Late Tithonian–Late Berriasian Differential Aggradation and Progradation of the Habshan Carbonate System

After this first cycle, the increased rate of accommodation and carbonate production resulted in strong aggradation of the Habshan lagoonal deposits in the northwestern part of the platform (Figure 2). The lower sedimentation rate to the southeast led to a progressive tilt of the successive depositional profiles, and to the development of relatively steep prograding clinoforms made of oolitic and bioclastic grainstone, deposited in a platform margin environment ("Habshan Oolite").

Late Berriasian–Late Valanginian Significant Fluctuations of Accommodation, Related to Eustatic Cycles and Regional Uplift

The top Habshan surface corresponds to a major exposure surface linked to the Late Berriasian–Early Valanginian lowstand related to an "icehouse" global context. The Thamama F, G and H ("Zakum" equivalent) transgression and aggradation is related to a major sea-level rise that followed the Early Valanginian lowstand. The top Thamama F (top "Zakum") surface corresponds to another major exposure surface related to the Late Valanginian–Hauterivian lowstand period, interpreted as a result of a regional uplift of the Arabian Plate ("Late Valanginian unconformity").

The proposed Late Jurassic–Early Cretaceous stratigraphic model provides new concepts for well correlations at both regional and reservoir scale, which may have an impact on reservoir models and prediction. It also allows building a coherent stratigraphic scheme for the Late Jurassic–Early Cretaceous interval from the UAE to the Sultanate of Oman (Razin et al., 2013).

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Stratigraphic aspects of the Upper Jurassic to Lower Cretaceous of Saudi Arabia

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The Upper Jurassic to Lower Cretaceous, Oxfordian to Valanginian, lithostratigraphic succession of Saudi Arabia is divided into the Jurassic Shaqra Group and the Cretaceous Thamama Group, the boundary of which lies within the uppermost Tithonian. This interval includes at least five third-order sequence boundaries and maximum flooding zones. J60 and K40 are two regionally recognized sequence boundaries, and J50 and J100 represent two regionally established Jurassic maximum flooding surfaces. The Upper Jurassic succession includes shallow- to deep-marine carbonates of the Hanifa (Oxfordian) and Jubaila (Kimmeridgian) formations, and shallow-marine carbonates and evaporites of the Arab (Kimmeridgian) and Hith (Kimmeridgian to Tithonian) formations. The Upper Jurassic to Lower Cretaceous succession includes the shallow to moderately deep carbonates of the Sulaiy Formation (Tithonian to Berriasian) with the overlying Yamama Formation being of Cretaceous age (Valanginian). These formations were deposited in a period of increasing global temperature, during a transitional phase leading to greenhouse.

Carbonates of each formation host grainstones and packstones of reservoir quality, including the Hanifa (Hanifa Formation), Arab D (Jubaila-Arab formations), Arab C to A (Arab Formation), Rimthan, Hith stringers and Manifa (Hith Formation), Lower Ratawi (Sulaiy Formation) and Upper Ratawi (Yamama Formation). Seals to these reservoirs are provided by transgressive muds of overlying sequences or, in the case of the Arab and Hith formations, by interbedded evaporites.

Chronostratigraphic control of the Oxfordian to Valanginian succession is determined using a variety of methods of variable refinement. Of the non-biostratigraphic techniques, the Callovian to Aptian strontium-isotope character is featureless except for a gradual increase in the ^{87}Sr/^{86}Sr isotope ratio, and provides very limited stratigraphic control. Of the carbon and oxygen isotopes, δ^{16}O displays a gradual decline from the Kimmeridgian to Middle Valanginian, but δ^{18}C displays a clearly defined positive trend at the basal Berriasian. Although the Oxfordian palaeomagnetic character is highly variable, the Kimmeridgian to Valanginian displays palaeomagnetic reversals at a lower frequency and these can be used for regional correlation.

The succession is difficult to biostratigraphically date with precision, owing to the generally restricted palaeoenvironments and the mostly endemic nature of the regionally significant species. Type sections of Saudi Arabian formations within the age of interest have been dated at outcrop using ammonites and nautiloids, supplemented by foraminifera. Subsurface equivalents are easily recognized using biofacies, but are dated mostly on benthonic foraminifera and calcareous alga, as calpionellids have not yet been identified in the basal Cretaceous carbonates and planktonic foraminifera are rare and long ranging. The elusive Jurassic/Cretaceous boundary is based on calcareous nannofossil evidence. With cautious sensitivity to biofacies diachroneity, high-resolution intraformational stratigraphy is possible with establishment of local biofacies-based events of correlative value.

