba (1999), based on the occurrence of first occurrences (FO) *Watznaueria britannica*, FO *W. manivitae* and last occurrence (LO) *Carinolithus superbus*.

The Sargelu-Dhruma Transition section is dated as Late Bajocian, corresponding to upper Subzone NJT 10b based on the presence of *W. manivitae* and *Carinolithus magharensis* and the absence of *C. superbus*. The interval from the Sargelu Limestone up to the Lower Najmah Shale is barren of nannoflora and the age is therefore indeterminate.

Nannofossil recovery in the Upper Najmah Shale is few and the assemblages are made up of *Watznaueria barnesae*, *W. britannica*, *W. manivitae*, *Cyclagelosphaera deflandrei* and *C. margerelii*, indicating Middle to Late Oxfordian, Subzone NJT 13b.

**Well C**

Extensive sampling conducted in Well C yielded a total of 53 samples, covering the interval from the Dhruma to Najmah Limestone formations, and gave ages from late Early Bajocian to Late Oxfordian (Figures 1 and 10, Table 3).

The rich nannofossil assemblages recovered in the Dhruma yield abundant *Cyclagelosphaera margerelii*, *Discorhabdus striata*, *D. criotus*, *Watznaueria britannica*, *W. contracta* and *W. manivitae*, allowing age assignment to late Early Bajocian to early Late Bajocian, Zone NJT 10a.

The upper part of the Sargelu-Dhruma Transition contains common to abundant nannofossils dominated by *Watznaueria britannica*, *W. contracta* and *W. manivitae* and the absence of *Watznaueria barnesae*. It suggests a Late Bajocian age, possibly corresponding to a horizon near the top of Subzone NJT 10b of Mattioli and Erba (1999).

Samples from the Sargelu Limestone to Najmah-Sargelu Transition are barren and the ages are, therefore, indeterminate.

Nannofossil recovery in the Lower Najmah Shale is few and the assemblages contain *Watznaueria barnesae*, *W. britannica*, *W. manivitae* and *Cyclagelosphaera margerelii*, but lack *Ansulasphaera helvetica*, indicating that the age ranges from Bathonian to Lower Oxfordian. *Cyclagelosphaera deflandrei* occurs in the Upper Najmah Shale suggesting a Middle Oxfordian, Zone NJT 13b or younger age. The Najmah Limestone is barren of nannofossils and its age is therefore indeterminate.

**Well D**

A total 25 samples were analyzed from Well D, covering the Sargelu to Jubaila formations, and gave ages from Bathonian to Kimmeridgian (Figures 1 and 10, Table 4). The Sargelu Formation is barren and its age is indeterminate. Nannofossil recovery from the top of the Najmah-Sargelu Transition to the Lower Najmah Shale is common with low diversity. The nannofossil assemblages consist of *Watznaueria barnesae*, *W. britannica*, *W. manivitae*, and *C. margerelii*, but *Ansulasphaera helvetica*, *Cyclagelosphaera deflandrei* and other marker species are absent suggesting an age ranging from Bathonian to Early Oxfordian, corresponding to Zones NJT 11 of Mattioli and Erba (1999) to NJT 13a of Casselato (2010).
Table 2: Distribution and species diversities of nannofossils in Well B (see Table 1 for explanation of symbols).

| Series                      | Stage / Substage | Zone                  | Core Depth (Feet) | Abundance | Axopodorhabdus abius | Axopodorhabdus cylindratus | Biscutum dubium | Biscutum novum | Bussonius prinsii | Carinolithus magharensis | Carinolithus superbus | Cyclagelosphaera deflandrei | Cyclagelosphaera margerelii | Cicatricosis glumacea | Didemnum minutum | Discorhabdus criotus | Discorhabdus striatus | Ethmorhabdus gallicus | Ethmorhabdus gracilis | Ethmorhabdus latescalus | Ethmorhabdus ocellatus | Ethmorhabdus oscallus | Ethmorhabdus squamis | Ethmorhabdus triqueter | Juracapsa spp. | Lotharingius crucicentralis | Podorhabdus grassei | Polypodorhabdus escaigii | Polypodorhabdus inconstans | Schizocapsa punctulata | Schizocapsa punctulata | Schizosphaerella punctulata | Tribiscutum spp. | Watznaueria barnesae | Watznaueria britannica | Watznaueria contracta | Watznaueria fossacincta | Watznaueria manivitae | Zeugrhabdotus erectus |
|-----------------------------|------------------|-----------------------|-------------------|-----------|----------------------|----------------------------|------------------|----------------|------------------|-----------------------------|--------------------------|--------------------------------|-----------------------------|--------------------------|----------------|-----------------|----------------|-------------------|------------------------|-----------------------------|------------------------|-----------------------------|------------------|-----------------|-----------------|-----------------|----------------|-----------------|----------------|------------------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Series | Stage / Substage | Nannofossil Zone | MFS | Formation | Core Depth (Feet) | Abundance - Preservation |
|--------|------------------|-----------------|-----|-----------|------------------|-------------------------|
|        | Barren           | J30              |     | Najmah Limestone | 13,620.00 B       | B                       |
|        |                  |                 |     | NJT 11–13a | 13,628.00 B       | B                       |
|        |                  |                 |     | NJT 10b    | 13,632.00 B       | B                       |
|        |                  |                 |     | Sargelu    | 13,636.00 B       | B                       |
|        |                  |                 |     | Sargelu-Dhuma Transition | 13,639.00 B | B |
|        |                  |                 |     | NJT 10a    | 13,644.00 B       | B                       |
|        |                  |                 |     | NJT 13b    | 13,648.00 A       | B                       |
|        |                  |                 |     |            | 13,651.00 A       | C                       |
|        |                  |                 |     |            | 13,656.00 C       | C                       |
|        |                  |                 |     |            | 13,660.00 C       | C                       |
|        |                  |                 |     |            | 13,664.00 A       | B                       |
|        |                  |                 |     |            | 13,668.00 A       | B                       |
|        |                  |                 |     |            | 13,670.00 B       | B                       |
|        |                  |                 |     |            | 13,674.00 A       | B                       |
|        |                  |                 |     |            | 13,682.00 A       | C                       |
|        |                  |                 |     |            | 13,686.00 F       | F                       |
|        |                  |                 |     |            | 13,690.00 F       | F                       |
|        |                  |                 |     |            | 13,696.00 B       | B                       |
|        |                  |                 |     |            | 13,702.00 F       | F                       |
|        |                  |                 |     |            | 13,705.00 B       | B                       |
|        |                  |                 |     |            | 13,710.00 B       | B                       |
|        |                  |                 |     |            | 13,714.00 F       | R                       |
|        |                  |                 |     |            | 13,718.00 C       | R                       |
|        |                  |                 |     |            | 13,722.00 B       | B                       |
|        |                  |                 |     |            | 13,726.00 B       | B                       |
|        |                  |                 |     |            | 13,730.00 B       | B                       |
|        |                  |                 |     |            | 13,734.00 B       | B                       |
|        |                  |                 |     |            | 13,738.00 B       | B                       |
|        |                  |                 |     |            | 13,742.00 B       | B                       |
|        |                  |                 |     |            | 13,746.00 B       | B                       |
|        |                  |                 |     |            | 13,750.00 B       | B                       |
|        |                  |                 |     |            | 13,754.00 B       | B                       |
|        |                  |                 |     |            | 13,758.00 B       | B                       |
|        |                  |                 |     |            | 13,760.00 B       | B                       |
|        |                  |                 |     |            | 13,766.00 B       | B                       |
|        |                  |                 |     |            | 13,770.00 B       | B                       |
|        |                  |                 |     |            | 13,774.00 A       | F                       |
|        |                  |                 |     |            | 13,778.00 A       | F                       |
|        |                  |                 |     |            | 13,780.00 C       | A                       |
|        |                  |                 |     |            | 13,786.00 F       | A                       |
|        |                  |                 |     |            | 13,790.00 F       | A                       |
|        |                  |                 |     |            | 13,794.00 R       | F                       |
|        |                  |                 |     |            | 13,797.00 F       | A                       |
|        |                  |                 |     |            | 13,804.00 A       | C                       |
|        |                  |                 |     |            | 13,808.00 A       | C                       |
|        |                  |                 |     |            | 13,812.00 A       | C                       |
|        |                  |                 |     |            | 13,816.00 A       | A                       |
|        |                  |                 |     |            | 13,820.00 A       | A                       |
|        |                  |                 |     |            | 13,823.00 A       | A                       |
|        |                  |                 |     |            | 13,828.00 B       | A                       |
|        |                  |                 |     |            | 13,836.00 A       | A                       |

Table 3: Distribution and species diversities of nannofossils in Well C (see Table 1 for explanation of symbols).
Jurassic stratigraphy, onshore Kuwait

Cyclagelosphaera deflandrei, recorded in the Upper Najmah Shale, indicates Middle Oxfordian age, Zone NJT 13b of Casellato (2010) or younger. Nannoflora recovery in the Najmah Limestone is very few and its age is indeterminate. Recovery of abundant Watznaueria manivitae and W. britannica from the Jubaila Formation suggests a Kimmeridgian age, possibly Zone NJT 14 of Casellato (2010).

Well E

A total 61 samples were analyzed from Well E, which represent the Dhurma to Jubaila formations and indicate a late Early Bajocian to Kimmeridgian age (Figures 1 and 10, Table 5). Nannofossil recovery from the Dhurma Formation and Sargelu-Dhruma Transition is good but its diversity is low. Age is Early to Late Bajocian, Zone NJT 10 of Mattioli and Erba (1999), based on the FO of W. manivitae and the LO of Discorhabdus striatus. Samples from the Sargelu Limestone to the lower part of the Upper Najmah Shale are barren of nannofossils and ages are indeterminate.

Nannofossil content of the Upper Najmah Shale is few to abundant, with long-ranging nannofossil taxa. The nannofossil assemblages consist of Watznaueria barnesae, W. britannica, W. manivitae and Cyclagelosphaera margerelii suggesting an age ranging from Bathonian to Oxfordian, corresponding to Zones NJT 11 of Mattioli and Erba (1999) to NJT 13 of Casellato (2010). Samples from Najmah Limestone are barren of nannofossils and ages are therefore indeterminate.
Table 5: Distribution and species diversities of nannofossils in Well E (see Table 1 for explanation of symbols).

| Series          | Stage / Substage | Nannofossil Zone | MFS | Formation | Core Depth (Feet) | Abundance - Preservation |
|-----------------|------------------|------------------|-----|-----------|------------------|--------------------------|
| Late Jurassic   | Kimmeridgian     | N J T 14         | Juba | Jubaila   | 15,508.00 A A A A | 15,508.50 A A A A |
|                 |                  |                  |     |           | 15,510.50 A C C C | 15,512.50 A C C C |
|                 | Indeterminate    |                  |     |           | 15,530.00 A A A A | 15,531.50 A A A A |
|                 |                  |                  |     |           | 15,537.00 B B B B | 15,541.00 B B B B |
|                 | Barren           |                  |     |           | 15,550.00 B B B B | 15,554.00 B B B B |
|                 |                  |                  |     |           | 15,558.00 B B B B | 15,562.00 B B B B |
| Middle to Late Jurassic | Najmah Limestone | J 50             |     |           | 15,560.00 A F A A | 15,566.00 A A A A |
|                 | Jennifer         | Najmah           |     |           | 15,570.00 B B B B | 15,576.00 B B B B |
|                 |                  |                  |     |           | 15,575.50 A A A A | 15,582.00 C C C C |
|                 |                  |                  |     |           | 15,586.00 C C C C | 15,590.00 C C C C |
|                 | Bajocian         | Najmah Limestone |     |           | 15,606.00 B B B B | 15,610.00 B B B B |
|                 |                  |                  |     |           | 15,615.50 B B B B | 15,619.50 B B B B |
|                 |                  |                  |     |           | 15,621.50 B B B B | 15,628.00 B B B B |
|                 |                  |                  |     |           | 15,632.00 B B B B | 15,637.50 B B B B |
|                 |                  |                  |     |           | 15,634.50 B B B B | 15,645.00 B B B B |
|                 |                  |                  |     |           | 15,644.50 B B B B | 15,650.00 B B B B |
|                 | Jennifer         | Najmah Limestone |     |           | 15,654.80 B B B B | 15,664.80 B B B B |
|                 |                  |                  |     |           | 15,658.00 B B B B | 15,678.00 B B B B |
|                 |                  |                  |     |           | 15,663.00 B B B B | 15,675.80 B B B B |
|                 |                  |                  |     |           | 15,675.80 B B B B | 15,690.00 B B B B |
|                 | N-S Transition   |                  |     |           | 15,680.00 B B B B | 15,686.80 B B B B |
|                 |                  |                  |     |           | 15,684.00 B B B B | 15,692.00 B B B B |
|                 | Barren to Sparse |                  |     |           | 15,696.80 B B B B | 15,704.75 B B B B |
|                 | Sargelu          |                  |     |           | 15,704.75 B B B B | 15,708.80 B B B B |
|                 |                  |                  |     |           | 15,712.90 B B B B | 15,721.00 A A A A |
|                 |                  |                  |     |           | 15,720.20 F F F F | 15,724.00 C C C C |
|                 |                  |                  |     |           | 15,728.00 R R R R | 15,731.50 R R R R |
|                 |                  |                  |     |           | 15,736.00 R R R R | 15,741.00 F F F F |
|                 | N-S Transition   |                  |     |           | 15,743.00 A A A A | 15,748.00 A A A A |
|                 |                  |                  |     |           | 15,751.00 A A A A | 15,754.00 A A A A |
|                 |                  |                  |     |           | 15,755.00 A A A A | 15,759.00 A A A A |
Nannofossil recovery in the Jubaila Formation is good but its diversity is low. Assemblages are dominated by *Watznaueria barnesae*, *W. britannica*, *W. manivitae*, and *Cyclagelosphaera margerelii*, suggesting a Kimmeridgian age, possibly corresponding to Zone NJT 14 of Casellato (2010). The stratigraphic position of this sample is just above the pre-Jubaila unconformity, separating the Jubaila Formation from the underlying Najmah Limestone.

**Well F**

A total 35 samples were analyzed from Well F, representing the Sargelu-Dhruma Transition, to the Jubaila Formation (Figures 1 and 10, Table 6). These samples are Late Bajocian to Kimmeridgian in age. The samples from the Sargelu-Dhruma Transition are likely Late Bajocian, corresponding to Zone NJT 10, based on the presence of nanno species *Watznaueria manivitae* and *W. britannica*, and by the absence of *W. barnesae*. Samples from the Sargelu are barren of nannofossils.

**Table 6: Distribution and species diversities of nannofossils in Well F** (see Table 1 for explanation of symbols).

| Series            | Stage / Substage | Nanno Zone | MFS | Formation | Core Depth (Feet) | Abundance |
|-------------------|------------------|------------|-----|-----------|-------------------|-----------|
| Late Jurassic     | Indeterminate    | Barren     | 151 | Gotnia    | 14,615.00 B      |           |
|                   |                  |            |     | Jubaila   | 14,619.00 B      |           |
|                   |                  |            |     |           | 14,620.00 B      |           |
|                   | Kimeridgian      | NJT 14     | j 60| Najmah    | 14,622.00 F F r  | F R       |
|                   |                  | Limestone  |     |           | 14,624.00 A A r  | F A A     |
|                   |                  |            |     |           | 14,627.00 B      |           |
|                   |                  |            |     |           | 14,635.00 A R r  | F A       |
|                   |                  |            |     |           | 14,641.00 C r    | F C       |
|                   |                  |            |     |           | 14,651.00 B      |           |
|                   |                  |            |     |           | 14,658.00 F f r  | F R       |
|                   | Middle Jurassic  | NJT 11−13  | j 50| Upper     | 14,669.00 A F f  | F A C     |
|                   |                  |            |     | Najmah    | 14,677.00 A C    | A F       |
|                   |                  |            |     | Shale     | 14,687.00 A A    | A A       |
|                   |                   |            |     |           | 14,703.00 C C    |           |
|                   |                   |            |     |           | 14,711.00 A C    | C C       |
|                   |                   |            |     |           | 14,719.00 A C    | A A       |
|                   |                   |            |     |           | 14,727.00 A A    | F C       |
|                   |                   |            |     |           | 14,735.00 C C    |           |
|                   |                   |            |     |           | 14,747.00 C C    |           |
|                   |                   |            |     |           | 14,753.00 C R    | C         |
|                   |                   |            |     |           | 14,761.00 B      |           |
|                   |                   |            |     |           | 14,776.00 B      |           |
|                   |                   |            |     |           | 14,784.00 B      |           |
|                   |                   |            |     |           | 14,793.00 B R    |           |
|                   | Middle Jurassic   | NJT 10     | j 30| Sargelu   | 14,800.00 R R    |           |
|                   |                  |            |     |           | 14,803.00 L C    |           |
|                   |                  |            |     |           | 14,807.00 L F    |           |
|                   |                  |            |     |           | 14,810.00 A L    |           |
|                   |                  |            |     |           | 14,814.00 A F    |           |
|                   |                  |            |     |           | 14,818.00 A C    |           |
|                   |                  |            |     |           | 14,822.00 A F    |           |
|                   |                  |            |     |           | 14,826.70 F      |           |
Nannofossil abundance in the Najmah-Sargelu Transition, Lower and Upper Najmah Shale and Najmah Limestone is common to abundant. The assemblages are comprised of long-ranging *Watznaueria barnesae*, *W. britannica*, *W. manivitae* and *Cyclagelosphaera margerelii*, but *Ansulasphaera helvetica*, *Cyclagelosphaera deflandrei* and other marker species are absent. On this basis, only an age ranging from Bathonian to Oxfordian, corresponding to Zones NJT 11 of Mattioli and Erba (1999) to NJT 13 of Casselato (2010), can be suggested.

The Jubaila Formation contains few to extremely abundant nannofossils, dominated by *Watznaueria manivitae*, *W. britannica* and *Cyclagelosphaera margerelii*. We infer that the samples above the pre-Jubaila unconformity are Kimmeridgian in age, corresponding to Zone NJT 14 of Casellato (2010). The evaporitic Gotnia Formation, however, is barren of nannofossils.

**Well G**

A total 50 samples were analyzed from Well G, representing the Sargelu-Dhruma Transition to the Jubaila Formation (Figures 1 and 10, Table 7). The samples are Late Bajocian to Kimmeridgian in age. The Sargelu-Dhruma Transition is dated as Late Bajocian, corresponding to Subzone NJT 10b based on the presence of *W. manivitae* and *Carinolithus magharensis* and the absence of *C. superbus*. Samples from the Sargelu Limestone to Najmah-Sargelu Transition are nearly barren of nannofossils and their age is indeterminate.

Nannofossil recovery in the Lower Najmah Shale is common to abundant. The nannofossil assemblages consist of *Watznaueria barnesae*, *W. britannica*, *W. manivitae* and *Cyclagelosphaera margerelii*, suggesting an age ranging from Bathonian to Early Oxfordian, corresponding to Zones NJT 11 of Mattioli and Erba (1999) to NJT 13 of Casselato (2010). There is a 34-foot core gap between the Lower Najmah Shale and Upper Najmah Shale.

The marker species *C. deflandrei* occurs in the Upper Najmah Shale, suggesting Middle to Late Oxfordian, Zone NJT 13b of Mattioli and Erba (1999). Most samples from the Najmah Limestone are barren of nannofossils.

Samples from the Jubaila Formation are mostly barren except the basal portion, which contains abundant nannofossils. It is dominated by *Watznaueria manivitae* and *W. britannica*, suggesting a Kimmeridgian age, possibly Zone NJT 14. The stratigraphic position of this sample is right above the base of the Jubaila Formation.

**Well H**

A total 39 samples were analyzed from Well H, all belonging to the Dhruma, Sargelu, Najmah and Jubaila formations (Figures 1 and 10, Table 8). Age of the samples is late Early Bajocian to probable Kimmeridgian. The Dhruma Formation is dated as late Early Bajocian to early Late Bajocian, corresponding to Subzone NJT 10a, based on the presence of zonal marker *C. superbus*.

The Sargelu-Dhruma Transition is dated as Late Bajocian and is assigned to Subzone NJT 10b, based on marker species *Carinolithus magharensis*, *Watznaueria britannica* and *W. manivitae*. Nannofossil content of the Sargelu Limestone up to the lower part of Upper Najmah Shale is few. Most of the samples are barren of nannofossils and age is indeterminate.

Nannofloral recovery in the upper part of the Upper Najmah Shale to the Najmah Limestone is rare to abundant with low diversity. The assemblages are comprised of *Watznaueria britannica*, *W. manivitae* and *W. barnesae*, suggesting an age ranging from Bathonian to Oxfordian, corresponding to Zones NJT 11 of Mattioli and Erba (1999) to NJT 13 of Casellato (2010). The Jubaila Formation is barren of nannofossils and its age could not be determined.
### Table 7: Distribution and species diversities of nannofossils in Well G
(see Table 1 for explanation of symbols).

| Series     | Stage / Substage | Nanno Zone | MFS | Formation         | Core Depth (Feet) | Abundance | Cannatius meghemaensis | Cyclagelosphaera deflectens | Cyclagelosphaera margaritae | Dicellobates cretaceus | Schizosphaerella punctula | Watznaueria barnesae | Watznaueria britannica | Watznaueria contracta | Watznaueria fossacincta | Watznaueria manivitae | Velasquezia minuta | Didemnid ascidian |
|------------|------------------|------------|-----|-------------------|-------------------|-----------|------------------------|----------------------------|----------------------------|------------------|---------------------|-----------------|----------------------|-------------------|----------------------|---------------------|----------------|------------------|
| Late Jurassic | Kimmeridgian      | Barren     |      | Gotnia - Jubbaila | 13,914.00         | B         |                        |                            |                            |                  |                     |                 |                      |                   |                     |                     |                |                  |
|             | Middle to Late Oxfordian | Barren, except in the lower part (C) and at the top part (A) | J30 |                       | 13,953.00         | B         |                        |                            |                            |                  |                     |                 |                      |                   |                     |                     |                |                  |
|             |                  |            |      | Upper Najmah Shale  | NJT 13b           | NO CORE    |                        |                            |                            |                  |                     |                 |                      |                   |                     |                     |                |                  |
| Late Jurassic | Bathonian to Oxfordian |                |      | Lower Najmah Shale | NJT 11-13       | 14,047.00  | C                      | C                           | F                           | C                |                     |                 |                      |                   |                     |                     |                |                  |
|             | Middle to Late Jurassic |                |      | Najmah-Sargelu Transition | 14,051.00       | A          | ?                      | F                           | A                           | A                |                     |                 |                      |                   |                     |                     |                |                  |
|             |                  |                |      | Sargelu            | J30              | 14,059.00  | F                      | C                           | F                           | C                |                     |                 |                      |                   |                     |                     |                |                  |
| Middle Jurassic | Late Bajocian |                |      | Sargelu-Dhurma Transition | 14,115.00       | B          | F                      |                             |                             | F                |                     |                 |                      |                   |                     |                     |                |                  |
|             |                  |                |      |                  |                  | 14,123.00  | A                      | F                           | F                           | F                |                     |                 |                      |                   |                     |                     |                |                  |
|             |                  |                |      |                  |                  | 14,127.00  | B                      | F                           | F                           | F                |                     |                 |                      |                   |                     |                     |                |                  |
|             |                  |                |      |                  |                  | 14,131.00  | B                      | F                           | F                           | F                |                     |                 |                      |                   |                     |                     |                |                  |
|             |                  |                |      |                  |                  | 14,135.00  | B                      | F                           | F                           | F                |                     |                 |                      |                   |                     |                     |                |                  |
|             |                  |                |      |                  |                  | 14,139.00  | B                      | F                           | F                           | F                |                     |                 |                      |                   |                     |                     |                |                  |
|             |                  |                |      |                  |                  | 14,143.00  | F                      |                             |                             | F                |                     |                 |                      |                   |                     |                     |                |                  |
|             |                  |                |      |                  |                  | 14,147.00  | A                      | F                           | F                           | F                |                     |                 |                      |                   |                     |                     |                |                  |
|             |                  |                |      |                  |                  | 14,151.00  | F                      |                             |                             | F                |                     |                 |                      |                   |                     |                     |                |                  |
|             |                  |                |      |                  |                  | 14,155.00  | C                      | R                           | F                           | F                |                     |                 |                      |                   |                     |                     |                |                  |
|             |                  |                |      |                  |                  | 14,159.00  | C                      | F                           | F                           | F                |                     |                 |                      |                   |                     |                     |                |                  |
|             |                  |                |      |                  |                  | 14,163.00  | A                      | F                           | F                           | F                |                     |                 |                      |                   |                     |                     |                |                  |
Table 8: Distribution and species diversities of nannofossils in Well H
(see Table 1 for explanation of symbols).

| Series | Stage / Substage | Nannofossil Zone | MFS | Formation | Core Depth (Feet) | Abundance |
|--------|------------------|------------------|-----|-----------|------------------|-----------|
|        |                  |                  |     |           |                  | Anoplanes infaustus |
|        |                  |                  |     |           |                  | Asteroides cylindricus |
|        |                  |                  |     |           |                  | Baculites novus |
|        |                  |                  |     |           |                  | Cnelolithus magnificus |
|        |                  |                  |     |           |                  | Cylindrospira defracta |
|        |                  |                  |     |           |                  | Cylindrospira truncata |
|        |                  |                  |     |           |                  | Deuterophragmium cretace |
|        |                  |                  |     |           |                  | Döbremites sp |
|        |                  |                  |     |           |                  | Klostera cf. |
|        |                  |                  |     |           |                  | Podorhabdites grassei |
|        |                  |                  |     |           |                  | Rucinolithus wisei |
|        |                  |                  |     |           |                  | Watznaueria barnesae |
|        |                  |                  |     |           |                  | Watznaueria bayackii |
|        |                  |                  |     |           |                  | Watznaueria britannica |
|        |                  |                  |     |           |                  | Watznaueria contracta |
|        |                  |                  |     |           |                  | Watznaueria manivitae |