Middle Jurassic to Early Cretaceous calcareous nannofossils from Onshore North Kuwait: A new record

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A new record of calcareous nannofossil datum markers from Middle Jurassic to Early Cretaceous (Bajocian to Valanginian) strata of onshore North Kuwait has been calibrated with nannofossil marker species of the global Jurassic to Early Cretaceous nannofossil biostratigraphy schemes of Bown and Cooper (1998), Bralower et al. (1989), Bown et al. (1998), Perch-Nielsen (1985), and compared with Lower to Middle Cretaceous calcareous nannofossil zones offshore Kuwait (Al-Fares et al., 1998)(Figures 1 and 2). The studied sections embrace, in ascending order, the Dhruma, Sargelu, Najmah, Gotnia, Hith, Makhul, Minagish and Ratawi formations, and comprise argillaceous limestones, grainstones, packstones, bituminous packstones, wackestones, dolomite, anhydrite, laminated bituminous calcareous mudstones and calcareous shales. These units represent a variety of environments from marginal marine (sabkha) and shallow hypersaline (salina), to fully marine mid- to outer-shelf settings (Neog et al., 2010; Crittenden et al., 2012).

The association of *Assipetra infracretacea, Calcicalithina oblongata, Rucinolithus wisei* and *Tubodiscus verenae* was identified in the Ratawi Limestone Member of the Ratawi Formation indicating the Lower Valanginian NK3a Subzone of Bralower et al. (1989). The nannofossils recorded in the Minagish Formation were few and include *A. infracretacea, C. oblongata, R. wisei, Cyclagelosphaera margerelii, Watznaueria barnesae,* and an influx of *Nannoconus* spp. suggesting a Late Berriasian age. The lower part of the Makhul Formation contains *A. infracretacea, C. margerelii, Polycostella senaria, W. barnesae, W. britannica* and *W. manivitiae* suggesting an age no older than the Early Berriasian.

Shale laminae in the Hith Formation contain the index fossil *Polycostella beckmanii* indicating a Late Jurassic (Tithonian) age. Nannoflora recovery in the lowest part of the non-evaporites portion of the