**Series**: Barren to Abundant

**Stage / Substage**: Middle Callovian to Upper Oxfordian

**Nannofossil Zone**: Barren

**MFS**: Lower Najmah Shale

**Formation**: Barren to Abundant

**Core Depth**: 15,103.00 B, 15,115.00 F R, 15,118.00 B, 15,123.00 B, 15,125.60 F R r r, 15,135.00 F R, 15,142.00 A F, 15,146.20 B, 15,154.60 F R C, 15,164.50 A F A, 15,172.50 A A F, 15,184.00 C C, 15,191.80 C C, 15,197.00 B, 15,204.00 B, 15,213.60 B, 15,222.60 B, 15,231.60 B, 15,238.60 B, 15,247.60 B, 15,255.60 B, 15,262.60 B, 15,269.60 B, 15,277.00 B, 15,287.60 B, 15,294.60 B, 15,302.60 B, 15,309.60 C C R R, 15,316.00 A R A C, 15,326.60 B, 15,333.60 A F F A A F, 15,343.60 A F F F A F C C, 15,349.00 A F F A R F C C, 15,354.60 A F R A F C A C C C R C F F, 15,359.60 F R R F R F, 15,361.00 A F R R ? A F A, 15,366.60 A R C C C C C, 15,371.00 A F F F A A R F ? F A, 15,373.00 C F C ? C C R C R C A.
Well I

Twenty-seven samples were analyzed from Well I, belonging to the Najmah-Sargelu Transition to Jubaila formations (Figures 1 and 10, Table 9). The samples are Bathonian to Kimmeridgian in age. Samples from the uppermost part of the Najmah-Sargelu Transition and lower part of Lower Najmah Shale are barren and their age could not be determined. Nannofossil recovery in the Lower Najmah Shale to Upper Najmah Shale is few to common and the assemblages contain *Watznaueria barnesae*, *W. britannica*, *W. manivitae* and *Cyclagelosphaera margerelii*, indicating an age ranging from Bathonian to Lower Oxfordian, corresponding to Zones NJT 11 of Mattioli and Erba (1999) to NJT 13 of Casellato (2010).

The marker species *C. deflandrei* occurs in the upper part of the Upper Najmah Shale and Najmah Limestone, suggesting an age not older than Middle Oxfordian, Subzone NJT 13b of Casellato (2010). Samples from the Jubaila Formation contain abundant nannofossils, dominated by *Watznaueria manivitae* and *W. britannica*, suggesting a Kimmeridgian age, possibly Zone NJT 14. The stratigraphic position of this sample is right above the base of the Jubaila Formation.

Table 9: Distribution and species diversities of nannofossils in Well I (see Table 1 for explanation of symbols).

| Series                      | Stage / Substage | Nanno Zone | MFS | Formation | Core Depth (Feet) | Abundance |
|-----------------------------|------------------|------------|-----|-----------|-------------------|-----------|
| Jurassic                    |                  |            |     |           |                   | 15,719.00 | A   |
|                             |                  |            |     |           |                   | 15,729.00 | A   |
|                             |                  |            |     |           |                   | 15,739.00 | A   |
|                             |                  |            |     |           |                   | 15,747.50 | A   |
|                             |                  |            |     |           |                   | 15,749.00 | C   |
|                             |                  |            |     |           |                   | 15,759.00 | B   |
|                             |                  |            |     |           |                   | 15,760.00 | C   |
|                             |                  |            |     |           |                   | 15,768.00 | B   |
|                             |                  |            |     |           |                   | 15,780.00 | r   |
|                             |                  |            |     |           |                   | 15,791.00 | A   |
|                             |                  |            |     |           |                   | 15,800.00 | C   |
|                             |                  |            |     |           |                   | 15,808.00 | F   |
|                             |                  |            |     |           |                   | 15,822.00 | A   |
|                             |                  |            |     |           |                   | 15,832.00 | B   |
|                             |                  |            |     |           |                   | 15,844.00 | C   |
|                             |                  |            |     |           |                   | 15,854.00 | C   |
|                             |                  |            |     |           |                   | 15,864.00 | C   |
|                             |                  |            |     |           |                   | 15,874.00 | C   |
|                             |                  |            |     |           |                   | 15,884.00 | R   |
|                             |                  |            |     |           |                   | 15,894.00 | C   |
|                             |                  |            |     |           |                   | 15,903.00 | C   |
|                             |                  |            |     |           |                   | 15,913.00 | C   |
|                             |                  |            |     |           |                   | 15,921.00 | B   |
|                             |                  |            |     |           |                   | 15,934.00 | F   |
|                             |                  |            |     |           |                   | 15,948.00 | C   |
|                             |                  |            |     |           |                   | 15,960.00 | B   |
|                             |                  |            |     |           |                   | 15,970.00 | B   |
Well J

A total of 24 samples were analyzed from Well J; these were assigned to the Sargelu and Najmah formations (Figures 1 and 10, Table 10). Samples from the Sargelu Limestone are barren of nannofossils and the age is indeterminate. The middle part of the Najmah Shale contains abundant assemblages such as *Watznaueria barnesae*, *W. britannica*, *W. manivitae*, *Cyclagelosphaera margerelii* and rare *Lotharingius hauffii*. Casellato (2010) recorded the LO of *L. hauffii* as Late Oxfordian, slightly above the Middle/Late Oxfordian boundary. The Najmah Limestone is nearly barren of nannofossils.

Well K

Twenty-six samples were analyzed from Well K, assigned to the Sargelu to Jubaila formations, suggesting a Late Bathonian to Kimmeridgian age, Zone NJT 12 to Zone NJT 13b of Casellato (2010) (Figures 1 and 10, Table 11). Samples from the Sargelu Limestone to Lower Najmah Shale are barren of nannofossils and the age is indeterminate. The index species *A. helvetica* occurs in the upper part of the Lower Najmah Shale to the lower part of the Upper Najmah Shale suggesting a Late Bathonian to Callovian age, equivalent to Zone NJT 12.

Nannofossil recovery in the upper part of the Upper Najmah Shale is rare to abundant, dominated by *Watznaueria barnesae*, *W. britannica* and *Cyclagelosphaera margerelii* and the absence of *A. helvetica* indicating an Oxfordian age, Zone NJT 13. Most of the samples from the Najmah Limestone are barren of nannofossils and the age is indeterminate.

Table 10: Distribution and species diversities of nannofossils in Well J

(see Table 1 for explanation of symbols).

| Series                  | Stage / Substage | Nannofossil Zone | MFS | Formation         | Core Depth (Feet) | Abundance      | *Cyclagelosphaera margerelii* | *Lotharingius hauffii* | *Tribiscutum beaminster* | *Watznaueria barnesae* | *Watznaueria britannica* | *Watznaueria manivitae* |
|-------------------------|------------------|------------------|-----|-------------------|-------------------|----------------|-----------------------------|------------------------|------------------------|-------------------------|--------------------------|-------------------------|
| Indeterminate           | Indeterminate    | Barren to Sparse | J50 | Najmah Limestone  | 11,899.00         | B              |                             |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 11,908.00         | F F             |                             |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 11,925.00         | B               |                             |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 11,940.00         | A F             | A C C                       |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 11,960.00         | F               | F                           |                        |                        |                         |                          |                         |
| Middle to Late Jurassic | Bathonian to      | NJT 11–13        | J40 | Upper Najmah Shale| 11,993.00         | B               |                             |                        |                        |                         |                          |                         |
|                         | Oxfordian        |                  |     |                   | 12,015.00         | C               | C R                         |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 12,041.00         | A F             | A F A                       |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 12,050.00         | A F             | A C A                       |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 12,069.00         | A F             | A A R                       |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 12,076.00         | A C F R         | A A A                       |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 12,090.00         | A A R           | A A A                       |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 12,101.00         | C F R           | R C F                       |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 12,112.00         | C L              |                             |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 12,122.00         | R                | R                           |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 12,138.00         | A F R            | A A F F                     |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 12,156.00         | B                |                             |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 12,183.00         | B                |                             |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 12,225.00         | B                |                             |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 12,245.00         | B                |                             |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 12,254.00         | B                |                             |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 12,257.00         | B                |                             |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 12,265.00         | B                |                             |                        |                        |                         |                          |                         |
|                         |                  |                  |     |                   | 12,277.00         | B                |                             |                        |                        |                         |                          |                         |

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The samples from the Jubaila Formation yield abundant nannofossils, dominated by Watznaueria barnesae, W. britannica and W. manivitae, suggesting a Kimmeridgian age, possibly Zone NJT 14. The stratigraphic positions of these samples are right above the pre-Jubaila unconformity, separating the Jubaila Formation above, from the Najmah Limestone below.

**AGE OF THE STUDIED ROCK UNITS**

Al-Sahlan (2005) published a short Letter to the Editor summarizing preliminary biostratigraphic and strontium-isotope data from analyses by Varol Research (1996, 1997, 1998, unpublished reports), ExxonMobil (1998, unpublished report) and Fugro-Robertson (2004, unpublished report). She converted strontium ages (Ma) to biostratigraphic, or biostratigraphy to ages, using the Geological Time Scale GTS 2004 (Gradstein et al., 2004). She showed the age interpretations derived from samples taken from various wells using the formation names of Yousif and Nouman (1997) in Minagish-27 Well.

Al-Moraikhi et al. (2014) published an extended abstract, which reported the ages of the Late Triassic and Jurassic formations and units in Kuwait. The names that they used are here reconciled with those that are currently practiced in KOC. Their study integrated the results obtained from calcareous nannofossils, palynology and strontium-isotope data. In the following discussion we first summarize the age interpretations of Al-Sahlan (2005) and Al-Moraikhi et al. (2014) for each formation, and then present our age interpretations.
Minjur Formation: Late Triassic (Norian–Rhaetian) and Early Jurassic (Hettangian–?Sinemurian)

The Minjur Formation is divided into the informal Upper, Middle and Lower members. Al-Moraikhi et al. (2014) reported that the Minjur Formation yielded palynological associations of Late Triassic age. In contrast, Fugro-Robertson (2000, unpublished report) reported that palynological data from a Burgan well suggests that the entire Upper Minjur Member, and possibly the upper part of the Middle Minjur Member are of Early Jurassic age (Hettangian or possibly Sinemurian age). The remainder of the Minjur Formation yields rich palynoflora of Late Triassic (Rhaetian–Norian) age. The transition between Minjur and Marrat formations has not yet been seen in core, but it is inferred from electrical logs at the top of the Minjur Formation as indicated in Figure 3 in Minagish-27 Well. Fugro-Robertson (2000, unpublished report) precludes the recognition of any intraformational hiatus in the Middle Minjur Member.

Marrat Formation: Late Sinemurian–Early or Middle Aalenian

The Marrat Formation is barren of nannofossils, and the following reports are taken from Al-Al-Sahlan (2005), Fugro-Robertson (2009, 2010, unpublished reports), and Al-Moraikhi et al. (2014).

The age of the Lower Marrat Member (Figure 3) is interpreted as Late Sinemurian–Early Toarcian based on the following evidence. The top of the Lower Marrat Member is Early Toarcian based on the common recovery of Nannoceratopsis triceras (Al-Sahlan, 2005). Strontium-isotope analyses from the Lower Marrat Member in the Umm Niqa Field indicate a Sinemurian age (ca. 194 Ma, Fugro-Robertson, 2009, unpublished report). Al-Sahlan (2005) independently suggested that the formation could be as old as Late Sinemurian based on the presence of the common to abundant foraminifera Amijiella amiji. It is most frequently found in the Upper Sinemurian–Pliensbachian, and can range as young as Late Bajocian (Whittaker et al., 1998), and Bathonian (Powers et al., 1966; Sartorio and Venturini, 1988).

Al-Moraikhi et al. (2014) assigned an Early Jurassic age for the Lower Marrat Member based on palynological associations recovered from cuttings that are dominated by sporomorphs. They did not find rich palynological associations in the cored sections from the upper part of the Unit C of the Middle Marrat Member. Generally, only sporomorphs are recorded in abundance, but calcareous nannofossils are not preserved. Strontium-isotope data place this interval between the Late Toarcian and Early Bajocian.

Sampled cuttings from the Upper Marrat Member (upper Unit B and Unit A) did not yield useful palynological or micropaleontological information (Al-Moraikhi et al., 2014). The carbon isotopes from cuttings delineate a slight negative trend, starting at maximum values in the Middle Marrat Member (Unit C). This trend is similar to the one recorded in the Late Aalenian to Early Bajocian globally stacked isotope data set (Al-Moraikhi et al., 2014).

Dhruma Formation: Middle or Late Aalenian to Late Bajocian

Al-Sahlan (2005) considered the age of the Dhruma Formation as ?Late Aalenian to Late Bajocian in South Kuwait. The questionable Late Aalenian age is based on the presence of very rare to rare dinoflagellates Dissiliodinium sp. and very rare to rare Dissiliodinium hyalinum (smooth) in the lower part of the Dhruma Formation. She considered the upper part of the Dhruma Formation as no-older-than Late Bajocian based on the frequent occurrence of nannofossil Watznaueria (Ellipsagelosphaera) britannica and co-occurrences of the age-diagnostic calcareous nannofossil Carinolithus superbus with the dinoflagellate Ceratothamnion sp. C of Colin et al. (1992). In West Kuwait the Dhruma Formation is Early to Middle Bajocian, and in North Kuwait, it is no-older-than Bajocian.

Al-Moraikhi et al. (2014), based on well-preserved palynomorphs and calcareous nannofossils recovered from core, reported an Early–Late Bajocian age for the Dhruma Formation.
In the Middle Jurassic (Bajocian) time *Watznaueria britannica* and *W. manivitae* are generally present and two species of nannolith genus *Carinolithus* (*C. superbus* and *C. magharensis*) are widely used as markers (Mattioli and Erba, 1999). Moreover, in onshore Kuwait the top of abundant recovery of nannofossil *Schizosphaerella punctulata*, occurs slightly below the LO of *C. superbus*, is very useful to recognizing the boundary between Subzones NJT 10a and NJT 10b. Care should be taken in applying the FO of *W. barnesae* as a zonal marker, as proposed by Mattioli and Erba (1999), due to some discrepancies in species concept used among the workers (Erba, 1990). The LO *Carinolithus magharensis*, therefore, is used in this study as an additional marker to identify the top of the Subzone NJT 10b.

The basal portion of the Dhroma Formation and the upper portion of the underlying Marrat Formation have not yet been cored and were not sampled for our study. In most of the studied wells (e.g. wells A, C and F), the base of the sampled Dhroma Formation occurs within Middle Bajocian Zone NJT 10 of Mattioli and Erba (1999), based on the presence of *W. manivitae* and *W. britannica*.

In Well B, the deepest sampled, the Dhroma Formation is dated as ?Middle or Late Aalenian to early Late Bajocian, equivalent to ?Subzone NJT 8c , Zone NJT 9, Subzone NJT 10a and lower Subzone NJT 10b of Mattioli and Erba (1999), based on the presence of first occurrences (FO) *Watznaueria britannica*, FO *W. manivitae* and last occurrence (LO) *Carinolithus superbus*.

In wells C, E and F, the upper portion of the Dhroma Formation contains abundant nannofossils such as *W. manivitae*, *W. britannica*, *D. criotus*, *D. strictus* and *L. crucicentralis* without any *W. barnesae* indicating a Late Bajocian age (Zone NJT 10). In wells B and H, the top of the Dhroma is near the last occurrence of *C. superbus* of Subzone NJT 10a, while in Well A, it is slightly lower than the top of Zone NJT 10b. The top of the Dhroma is between the LO of *C. superbus* and the LO of *C. magharensis*, and Late Bajocian in age (Zone NJT 10a).

The age of the Dhroma Formation is considered Late Aalenian, but presumably as old as Middle Aalenian, to Late Bajocian as consistent with the assignment by Al-Sahlan (2005), and Early–Middle Bajocian as reported by Al-Moraikhi et al. (2014). We conclude that the Lower/Middle Jurassic (Toarcian/Aalenian) boundary may be located in the Marrat Formation, possibly at the base of the Upper Marrat, where a karsted unconformity has been recognized in core.

**Sargelu Formation: Late Bajocian to Middle Bathonian**

Al-Sahlan (2005) dated the lower part of the Sargelu Formation *sensu* Yousif and Nouman (1997) as Middle and Late Bathonian based on numerous to common occurrence of *Durotrigia filapicat*, and the presence of *Gonyaulacysta pectinigera* and *Korystocysta gochtii/kettonensis*. She dated the top Sargelu as Callovian or ?older based on the abundant presence of *Dichadogonyaulax sellwoodii*. According to the average ages in GTS 2004, the estimated age of the top Sargelu by strontium-isotope analyses is 167.5 Ma near the Bathonian/Bajocian boundary. This age is significantly older than the estimate obtained by biostratigraphy (Callovian or ?older; i.e. greater than 161.2 Ma).

In the figure of Al-Sahlan (2005), the Sargelu Formation *sensu* Yousif and Nouman (1997) is shown as Late Bajocian to Early Bathonian, with an unconformity spanning Early Bathonian to Middle Oxfordian separating it from the overlying Najmah Formation. This unconformity is apparently based on strontium-isotope results. Detailed description of more than 12 cores, which continuously span this interval, by the present authors has revealed no sedimentological evidence of an unconformity. We believe a very condensed section may contain much of the “missing” interval when sampled more closely. Our sampling interval was reduced from about 4 ft to a few inches in such zones.

Calcareous nannofossils recovered by Al-Moraikhi et al. (2014) from the Sargelu Formation, as defined in our paper, suggest a Late Bajocian to Early Callovian age. They also identified dinocyst associations that suggest a Middle Bathonian age for the upper part of the Sargelu Formation.

In this paper the Sargelu Formation is formally subdivided into the Sargelu-Dhroma Transition, and the overlying Sargelu Limestone. The upper part of the Sargelu-Dhroma Transition contains rare nannofossils and its diversity is low. The assemblages include *Watznaueria britannica*, *W. manivitae* and...
C. magharensis, which indicate a Late Bajocian age, Zone NJT 10b of Mattioli and Erba (1999). In Well B, the top of Sargelu-Dhruma Transition coincides with the last occurrence of C. magharensis, while in Well H it is below the last occurrence of C. magharensis.

The Sargelu Limestone is nearly barren of nannofossils. By stratigraphic position between two dated units, the Late Bajocian Sargelu-Dhruma Transition and Late Bathonian–Middle Callovian Lower Najmah Shale, the age of the Sargelu Limestone (and undated Najmah-Sargelu Transition) is interpreted as Early to Middle Bathonian, Zone NJT 11. An influx of planktonic foraminifera Globuligerina spp., seen at the lower part of the Sargelu Limestone in Well H, support the age determination of this unit since the genus Globuligerina first appeared in the Bathonian (Boudagher-Fadel, 2013).

Najmah Formation: Late Bathonian to Oxfordian

Al-Sahlan (2005) considered the Najmah Formation sensu Yousif and Nouman (1997) as no older than Oxfordian, based on the presence of the dinoflagellate Systematophora spp. and the nannofossil Stephanolithion bigeti maximum (earliest Oxfordian–latest Callovian) from the lower part of the formation. Based on calcareous nannofossils, Al-Moraikhi et al. (2014) interpreted the Lower Najmah Shale (their Formation) as Late Bathonian to Early Callovian age, in agreement with the strontium-isotope record that they obtained.

Najmah Shale: Late Bathonian and Callovian

Ansulasphaera helvetica and Cyclagelosphaera deflandrei were noted as Late Bathonian–Callovian and Oxfordian markers, respectively, in the Tethys realm (Bown and Cooper, 1998; Casellato, 2010). The two species were recorded in onshore Kuwait where they are known as markers for age determination of the Najmah Shale. Rare specimens of L. hauffii were recorded in the Upper Najmah Shale and used as an important marker for Late Oxfordian (Casselato, 2010).

The Najmah Shale is formally subdivided into, from older to younger, the Najmah-Sargelu Transition, Lower Najmah Shale and Upper Najmah Shale. The Najmah-Sargelu Transition is barren of nannofossils. Based on stratigraphic position its age is estimated as Early to Middle Bathonian or perhaps as late as Callovian, in the range of NJT 11–13.

Calcareaous nannofossil recovery in the Lower Najmah Shale is rare to abundant, and diversity is generally low. In wells C, D, E, F, G, I and J, this unit contains long-ranging taxa such as Cyclagelosphaera margerelii, Watznaueria barnesae, W. britannica, and W. manivitae. On this basis, only an age ranging from NJT 11 to NJT 13 can be interpreted. Nonetheless, in Well K, Ansulasphaera helvetica, an index species for Late Bathonian–Callovian Zone NJT 12 is observed in the upper part of Lower Najmah Shale and lower part of the Upper Najmah Shale. These finding suggest that the age of the Lower Najmah Shale may range from Late Bathonian, or older, to Middle Callovian, and the boundary between the Lower and Upper Najmah Shales is placed in the Callovian Stage.

Calcareaous nannofossil recovery within the Upper Najmah Shale in wells A to K is few to abundant, and diversity is generally low. The assemblages contain long-ranging taxa such as Cyclagelosphaera margerelii, Watznaueria barnesae, W. britannica, and W. manivitae. On this basis, only an age ranging from NJT 11 to NJT 13 can be interpreted. However, in Well K, Ansulasphaera helvetica, an index species for Late Bathonian–Callovian Zone NJT 12 is observed in the lower part of the Upper Najmah Shale. In Well K, and in wells C and I, Cyclagelosphaera deflandrei, a zonal marker for the base of Middle Oxfordian Subzone 13b is observed (Table 9). In Well J it yields rare Lotharingius hauffii (Table 10), indicating that the age of the Upper Najmah Shale in the onshore Kuwait area may range from Middle Callovian to Late Oxfordian, within Zone NJT 13.

Najmah Limestone: ?Middle Oxfordian and Early Kimmeridgian

Calcareaous nannofossil recovery within the Najmah Limestone is barren to abundant and its diversity is generally low. Nannofossil assemblages occurring in the unit include Watznaueria barnesae, W. britannica, W. manivitae, Cyclicargolithus deflandrei and C. margerelii indicating Middle to Late Oxfordian in age or younger. Dating by palynomorphs indicates that the unit is not older than Kimmeridgian (Millennia, 2014, unpublished report).
Jurassic stratigraphy, onshore Kuwait

Jubaila Formation: Kimmeridgian

Al-Moraikhi et al. (2014) reported that a sample taken from just below the evaporites of the Gotnia Formation (Jubaila Formation of this paper), yielded calcareous nannofossil and dinoflagellate cyst assemblages containing taxa that are widely known to occur in the Late Jurassic (Oxfordian–Kimmeridgian). They added that strontium-isotope data place this interval in the Late Callovian to Middle Kimmeridgian.

The influx of nanno assemblages dominated by Watznaueria manivitae, Watznaueria britannica and Cyclagelosphaera deflandrei were found in the Jubaila Formation in wells E, F, G, I, and K. These assemblages indicate a Kimmeridgian age (Zone NJT 14 of Casellato, 2010) as also reported by Bown et al. (1998). Based on the abundance of the large-diameter and highly birefringent specimens of W. manivitae, we correlate this assemblage with the Kimmeridgian Zone Cyclagelosphaera margerelii of Haq (1983) and with Zone NJT 14 of Casellato (2010).

Gotnia and Hith Formations

In our study, the Gotnia and Hith formations were not dated due to the absence of calcareous nannofossils. Al-Sahlan (2005) reported that the Hith Formation, based on strontium-isotope analysis in West Kuwait, is assigned an approximate age of Kimmeridgian–Tithonian, which would confine the Gotnia Formation to Kimmeridgian. In the figure of Al-Sahlan (2005) the Hith Formation is separated from the overlying Makhul Formation by a hiatus in the Tithonian.

Makhul Formation: Late Tithonian–Berriasian

Al-Sahlan (2005) reported that in offshore Kuwait, the presence of the dinocyst Muderongia sp. cf. A Davy (1979) suggests Middle and Late Tithonian age for the Makhul Formation, and the occurrence of Phoberocysta neocomica indicates an age no-older-than Berriasian. Al-Moraikhi et al. (2014) identified Jurassic calcareous nannofossils and dinoflagellate cysts of Late Jurassic age from cored sections from the Makhul Formation.

Species of the nannolith genus Nannoconus contribute to the robust nannofossil assemblages and are widely used as markers in the Late Jurassic–earliest Cretaceous interval (Casellato, 2010). The FO of Nannoconus steinmannii minor, which occurs at the base of magneto zone M18r (Channell et al., 2010), is now widely used as a marker for the Tithonian/Berriasian (Jurassic/Cretaceous) boundary. It was found in the argillaceous mudstone of the Makhul Formation in the Minagish Field (Millennia, 2013, unpublished report), where nannofossil assemblages are poor with low species diversity.

The upper part of the Makhul Formation contains rare Nannoconus steinmannii minor and Nannoconus kampneri minor, indicating a Berriasian age, Zone CC 1 of Bergen (1994). Moreover, the Tithonian Conusphaera mexicana minor and Conusphaera mexicana mexicana were recorded at the lower part of the Makhul Formation, above the last occurrence of abundant radiolaria at the Ratqa Field (Varol Research, 1988, unpublished report). These two remarkable findings suggest that the age of the Makhul Formation in onshore Kuwait ranges from Tithonian to Berriasian, and the Jurassic/ Cretaceous boundary is located within the formation.