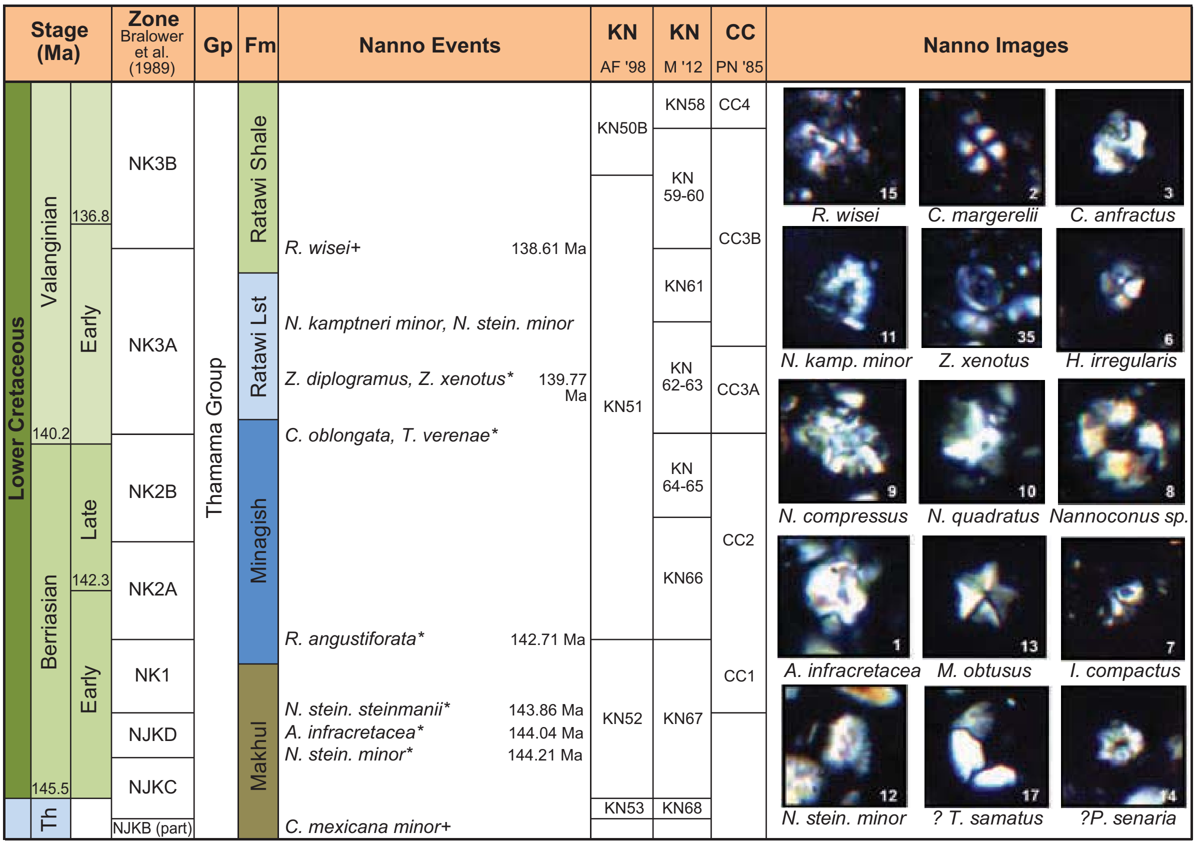

Figure 1: Berriasian to Valanginian calcareous nannofossil biostratigraphic zones and events of onshore Kuwait area. Stage and NK zone after Bralower et al. (1989, op cit Bown et al., 1998), KN AF zones after Al-Fares et al. (1998), KN M zones after Packer et al. (2012), CC zones after Perch-Nielsen (1985). * = appearance; + = disappearance.

Gotnia Formation (Neog et al., 2010), herein correlated with the calcareous bituminous mudstone of the Najmah 1 Member (Yousif and Nouman, 1997), is abundant and contains *Watznaueria* spp. but *Lotharingius crucicentralis* and *Nannoconus* spp. absence suggest that the sediments were deposited within Kimmeridgian to Tithonian interval in a marine inner to middle-shelf setting. The non-evaporitic portion of the Gotnia Formation overlies unconformably the Najmah Limestone and is overlain conformably by the Gotnia evaporites Formation. It might correspond with the Jubaila Formation that is sandwiched between the Najmah Limestone and Gotnia evaporites distributed in the Gotnia Basin of Kuwait (Al-Sahlan et al., 2011).

The Najmah Limestone is barren of nannofossils, yet the upper Najmah Shale contains the robust and dissolution resistant species *W. barnesae* and the high birefringence *W. manivitiae, W. britannica* and *W. fossacincta* indicating Oxfordian–Callovian lower NJ19 zone or older. The majority of the specimens are poorly preserved with the inner part of the coccolith covered by oil staining. The lower Najmah Shale contains common to few, moderate to poorly preserved *W. britannica* and *W. manivitiae* but *C. magharensis* absence, suggesting Early Callovian–Upper Bathonian ?NJ12-NJ11 zones. The Sargelu Formation is barren of nannoflora. Nannofossil assemblages in the Dhruma/Sargelu transition contain *C. magharensis, Discorhabbus striatus* and *W. contracta* suggesting the Bajocian NJ10 Zone of Bown et al. (1998).

The Dhruma Formation consists of calcareous bioclastic shale interbedded with wackestone and mudstone that yield common to abundant nannofossils. The NJ10 Zone of Bown et al. (1998) was recognized in this formation that suggests a correlation with the Bajocian. The upper NJ10 assemblages are characterized by the presence of *L. crucicentralis, W. contracta* and *W. britannica,* while the lower NJ10 assemblages are marked by the abundance of *Schizosphaerella punctulata* with *D.*