JURASSIC CHRONO- AND SEQUENCE STRATIGRAPHY, CENTRAL SAUDI ARABIA OUTCROPS

Before we present our interpretation of the sequence stratigraphy of onshore subsurface Kuwait, we include here an up-to-date review of the sequence stratigraphy of the Jurassic System in central Saudi Arabia outcrops. Al-Husseini (1997, 2009, see references therein) reviewed the published literature of the lithostratigraphic nomenclature, ranking, stage assignments and possible third-order architecture of the Upper Triassic and Jurassic formations in central Saudi Arabia outcrops. The present review builds from his summary of the literature, but with revisions based on field observations and interpretations sent as written communications in 2015 by Y.-M. Le Nindre, and discussions by R.B. Davies (Figure 11).
Figure 11: Regional correlations of the Jurassic System between the outcrop area in Saudi Arabia and the subsurface of Kuwait, based on nannofossil data in this paper. Geological Scale GTS 2015 from International Commission on Stratigraphy (ICS).
Sharland et al. (2001) did not define sequence boundaries (SB) and so in this paper we attempt to identify and name SBs based on evidence; for example, hiatuses (missing time) or subaerial exposure, or other sedimentological observations. The basal boundary of a sequence is given the same alphanumerical code as the sequence that contains the MFS; for example SB J30 occurs at the base of Sequence J30, which contains MFS J30.

**Marrat Formation and MFS J10**

In Saudi Arabia the Triassic/Jurassic boundary separates the Upper Triassic (Upper Norian–Rhaetian) Minjur Sandstone of the Buraydah Group, from the Toarcian Marrat Formation of the Jurassic Shaqra’ Group (Vaslet et al., 1983, 1988, 1991; Manivit et al., 1985a, b, 1990). The Marrat Formation consists of the Upper, Middle and Lower members. Sharland et al. (2001) followed Énay et al. (1987) by positioning Middle Toarcian MFS J10 in the Upper Member (bifrons ammonite Zone), and named the hiatus in the Early Jurassic Hettangian, Sinemurian and Pliensbachian stages as the “Early Jurassic Unconformity”.

Y.-M. Le Nindre proposed a revision to the interpretations of Énay et al. (1987) and Sharland et al. (2001). He notes that although the entire Marrat was assumed as Toarcian in age, foraminifera of the Lower Marrat Member indicate an Early Jurassic age compatible with Pliensbachian, and interprets this member as the transgressive part of the formation. He added that the base of the Middle Marrat is dated by brachiopods and ammonites (Bouleiceras, Protogrammoceras) as Early Toarcian Serpentinus Zone (Vaslet et al., 1983; Manivit et al., 1985b), and the rest of the member does not contain age-indicative markers. The main marine flooding interval occurs in the lowest part of the Middle Member, where the marine fauna is most diverse (Le Nindre et al., 1990) immediately followed by red shale deposition.

The base of the Upper Marrat Member is dated by ammonites (Nejdia and Hildoceras) as Middle Toarcian Bifrons Zone. This event is of short duration although the carbonate of the Upper Marrat, of confined environment, has some extent northward. The rest of the member is undated; it could extend to Late Toarcian and even the Aalenian. Y.-M. Le Nindre considers the Upper Marrat Member represents a regression ending with gypsum in the reference section. He therefore proposes that MFS J10 may be better positioned in the lower part of the Middle Marrat and assigned an Early Toarcian age (Serpentinus ammonite Zone).

**Lower and Middle Dhruma Members, MFS J20 and MFS J30**

The Aalenian Unconformity separates the Toarcian Marrat Formation from the Middle Jurassic Dhruma Formation (Le Nindre et al., 1990). Powers (1968) and later Vaslet et al. (1983) subdivided the Dhruma Formation into formal and informal units. Powers (1968) defined the Lower, Middle and Upper Dhruma members (formal), and ten lithological units (informal): units 1 to 4 for the Lower Dhruma Member; units 5 to 8 for the Middle Dhruma Member; and units 9 and 10 for the Upper Dhruma Member. In addition, Powers (1968) defined three informal members: Dhibi limestone member (upper Lower Dhruma Member), ‘Atash and Hisyan members (Upper Dhruma Member). Vaslet et al. (1983), from sections within the Wadi Ar Rayn Quadrangle, kept the informal members, and defined seven informal units in equivalence with the ten of Powers (1968): D1 (= 1, 2) and D2 units (= 3, 4 and includes Dhibi limestone member) for the Lower Dhruma Member; D3 Unit (= 5, Thanbites Zone), D4 Unit (= 6, Tulites Zone), D5 Unit (= 7, Micromphalites Zone), and D6 Unit (= 8, Dhrumaites Zone), for the Middle Dhruma Member; and D7 Unit (= 9, ‘Atash member; and 10, Hisyan member), for the Upper Dhruma Member. Later, Le Nindre (1987) and Manivit et al. (1990), following Powers (1968), formalized the Khashm ad Dibi section as the Dhruma Formation type section.

The Lower Bajocian MFS J20 is positioned in the upper part of the D1 Unit, as proposed by Sharland et al. (2001) based on the study by Énay et al. (1987). Units D1 and D2, together are interpreted as a third-order transgressive-regressive sequence: Sequence J20, bounded by lowermost Bajocian SB J20 and Upper Bajocian SB J30 (Y.-M. Le Nindre).
Y.-M. Le Nindre interpreted the Upper Bajocian–Bathonian Middle Dhroma Member (D3 to top of D6) as a third-order sequence with Lower Bathonian MFS J30 in the D5 Unit based on transgression geometry and last ammonite occurrence southward, and as adopted by Sharland et al. (2001). R.B. Davies favors placing MFS J30 in the D4 Unit in order to maintain its position in the middle of the carbonate interval that represents the maximum marine incursion (Énay et al., 2009, their figure 4), and notes that a pick in either the D4 or D5 units retains MFS J30 in the Zigzagoceras ammonite Zone. Énay et al. (2009) also positioned MFS J30 in the D5 Unit, and considered the overlying “Wadi ad Dawasir Delta” as the regressive deposits of Sequence J30, with a short hiatus in Late Bathonian. They placed SB J40 in Upper Bathonian between the Wadi ad Dawasir Delta and D6 Unit, whereas Y.-M. Le Nindre places SB J40 at the top of the D6 Unit.

Upper Dhroma Member and Tuwaiq Mountain Limestone: MFS J40

The Callovian Tuwaiq Mountain Limestone consists of three units, from base-up: T1, T2 and T3 (Vaslet et al., 1983). We adopt the model of Y.-M. Le Nindre, which considers the Callovian Upper Dhroma Member (D7 Unit) and Tuwaiq Mountain Limestone as Sequence J40. Both Y.-M. Le Nindre and R.B. Davies position Middle Callovian MFS J40 at the T2/T3 boundary, and much higher than the position chosen by Sharland et al. (2001) in the Hisyan member of the D7 Unit.

Powers (1968) noted that the Tuwaiq Mountain Limestone rests on the gently eroded surface of the Hisyan Member (D7 Unit), but evidence for this unconformity was not observed by D. Vaslet (2015, written communication). Powers (1968) added that in the subsurface, at Jauf and Safaniya, all but the pre-Dhibi part of the formation (D2 Unit) has been removed and the Lower Dhroma Member in these two areas is overlain respectively by the Tuwaiq Mountain and Hanifa formations. The criteria for identifying such a significant subsurface unconformity may depend on the questionable identification of foraminifera and cannot be verified by D. Vaslet (2015, written communication) or Y.-M. Le Nindre.

Hanifa Formation: MFS J50 and J60

Sequence boundary SB J50 between the Callovian Tuwaiq Mountain Limestone and Oxfordian Hanifa Formation corresponds to a hiatus (at least Early Oxfordian Mariae Zone, and possibly Late Callovian, Y.-M. Le Nindre). The late Early and Middle Oxfordian lower Unit H1 of the Hanifa Formation is named the Hawtah Member (Vaslet et al., 1991). It contains the main flooding surface of the Hanifa Formation, which is correlated to the Middle Oxfordian MFS J50 of Sharland et al. (2001); specifically in the lithological assemblage H1(4) Eusaspidoceras gr. Catena-perannatum Sowerby, Middle Oxfordian Plicatilis Zone (Y.-M. Le Nindre). The upper H2 Unit of the Hanifa Formation is the Late Oxfordian–Early Kimmeridgian Ulayyah Member (Vaslet et al., 1991). The Hawtah and Ulayyah members are separated by a reworked surface, which could be a possible position for a SB, possibly SB 60, if the Hawtah and Ulayyah are interpreted as two depositional sequences (Hughes et al., 2008; Y.-M. Le Nindre).

Sharland et al. (2001) interpreted the age of MFS J60 as Early Kimmeridgian and assumed that it is absent in Saudi Arabia. However, biostratigraphic evidence indicates that the Ulayyah Member contains a Lower Kimmeridgian marly interval (lithological assemblage H2(4) A. jaccardi sp. and echinoids) that may contain MFS J60 (Le Nindre, 1987, this paper), see alternative position in Jubaila Formation discussed below). Hughes et al. (2008) summarized the biostratigraphic evidence for the age of the Ulayyah Member, which also suggests that it extends into the Early Kimmeridgian, but did not correlate the MFS in the Ulayyah Member to MFS J60. R.B. Davies believes that placing MFS J60 in the Ulayyah Member at outcrop is possible, but remains to be proven.

Jubaila Formation and Arab D Member: Alternative Positions for MFS J60 and MFS J70

Y.-M. Le Nindre described the interval between the Ulayyah Member and overlying Kimmeridgian Jubaila Limestone Formation as consisting of sandstone and conglomerates (south of 22°30′N) and a complex transition elsewhere. The Jubaila Formation consists of the J1 and J2 units, separated by
a red karstified, dolomitic horizon with minor erosion in central Saudi Arabia. The J1–J2 transition may contain an unconformity, but according to Y.-M. Le Nindre it cannot be mapped as such, nor interpreted as a hiatus without accurate biostratigraphic control. He added that the lower J1 Unit (A. Jaccardi, Perisphinctes jubailensis, and Nautilus Paracenoceras aff. Wepferi) also provides a possible position for MFS J60. R.B. Davies agrees with the possibility that MFS J60 could be in either the Ulayyah Member of the Hanifa Formation, or in the J1 Unit of the Jubaila Formation, if they are both dated as Early Kimmeridgian.

Above the Jubaila Formation, the Arab D Member of the Arab Formation consists of the lower carbonate and overlying Arab D anhydrite intervals, with the Arab D reservoir approximately corresponding to the Jubaila J2 Unit and Arab D carbonates (Powers, 1968). Y.-M. Le Nindre suggests that the Jubaila J2 Unit and the Arab D Member (inclusive of the Arab D anhydrite) could represent a sequence, but that no MFS has been assigned to it. Accordingly he suggests that Early Kimmeridgian MFS J60 could be in either the Ulayyah Member of the Hanifa Formation (as explained above), or in the Jubaila J1 Unit; in this scenario Kimmeridgian MFS J70 could be positioned in the Jubaila J2 Unit. R.B. Davies believes various options for the positions of MFS J60 and MFS J70 are possible but that further work, not only in Saudi Arabia and Kuwait, but also in other parts of the Arabian Plate is required to identify the best positions for these Lower Kimmeridgian MFSs.

**Arab C, B and A Members, and Hith Formation: MFS J80 to MFS J100**

The Arab C and Arab B members represent sequences J80 and J90, containing MFS J80 and J90 of presumed Kimmeridgian age in their lower carbonate intervals (Sharland et al., 2001). Sequence boundaries SB J80, SB J90 and SB J100 are respectively positioned at the top of the Arab D, Arab C and Arab B anhydrites.

The Arab A Member consists of a carbonate interval containing MFS J100 of presumed Kimmeridgian age, and is overlain by the Tithonian Hith Anhydrite, the youngest formation of the Jurassic Shaqra’ Group (Powers, 1968). Hughes and Naji (2009) described the transition from the Hith to Sulaiy formations in the offshore Manifa Field, Saudi Arabia, to consist of the lower anhydrite member, transitional anhydrite-carbonate member, and upper carbonate member, the latter containing the Manifa reservoir (Powers, 1968), or informal “Manifa member” (Wilson, 1985). The Tithonian Manifa member is interpreted as heralding a regional transgression, which deposited the Late Jurassic–Early Cretaceous Sulaiy Formation of the Thamama Group. The Jurassic/Cretaceous (JK) boundary is placed in the Sulaiy Formation (see review in Wolpert et al., 2015).

**SEQUENCE STRATIGRAPHY OF ONSHORE KUWAIT AND CORRELATION TO CENTRAL SAUDI ARABIA**

In the following discussion we pick the positions of MFSs and SBs in Minagish-27 Well (Figures 3, 4 and 7), and compare them to those picked by Sharland et al. (2001 their figures 4.36 and 4.49) in the same well. The positions are used to correlate the cross-sections in Kuwait (Figures 5 and 6), and to central Saudi Arabia outcrops (Figure 11). In Table 12 we estimate the ages of the MFSs using GTS 2015 (International Commission on Stratigraphy, 2015). It is important to recognize that the Kuwait section was largely deposited in an outer platform to intrashelf basin depositional setting while the section exposed in the Saudi Arabian outcrops was in an inner platform setting. This resulted in significant differences in lithostratigraphy, rates of sedimentation, and position and length of hiatuses.

**Maximum Flooding Surface MFS J10**

The oldest Jurassic maximum flooding surface in the framework of Sharland et al. (2001) is the Middle Toarcian MFS J10. They placed MFS J10 in high-GR shales at the base of Unit C of the Marrat Formation in Minagish-27 Well at ca. 14,665 ft (Figure 3). In core, those sediments proved to be shallow lagoonal but were deepening upward. Al-Eidan et al. (2009) revised the pick for MFS J10 to a position that is about 200 ft higher at 14,470 ft in the Middle Marrat Member, where there is a
“drowning unconformity” with lime mudstone turbidite packages downlapping onto that surface. Thus we interpret MFS J10 to mark the base of the intrashelf basin that developed and subsequently infilled during Middle Marrat (mid-Toarcian) deposition.

**Sequence J20: Late Aalenian to Middle Bajocian**

Sequence J20 in Kuwait is interpreted as the Upper Marrat Member and Dhruma Formation, with SB J20 corresponding to a Late Toarcian–Early Aalenian hiatus, and SB J30 separating the Dhruma and Sargelu formations (Figures 3 and 4). The age of Sequence J20 is interpreted as Late Aalenian–Early Bajocian (Figure 11). Lower Bajocian MFS J20 is positioned at 13,458 ft in Minagish-27 Well in the Dhruma Formation as in Sharland et al. (2001; Figure 4). The Early Bajocian Lower Dhruma Member (D1 and D2 units) in central Saudi Arabia is correlated to the upper part of Sequence J20 in Kuwait (Figure 11).

**Sequence J30: Late Bajocian and Bathonian**

Sharland et al. (2001) interpreted MFS J30 as Early Bathonian and positioned it at 13,258 ft in Minagish-27 Well in the argillaceous limestone within the Sargelu Formation sensu Yousif and Nouman (1997), as consistent with our pick at 13,256 ft. We place SB J30 at the Dhruma/Sargelu boundary at 13,377 ft, and interpret the age of Sequence J30 as Late Bajocian and Bathonian. We correlate Sequence J30 in Kuwait to the Late Bajocian–Bathonian Sequence J30 sensu Y.-M. Le Nindre in central Saudi Arabia, consisting of the Middle Dhruma Member (D3 to D6 units; Figure 11).

**Sequence J40: Callovian**

Sharland et al. (2001) interpreted MFS J40 as Middle Callovian and positioned it in the high gamma-ray shales near top Sargelu Formation sensu Yousif and Nouman (1997). In Minagish-27 Well, they picked MFS J40 at 13,153 ft, which corresponds to the top of the Najmah-Sargelu Transition of the Najmah Formation.

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**Table 12: Ages of the numbered major Arabian Plate Maximum Flooding Surfaces of Sharland et al., 2001 as calibrated to GTS 2015 (ICS, 2015) and used on the present study.**

| Maximum Flooding Surface | Position          | Age Sharland et al. (2001) | This Study Recalibrated to GTS 2015 |
|--------------------------|-------------------|-----------------------------|------------------------------------|
| Top Tithonian            | J 110             | 144.2                       | 145.0                              |
| Upper Tithonian          | J 100             | 147.0                       | 147.0                              |
| Top Kimmeridgian         | J 90              | 150.7                       | 152.1 ± 0.9                        |
| Upper Kimmeridgian       | J 80              | 151.25                      | 153.0                              |
| Upper Kimmeridgian       | J 70              | 151.75                      | 153.5                              |
| Lower Kimmeridgian       | J 60              | 152.25                      | 154.0                              |
| Top Oxfordian            | J 50              | 154.0                       | 157.0 ± 0.0                        |
| Middle Oxfordian         | J 40              | 156.0                       | 160.4                              |
| Top Callovian            | J 30              | 159.4                       | 163.5 ± 1.0                        |
| Lower Callovian          | J 20              | 162.0                       | 164.8                              |
| Lower Bathonian          | J 10              | 168.0                       | 167.6 ± 1.2                        |
| Top Bathonian            | J 10              | 168.3 ± 1.3                 |                                    |
| Lower Bajocian           | J 20              | 175.0                       | 169.6                              |
| Top Aalenian             | J 40              | 178.5 ± 1.4                 |                                    |
| Top Toarcian             | J 30              | 180.1                       | 174.1 ± 1.0                        |
| Top Pliensbachian        | J 10              | 185.0                       | 178.4 ± 1.0                        |

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We interpret the MFS at 13,153 ft as picked by Sharland et al. (2001) as a minor flooding event, and instead select a higher position at 13,116 ft just above the base of the Upper Najmah Shale (13,118 ft). Our higher position for MFS J40 appears to be a more significant sedimentological flooding surface, and probably closer to a position in Middle Callovian. In Minagish-27 Well, the Lower Wedge, which was encountered in several wells, does not occur (Figures 4 to 6, Enclosure I). It is interpreted as the transgressive systems tract (TST) of Sequence J40. We place SB J40 at 13,166 ft, and SB J50 at 13,085 ft (base Upper Wedge).

The age of Kuwait’s Sequence J40 is interpreted as Callovian, and it would therefore correlate to Saudi Arabia’s Sequence J40, consisting of the Upper Dhruma Member (D7 Unit), and the Tuwaiq Mountain Limestone, with MFS J40 at the boundary of the T2 and T3 units in central Saudi Arabia (Y.-M. Le Nindre).

**Sequence J50: Early and Middle Oxfordian**

Sharland et al. (2001) interpreted MFS J50 as Middle Oxfordian and positioned it in the condensed organic-rich limestones of Najmah Unit 4 of Yousif and Nouman (1997). In Minagish-27 Well, however, they picked MFS J50 at 13,074 ft in Najmah Unit 3 (Figure 4). In Well K the Callovian/Oxfordian boundary is approximately placed at the base of Najmah Unit 3, which implies that Middle Oxfordian MFS J50 should be positioned in Najmah Unit 3 (not Callovian “Najmah Unit 4”).

We follow the interpretation of Y.-M. Le Nindre and position MFS J50 at 13,038 ft, precisely at the top of the Upper Wedge (top Najmah Unit 3, Figure 4). This interpretation implies the Upper Wedge is the transgressive systems tract (TST) of Sequence J50. Moreover, where the Upper Wedge is absent, an early to mid Early Oxfordian hiatus would occur, as in the case of the “missing” *Marina* Biozone in central Saudi Arabia between the Hanifa and Tuwaiq Mountain Limestone (Y.-M. Le Nindre). This interpretation implies that Middle Oxfordian MFS J50 at the top of the Upper Wedge correlates to the MFS J50 in the Hawtah Member of the Hanifa Formation in Saudi Arabia outcrops.

**Sequence J60 and J70: Early Kimmeridgian**

Sharland et al. (2001) interpreted MFS J60 as Early Kimmeridgian and positioned it in the organic-rich limestones close to base of Najmah Unit 2 of Yousif and Nouman (1997, Figure 3). They picked MFS J60 at 13,010 ft, approximately corresponding to the boundary between the Najmah Upper Shale and Najmah Limestone (13,017 ft). Najmah Unit 2 is dated as Oxfordian and therefore their position for MFS J60 is incompatible with a Late Kimmeridgian age. They positioned Upper Kimmeridgian MFS J70 at ca. 12,955 ft in Minagish-27 Well in the organic-rich limestone of Najmah Unit 1 corresponding to the Jubaila Formation in our paper.

As in the case of Saudi Arabia (see discussion by Y.-M. Le Nindre and R.B. Davies, above), the positions of Lower Kimmeridgian MFS J60 and MFS J70 are not adequately constrained by precise age-indicative data in Kuwait. Our interpretation is also rendered difficult because we are convinced that the Jubaila Formation is bounded by unconformities that introduce hiatuses and missing section in this interval.

Our preferred interpretation is that the upper part of the Najmah Limestone is eroded by the pre-Jubaila unconformity/hiatus. We therefore suggest that MFS J60 onlaps the unconformity and position it just above the top of the Najmah Formation (12,955 ft) at 12,954 ft in lowermost Jubaila Formation in Minagish-27 Well (Figure 4). We position MFS J70 either at 12,928 ft in the clean limestones at the base of the overlying Gotnia 4th Anhydrite, or at 12,940 ft in the middle of the Jubaila Formation (Figure 4). A minor hiatus may occur between the top Jubaila and base Gotnia 4th Anhydrite.

**MFS J80, J90 and J100: Gotnia and Hith Formations**

The Gotnia Formation is characterized from base-up by four pairs of anhydrite and salt intervals, and is overlain by the anhydrites of the Hith Formation (Figure 7 and Enclosure II). Detailed logs
presented by Neog et al. (2010) show that the lithology of the intermediate part of the Gotnia Formation, from the 4th Salt to the 1st Salt, evolves from: (1) halite, (2) anhydrite, (3) dolomite, (4) limestone, (5) dolomite, (6) anhydrite, and back to (7) halite. The massive halite intervals are the most restricted and therefore were deposited during sea-level lowstands. The thin limestone beds bounded by the 3rd, 2nd and 1st Anhydrites are interpreted as flooding events and were chosen by Sharland et al. (2001) as the positions of Late Kimmeridgian MFS J80, MFS J90 and MFS J100, respectively. They correlated these three MFSs to the Arab C, Arab B and Arab A carbonates of the Arab Formation in Saudi Arabia (Figure 11).

Our study does not include new biostratigraphic or other age data, or well control over the Rimthan Arch and northern Saudi Arabia. Accordingly, we adopt the interpretations of Sharland et al. (2001). In Minagish-27 Well we position MFS J80 at 12,682 ft, MFS J90 at 12,284 ft, and MFS J100 at 11,865 ft (Figure 7).

Sequence Boundary SB J110 and MFS J110

The contact between the Hith Formation and overlying Makhul Formation is taken as SB J110, and it occurs in Kuwait in Upper Tithonian at 11,199 ft in Minagish-27 Well (Figure 3). MFS J110 is positioned in the lower part of the Makhul Formation and above the uppermost Hith anhydrite bed, as consistent with the type section of the Hith-Sulaiy transition in Dahal Hit in Saudi Arabia (Wolpert et al., 2015).

CONCLUSIONS

This paper presents and formalizes the currently practiced lithostratigraphic nomenclature and definitions that are used in Kuwait Oil Company to describe the Jurassic subsurface rock units of onshore Kuwait. The ages of several Middle and Late Jurassic units are dated in 11 wells using calcareous nannofossil biostratigraphy. Units that we are unable to date using this technique are assigned ages based on stratigraphic position or previous biostratigraphic and strontium-isotope dating studies in Kuwait.

Based on our biostratigraphic dating, sedimentological criteria from core description, and correlation of electrical logs we have constructed a sequence-stratigraphic framework consisting of maximum flooding surfaces (MFS) and sequence boundaries (SB). The positions of Arabian Plate Jurassic MFS J10 to MFS J110, as dated and picked in the reference Minagish-27 Well by Sharland et al. (2001), are revised in several cases. The paper also presents a review and discussion of the sequence stratigraphy of central Saudi Arabia’s Jurassic MFSs and SBs by Y.-M. Le Nindre and R.B. Davies, which provided many significant insights and constraints for our interpretations.

We conclude that our stratigraphic positions for Toarcian MFS J10 to Middle Oxfordian MFS J50, and Middle Aalenian SB J20 to Lower Oxfordian SB J50, are supported by the presented data and interpretations. As in the case of Saudi Arabia’s outcrops, the positions of Kimmeridgian MFS J60 and MFS J70, and SB J60 to SB J80, are not adequately constrained by biostratigraphic or other age-indicative control. We believe that this interval contains condensed sections and unconformities, which render stratigraphic picks in wells ambiguous.

We follow Sharland et al. (2001) and place MFS J80 to MFS J100 in the thin limestone beds in the Gotnia Formation, and assume that they correlate to the Arab C, Arab B and Arab A carbonates of the Arab Formation in Saudi Arabia. Our control is insufficient to make a definitive correlation for the interval spanning the Jubaila, Arab, Gotnia and Hith formations across the NE-trending Rimthan Arch, which runs approximately parallel to the Kuwait-Saudi Arabia border. The youngest Jurassic event that we recognize is Middle Tithonian SB J110, which occurs at the top of the Hith Formation, with the Jurassic/Cretaceous boundary occurring in Kuwait’s Makhul Formation and the Sulaiy Formation in Saudi Arabia.
TAXONOMIC APPENDIX

Genera, species and subspecies of calcareous nannofossil used in the stratigraphic distribution charts (Tables 1–11) are listed in alphabetical order. Most of references to original description and/or subsequent pertinent illustration are given. See the Nannotax3 website and references therein for full information regarding taxonomy and references. Few remarks to clarify species concepts and species distribution in the studied wells are included.