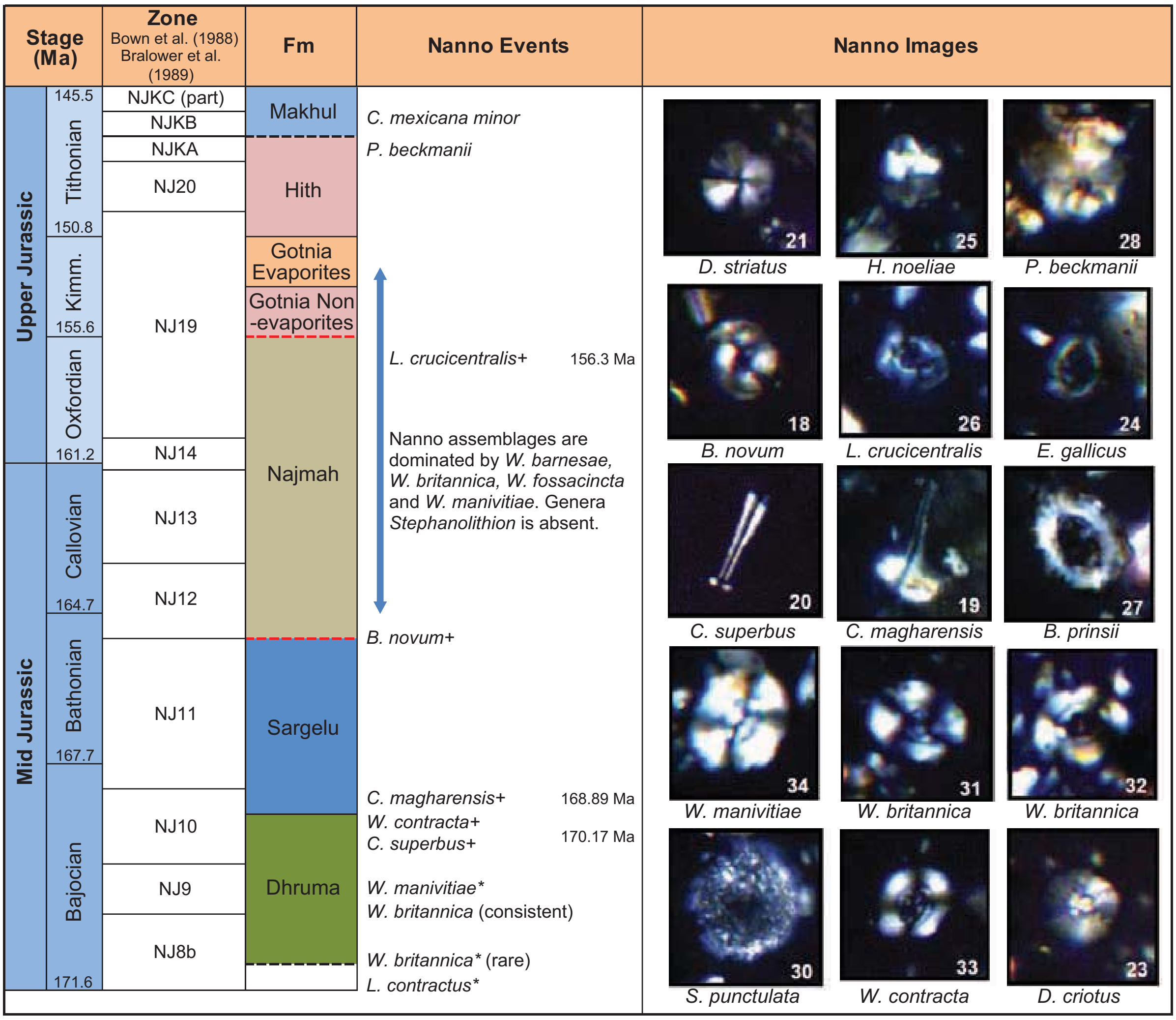

Figure 2: Bajocian to Tithonian calcareous nannofossil biostratigraphic zones and events of onshore Kuwait area. Stage and NJ zone after Bown and Cooper (1998) and Nanno events after Packer et al. (2012). * = appearance; + = disappearance.

criotus. Nannofossil assemblages in the samples indicate that the Dhruma Formation was deposited in a marine environment, more distal than the overlying Sargelu Formation, at mid to outer-shelf depositional environment.

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Structural and stratigraphic trapping of hydrocarbons within Late Jurassic to Early Cretaceous section as observed from drilling and 2-D/3-D seismic in Partitioned/Divided Zone of the Kingdom of Saudi Arabia/Kuwait

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Introduction

Structural and stratigraphic traps in the Partitioned/Divided Zone (PZ) between the Kingdom of Saudi Arabia and Kuwait suggest minimal tectonics during carbonate build-ups within the Late Jurassic to Early Cretaceous (Figure 1). Today, these same reservoirs are structurally compartmentalized as determined from pressure data, wells and the incorporation of an array of 2-D/3-D seismic data (Figure 2).

The application and knowledge of regional tectonics indicates that left-lateral, strike-slip faulting produced many transpressional structures within the Arabian Peninsula. The transpressional faults form the traps and can be mapped using 2-D and 3-D seismic data. They are sub-vertical and trend NS to NNW with *en-echelon* faults trending NW-SE to SW-NE. In addition minor transtensional faults further provide a pathway for the migration of hydrocarbon. This structural framework was affected by single to multiphase inversion with a late stage *en-echelon* "collapse graben" faults that compartmentalize the Late Jurassic to Early Cretaceous hydrocarbon reservoirs (Figure 3).

Exploring and appraising Late Jurassic to Early Cretaceous reservoirs require combining our knowledge about the original depositional models where "optimum reservoir facies" reside and an awareness of structural/stratigraphic traps. *Is the trap further compartmentalized?* In the Partitioned/Divided Zone area we are applying the model from the Triassic Marrat to Eocene and through drilling to confirm additional traps (Figure 4).

Example

A recently drilled example is illustrated in the shallow Partitioned/Divided Zone reservoirs through the application of structural principles to predict structural traps where faults are linked to Jurassic and Cretaceous reservoirs (Figure 4). Similar structural mix-mode deformation is confirmed within Oman by Filbrandt et al. (2006, Figure 5). In this study both mixed-mode transpressional and transtensional traps are illustrated using Partitioned/Divided Zone examples. For the Ratawi reservoirs in the Partitioned/Divided Zone the compartmentalization is seen by NE-trending strike-slip faults. The compartmentalization was confirmed through variation of pressure data (Figure 6).

Our study emphasizes linking sequence-stratigraphic and tectonic concepts to illustrate optimal locations for future exploration and appraisal drilling leading to additional development area for more production within the Partitioned/Divided Zone of the Kingdom of Saudi Arabia and Kuwait.