**Ansulasphaera helvetica** Grun and Zweili, 1980
(Plate 1, Figures 1-3)
Ansulasphaera helvetica Grun and Zweili, 1980, p. 261-262, pl. 4, figs. 6-11; text-fig. 19. Roth, 1983, pl. 1, figs. 4-7, 11-13. Bown and Cooper (1998) pl. 4.14, figs. 26-28.
**Remarks:** This species has been described from the Callovian strata of Jura Mountains of Switzerland. Bown and Cooper (1998) recorded the FO of this species in the Upper Bathonian and used it as a marker for the top of NJ 11 Zone of Boreal Nannofossil zones. Casellato (2010) recorded the LO of this species in the Upper Callovian shortly before the LO of *Cyclagelosphaera wiedmannii*. In the present study, rare specimens of this species occur in the Najmah Shale at wells J and K, and used it as an additional zonal marker for the base and the top of NJT 12 Zone.

**Assipetra infracretacea** (Thierstein, 1973) Roth, 1973
Assipetra infracretacea (Thierstein, 1973) Roth, 1973. Thierstein, 1973, p. 46, pl. 1, figs. 1-19. Roth, 1973, p. 729, pl. 25, figs. 5, 7.
**Remarks:** This is the only species which belongs to the genus *Assipetra*. Its range is Valanginian to Aptian. This species was found in the Najmah Limestone Member in Well H as reworked species.

**Axopodorhabdus atavus** (Grun et al., 1974) Bown, 1987
Axopodorhabdus atavus (Grun et al., 1974) Bown (1987). Bown and Cooper (1998), pl. 4.14, figs. 11-12.
**Remarks:** In the present study, this species was recorded in Well B.

**Axopodorhabdus cylindratus** (Noel, 1965) Wind and Wise, 1976
Axopodorhabdus cylindratus (Noel, 1965) Wind and Wise, 1976. Noel, 1965, p. 103, pl. 9, figs. 3, 7, text-fig. 30. Wise and Wind, 1976, p. 297, pl. 80, figs. 5-6, pl. 81, figs. 1-4, figs. 88, figs. 5-6. Thierstein, 1976, pl. 2, figs. 10-11. Bown and Cooper (1998), pl. 4.14, figs. 13-14.
**Remarks:** In the present study, this species was recorded in Wells B and H.

**Biscutum dubium** (Noel, 1965) Grun in Grun et al., 1974
Biscutum dubium (Noel, 1965) Grun in Grun et al., 1974. Noel, 1965, p. 76, pl. 7, figs. 1-13. Bown and Cooper (1998) pl. 4.12, figs. 9-10. Mattioli and Erba (1999) pl. 2, fig. 1.
**Remarks:** In the present study, this species was recorded in Well B.

**Biscutum novum** (Goy, 1979) Bown, 1987
(Plate 1, Figures 4-5)
Biscutum novum (Goy, 1979) Bown, 1987. Bown and Cooper (1998) pl. 4.13, figs. 19-21.
**Remarks:** In the present study, this species was recorded in wells B, C and H.

**Bussonius prinsii** (Noel, 1973) Goy, 1979
(Plate 1, Figure 6)
Bussonius prinsii (Noel, 1973) Goy, 1979. Bown and Cooper (1998) pl. 4.15, figs. 1-2.
**Remarks:** In the present study, this species was recorded in Well B.

**Carinolithus magharensis** (Moshkovitz and Ehrlich, 1976) Bown, 1987
(Plate 1, Figures 7-8)
Carinolithus magharensis (Moshkovitz and Ehrlich, 1976) Bown, 1987. Moshkovitz and Ehrlich, 1976, p. 16, pl. 8, figs. 12-15. Bown and Cooper (1998) pl. 4.13, figs. 6-9. Mattioli and Erba (1999), pl. 3, figs. 19-20.
Remarks: Moshkovitz and Ehrlich (1976), Erba (1990), Mattioli and Erba (1999), Mattioli et al. (In Bown and Cooper, 1998), Ogg et al. (2008) recorded the LO *C. magharensis* in latest Bajocian and de Kaenel et al. (1996) calibrated the LO of *Carinolithus magharensis* shortly after the LO of *Carinolithus superbus*. Our present study shows this event at the top of the Sargelu-Dhruma Transition.

*Carinolithus superbus* (Deflandre in Deflandre and Fert, 1954) Prins in Grun et al., 1974

(Plate 1, Figure 9)

*Carinolithus superbus* (Deflandre in Deflandre and Fert, 1954) Prins, 1974. Deflandre in Deflandre and Fert, 1954, p. 160, fig. 93, pl. 15, figs. 24-25. Prins, 1974, p. 1, fig. 7. Bown and Cooper (1998) pl. 4.13, figs. 10-11. Mattioli and Erba (1999), pl. 2, fig. 15.

Remarks: In onshore Kuwait, this species occurs rarely and its LO is at the upper part of the Dhruma Formation. This LO of this species marks the upper boundary of the NJT 10a Subzone (Mattioli and Erba, 1999), right above the Lower/Upper Bajocian boundary (de Kaenel et al., 1996; Bown et al., 1988; Mattioli and Erba, 1999).

*Cyclagelosphaera deflandrei* (Manivit, 1966) Roth, 1973

(Plate 1, Figures 10-11)

*Cyclagelosphaera deflandrei* (Manivit, 1966) Roth, 1973, Manivit, 1966, p. 268, fig. 1a-c. Roth, 1973, p. 723-724, pl. 26, fig. 7, Thierstein, 1976, pl. 2, figs. 20-21. Roth, 1983, pl. 2, figs. 1-2. Bown and Cooper (1998) pl. 4.15, figs. 4-5.

Remarks: This species is characterized by having a large, highly birefringent placoliths that are circular to slightly subcircular occur in Middle Callovian to Valanginian interval (Roth, 1983). Casellato (2010) recorded the FO of this species in the upper part of Middle Oxfordian shortly after the NJT 13 a/b Sub-zonal boundary and can be used as an additional marker for the sub-zonal boundary. Rare specimen of this species occurs in the Najmah Shale in Well I.

*Cyclagelosphaera margerelii* Noel, 1965

(Plate 1, Figures 12-13)

*Cyclagelosphaera margerelii* Noel, 1965, p. 130, pl. 17, figs. 4-9; pl. 18, figs. 1-2; pl. 20, figs. 2-4. Roth and Thierstein, 1972, pl. 16, figs. 19-22. Roth, 1978, pl. 1, fig. 8. Roth, 1983, pl. 5, figs. 8-10. Mattioli and Erba (1999) pl. 3, figs. 17-18.

Remarks: This species is characterized by small in overall size and has small central opening. It is one of the important constituents of Middle to Upper Jurassic assemblages. The first appearance of this species has been regarded as an important event of Middle Aalenian age but some discrepancies exist in the literature possibly due to different taxonomic concepts (Mattioli and Erba, 1999). Mattioli and Erba (1999) reported that the FO of this species occurs in Middle Aalenian age. Its last occurrence occurs in Albian (Thierstein, 1973).

*Cyclagelosphaera tubulata* (Grun and Zweili, 1980) Cooper, 1987

(Plate 1, Figures 14-15)

*Cyclagelosphaera tubulata* (Grun and Zweili, 1980) Cooper, 1987. Bown and Cooper (1998) pl. 4.15, figs. 7-8.

Remarks: This species was recorded in wells B, H, I, K and L. Range of this species is Late Bajocian to Tithonian (Bown and Cooper, 1998).

*Diadacticus constans* Goy, 1979

*Diadacticus constans* Goy, 1979. Bown and Cooper (1998) pl. 4.10, figs. 16-17.

Remarks: In the present study, this species was recorded only in Well H.
Jurassic stratigraphy, onshore Kuwait

Discorhabdus criotus Bown, 1987
(Plate 2, Figures 2-4)

Discorhabdus criotus Bown, 1987. Mattioli and Erba (1999) pl. 3, figs. 1-3.

Remarks: Discorhabdus includes the round forms, whereas Biscutum includes the more or less elliptical coccoliths with radially arranged interlocking elements in the distal shield. The FO of this species was found in late Middle Toarcian age, based on sections in the Mediterranean Province (Mattioli and Erba, 1999). Our present work indicates that, Discorhabdus criotus ranges from the top of Dhruma Formation down to the deepest sample of wells B and H. The FO of D. criotus presumably deeper than our deepest sample.

Plate 1: Middle to Upper Jurassic calcareous nanofossils identified from core samples in onshore Kuwait. All light micrograph crossed nicols (XPL), approximate magnification x 3,000. Well name, core depth and stratigraphic interval are listed.

(1) Anuslasphaera helvetica, XPL, Well V, 10,228.00 ft, Najmah Shale Member;
(2) Anuslasphaera helvetica, XPL, Well K, 10,579.50 ft, Najmah Shale Member;
(3) Anuslasphaera helvetica, XPL, Well K, 10,579.50 ft, Najmah Shale Member;
(4) Biscutum novum, XPL, Well V, 10,531.00 ft, Dhruma Formation;
(5) Biscutum novum, XPL, Well B, 14,371.50 ft, Dhruma Formation;
(6) ?Bussonius prinsii, XPL, Well B, 14,358.50 ft, Dhruma Formation;
(7) Carinolithus magharensis XPL, Well K, 10,596.00 ft, Najmah Shale Member;
(8) Carinolithus magharensis, XPL, Well B, 14,334.70 ft, Dhruma Formation;
(9) Carinolithus superbus, XPL, Well B, 14,371.50 ft, Dhruma Formation;
(10) Cyclagelosphaera deflandrei, XPL, Well C, 13,648.00, Najmah Formation;
(11) Cyclagelosphaera deflandrei, XPL, Well V, 10,228.00 ft, Najmah Shale Member;
(12) Cyclagelosphaera margerelii, XPL, Well V, 10,228.00 ft, Najmah Shale Member;
(13) Cyclagelosphaera margerelii, XPL, Well V, 10,228.00 ft, Najmah Shale Member;
(14) Cyclagelosphaera tubulata, XPL, Well K, 10,445.00 ft, Jubaila Formation;
(15) Cyclagelosphaera tubulata, XPL, Well B, 14,323.20 ft, Sargelu Formation.
**Discorhabdus striatus** Moshkovitz and Ehrlich, 1976  
(Plate 2, Figures 5-10)  
*Discorhabdus striatus* Moshkovitz and Ehrlich, 1976, p. 14, pl. 7, figs. 1-5. Mattioli and Erba (1999), pl. 2, figs. 16, 19-20.  
**Remarks:** According to Bown et al. (1988) this species can be distinguished from *D. ignotus* because of its larger size, completely closed central area and brighter birefringence colors in polarizing light.

**Ethmorhabdus gallicus** Noel, 1965  
(Plate 2, Figures 11-12)  
*Ethmorhabdus gallicus* Noel, 1965, p. 110, pl. 10, figs. 1, 2, 5; text figs. 33-34. Thierstein, 1976, pl. 2, figs. 15-18. Bown and Cooper (1998) pl. 4.14, figs. 16-17.  
**Remarks:** This long range species, from Upper Toarcian to Upper Tithonian (Bown and Cooper, 1998) was recorded in Well B.

**Lotharingius crucicentralis** (Medd, 1971) Grun and Zweili, 1980  
(Plate 2, Figures 13-14)  
*Lotharingius crucicentralis* (Medd, 1971) Grun and Zweili, 1980. Medd, 1971, p. 829, pl. 1, figs. 1-2. Thierstein, 1976, pl. 2, figs. 8, 9. Roth, 1983, pl. 3, figs. 15-16. Bown and Cooper (1998) pl. 4.15, figs. 16-18. Mattioli and Erba (1999) pl. 2, figs. 9-10.  
**Remarks:** Following Mattioli and Erba (1999) this species is characterized by its distinctive rim shape, cross structure in the central area and bright birefringence colors. Ogg et al., 2008 recorded the LO of this species in mid Oxfordian at the base of magneto zone M31.

**Nannoconus globulus** Bronnimann, 1965  
*Nannoconus globulus* Bronnimann, 1965, p. 37, text fig. 2 i-m, pl. 2, figs. 14, 16, 20, 21.  
**Remarks:** Range of this species is Upper Tithonian or Lower Berriasian–Upper Aptian (Bown and Cooper, 1998).

**Nannoconus kamptneri minor** Deres and Achriteguy, 1980  
*Nannoconus kamptneri minor* Deres and Achriteguy, 1980. Bown and Cooper (1998) pl. 4.16, figs. 13.  
**Remarks:** The first occurrences of this species has been suggested as markers for the position of the Tithonian/Berriasian Boundary (Jurassic/Cretaceous boundary), which occurs at the base of magneto zone M18r (Channell et al., 2010). In the present study this species was recorded in the Minagish Field (Millennia, 2013, unpublished report).

**Nannoconus steimannii minor** Deres and Achriteguy, 1980  
*Nannoconus steimannii minor* Deres and Achriteguy, 1980, Bown and Cooper (1998) pl. 4.16, figs. 14.  
**Remarks:** The first occurrences of this species has been suggested as markers for the position of the Tithonian/ Berriasian Boundary (Jurassic/Cretaceous boundary), which occurs at the base of magneto zone M18r (Channell et al., 2010).

**Podorhabdus grassei** Noel, 1965  
(Plate 2, Figure 15)  
*Podorhabdus grassei* Noel, 1965, p. 103, pl. 9, figs. 1-2.  
**Remarks:** Following Roth, 1983, this species is characterized by having a thick stem and two pores.

**Polycostella beckmanii** Thierstein, 1971  
*Polycostella beckmanii* Thierstein, 1971, p. 483, pl. 2, figs. 5-16. Bown and Cooper (1998) pl. 4.16, figs. 18-19.  
**Remarks:** The first occurrence of this species occurs in the Lower Tithonian, and applied it as lower boundary for the NJT 15b Subzone (Casellato, 2010).

**Polypodorhabdus escaigii** Noel, 1965  
*Polypodorhabdus escaigii* Noel, 1965, p. 109, pl. 10, figs. 6-8, text fig. 32. Thierstein, 1976, pl. 2, figs. 22-25. Bown and Cooper (1998) pl. 4.13, figs. 18-20.  
**Remarks:** Known range of this species is Aalenian–?Albian (Bown and Cooper, 1998). In the present study this species was recorded only in Well B.
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Retecapsa spp
(Plate 3, Figure 1)
Remarks: In the present study this forms were recorded in Well B.

Rucinolithus wisei Thierstein, 1971
Rucinolithus wisei Thierstein, 1971, p. 482; pl. 4, figs. 11-15. Thierstein, 1976, pl. 3, figs. 21-22.
Remarks: Known range of this species is Lower Tithonian–Upper Valanginian (Thierstein, 1973).

Schizosphaerella punctulata Deflandre and Dangeard, 1938
(Plate 3, Figures 2-5)
Schizosphaerella punctulata Deflandre and Dangeard, 1938, p. 1115, figs. 1-6. Bown and Cooper (1998) pl. 4.16, figs. 21-22.
Remarks: In onshore Kuwait, the peak abundance of this species occurs in the upper part of the Dhruma Formation, slightly below the LO of C. superbus.
Stephanolithion speciosum Deflandre, 1954
Stephanolithion speciosum Deflandre, 1954. Deflandre and Fert, 1954, p. 146, pl. 15, figs. 7-8. Bown and Cooper (1998) pl. 4.11, figs. 23-25.

**Remarks:** Known range of this species is Lower Bajocian–Lower Callovian (Bown and Cooper, 1998). In the present study, this species was recorded only in Well C.

Watznaueria barnesae (Black, 1959) Perch-Nielsen, 1968
(Plate 3, Figures 6-7)
Watznaueria barnesae (Black) Perch-Nielsen, 1968, Black and Barnes, 1959, p. 325, pl. 9, figs. 1, 2. Perch-Nielsen, 1968, p. 69-70, pl. 22, figs. 1-7, pl. 23, figs. 1, 4, 5, 16, text-fig. 32. Roth, 1983, pl. 2, figs. 3-4. Bown and Cooper (1998) pl. 4.15, figs. 23-24. Mattioli and Erba (1999), pl. 3, figs. 12, 15-16

**Remarks:** In literature, some discrepancies emerge regarding this very distinctive event. It is probably due to a taxonomic problem between \( W. \) barnesae and \( W. \) fossacincta (Erba, 1990, *fide* Mattioli and Erba, 1999). The remarkable differences between the two species are in their central area where \( W. \) barnesae is completely closed. In \( W. \) fossacincta it is slightly opened with relatively brighter birefringence colors. The FO of \( Watznaueria barnesae \) marks the lower boundary of the NJT 11 of Mattioli and Erba (1999).

Watznaueria bayackii
Watznaueria bayackii Worsley, 1971, p. 23, pl. 1, figs. 21-23.

**Remarks:** In the present study, this species was recorded in wells A, C, D and H.

Watznaueria britannica (Stradner, 1963) Reinhardt, 1964
(Plate 3, Figures 8-10)
Watznaueria britannica (Stradner) Reinhardt, 1964. Stradner, 1963, p. 176, pl. 1, figs. 7, 7a. p. 753, pl. 2. Reinhardt, 1964, fig. 3, text-figure 5. Thierstein, 1978, pl. 4, figs. 24-25. Roth, 1983, p. 608. Bown and Cooper (1998) pl. 4.15, figs. 25-26. Mattioli and Erba (1999), pl. 3, figs. 9-10.

**Remarks:** Following Roth (1983), we only assign specimens to this species that shows a clear and relatively highly birefringent double bridge crossing an open central area. Specimens with a low birefringent bridge or a placolith central area structure are assigned to \( Watznaueria communis \). Mattioli and Erba (1999) considered the FO \( Watznaueria britannica \) is a very important marker for the Aalenian/Bajocian boundary in the Tethyan Realm, as it is found in the uppermost Aalenian or at the base of the Bajocian. In the present study, the FO \( Watznaueria britannica \) was found in the lower part of the Dhrauma Formation in wells B and H.

Watznaueria contracta (Bown and Cooper, 1989) Cobianchi, Erba & Pirini-Radrizzani, 1992
(Plate 3, Figures 11-13)
Watznaueria contracta (Bown and Cooper, 1989) Cobianchi, Erba & Pirini-Radrizzani, 1992. Mattioli and Erba (1999) pl. 3, fig. 7.

**Remarks:** This species is distinguished from \( Lotharingius contracta \) by the presence of a Watznaueriacean rim and its FO is characteristic of the basal Aalenian (Mattioli and Erba, 1999).

Watznaueria fossacincta (Black, 1971a) Bown in Bown and Cooper, 1989
(Plate 3, Figures 14-15)
Watznaueria fossacincta (Black, 1971a) Bown, 1989. Bown and Cooper, 1989, pl. 4.15, fig. 27. Roth, 1983, pl. 2, figs. 17-18. Mattioli and Erba (1999) pl. 3, fig. 11.

**Remarks:** Roth (1983) and Perch-Nielsen (1985) suggest that \( Watznaueria communis \) appear to be junior subjective synonyms of \( Watznaueria fossacincta \) (Black, 1971) Bown, 1989. This species is characterized by having a relatively small central area with a low birefringent bridge or a plate-like central area structure (Roth, 1983). Often, the central structure is missing, possibly because of dissolution. This species first occurs in the Middle Jurassic Early Bajocian (Bown, 1989).

Watznaueria manivitae Bukry, 1973
(Plate 3, Figures 16-18)
Watznaueria manivitae Bukry, 1973, p. 877. Bown and Cooper (1998) pl. 4.15, fig. 28. Mattioli and Erba (1999) pl. 3, figs. 13-14.
Plate 3: Middle to Upper Jurassic calcareous nannofossils from core samples in onshore Kuwait. All light micrograph crossed nicols (XPL), approximate magnification x 3,000. Well name, core depth and stratigraphic interval are listed.

1. ?Retecapsa spp, XPL, Well B, 14,306.50 ft, Sargelu-Dhruma Transition;
2. Schizosphaerella punctulata, XPL, Well B, 14,330.75 ft, Dhruma Formation;
3. Schizosphaerella punctulata, XPL, Well B, 14,386.90 ft, Dhruma Formation;
4. Schizosphaerella punctulata, XPL, Well B, 14,358.50 ft, Dhruma Formation;
5. Schizosphaerella punctulata, XPL, Well B, 14,389.50 ft, Dhruma Formation;
6. Watznaueria barnesae, XPL, Well B, 14,165.50 ft, Najmah Formation;
7. Watznaueria barnesae, XPL, Well K, 10,445.00 ft, Jubaila Formation;
8. Watznaueria britannica, XPL, Well K, 10,445.00 ft, Jubaila Formation;
9. Watznaueria britannica, XPL, Well C, 13,648.00 ft, Najmah Formation;
10. Watznaueria britannica, XPL, Well E, 15,508.00 ft, Upper Najmah Shale Member;
11. Watznaueria contracta, XPL, Well B, 14,311.70 ft, Sargelu-Dhruma Transition;
12. Watznaueria contracta, XPL, Well H, 15,354.60 ft, Sargelu Formation;
13. Watznaueria contracta, XPL, Well B, 14,306.50 ft, Sargelu Formation;
14. Watznaueria fossacincta, XPL, Well B, 14,168.50 ft, Najmah Formation;
15. Watznaueria fossacincta, XPL, Well B, 14,168.50 ft, Najmah Formation;
16. Watznaueria manivitae, XPL, Well C, 13,808.00 ft, Sargelu Formation;
17. Watznaueria manivitae, XPL, Well K, 10,445.00 ft, Jubaila Formation;
18. Watznaueria manivitae, XPL, Well V, 10,239.00 ft, Najmah Shale Member;
19. Zeugrhabdotus erectus, XPL, Well B, 14,323.30 ft, Sargelu Formation;
20. Zeugrhabdotus erectus, XPL, Well C, 13,812.00 ft, Sargelu Formation.
Remarks: In the literature, the nanno species of *Watznaueria manivitae* and *Cyclagelosphaera deflandrei* were often assimilated (Erba, 1990). Both species are large in size (probably larger than 9 µm). *W. manivitae* is characterized by a large, highly birefringent placoliths that are circular to slightly subcircular shape and shows a distinctive black cross on a bright yellowish white background. It is a very solution resistant and its FO is regarded as an excellent event of middle Early Bajocian (Mattioli and Erba, 1999). In the present study, the FO *Watznaueria manivitae* was observed at the lower part of the Dhruma Formation in Well H.

*Zeugrhabdotus embergeri* (Noel, 1959) Perch-Nielsen, 1984

*Zeugrhabdotus embergeri* (Noel, 1959) Perch-Nielsen, 1984. Noel, 1959, p. 164, pl. 1, figs. 5-8. Bown and Cooper (1998) pl. 4.10, figs. 4-5.

**Remarks:** In the present study, this species was recorded as reworked fossils in Well K.

*Zeugrhabdotus erectus* (Deflandre in Deflandre and Fert, 1954) Reinhardt, 1965

*Zeugrhabdotus erectus* (Deflandre in Deflandre and Fert, 1954) Reinhardt, 1965. Deflandre in Deflandre and Fert, 1954, p. 150, pl. 15, figs. 14-17; text figs. 60-62. Bown and Cooper (1998) pl. 4.10, figs. 6-10.

**Remarks:** Following Roth (1983), we assigned small specimens of *Zygodiscus (=Zeugrhabdotus)* with a single bar and a small stem or knob to this species.

Didemnid ascidian spicules.

*Velasquezia minuta* (Bonet & Benveniste-Velasquez) Varol 2006

*Velasquezia minuta* (Bonet & Benveniste-Velasquez) Varol, 2006, p. 48-49, pl. 1, fig. 29.

**Remarks:** This form was recorded in Well G. According to Varol (2006) ranges of this species is Upper Jurassic–Pleistocene.

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ERRATA

In Figure 1, northernmost well named “V” is Well AA, and in the caption, the last sentence should read: “Nannofossil data was obtained for wells A-K and AA”. In the explanation for Plate 1, V should be changed to AA for numbers 1, 4, 11, 12, and 13. For Plate 3, V should be changed to AA for number 18.
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Enclosure I: Southeast-northwest cross-section of Middle and Upper Jurassic, showing thickness variations within this interval. Note the presence of two wedges (yellow), one in the Lower Najmah Shale and one in the Upper Najmah Shale. Gamma-ray logs are logarithmic and color scheme in legend indicates deflection amplitudes. See Figure 1 for well location and spacing.
Calcareous nannofossil zonation and sequence stratigraphy of the Jurassic System, onshore Kuwait

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(with contributions from Y.-M. Le Nindre and R.B. Davies)
GeoArabia, 2015, v. 20, no. 4, p. 125–180, with 2 Enclosures

ENCLOSURE II

Figure 4

Enclosure II: North-south cross-section showing correlation of the Gotnia and Hith formations. Note that 3rd Gotnia salt and anhydrite are absent in wells T and R in the south and in wells X, Y, Z and 2 towards the north. Northernmost Well Z is also missing 3rd Gotnia salt and anhydrite. Gamma-ray logs are logarithmic and color scheme indicates deflection amplitudes. See Figure 1 for well location and spacing.