Stratigraphic organisation of the Jurassic sequence in Interior Oman, Arabian Peninsula

Mathieu Rousseau, Gilles Dromart, Henk Droste and Peter Homewood

ABSTRACT

A stratigraphic model is proposed for the Jurassic sequence in Interior Oman. The model is based on regional well-log correlations, outcrop analysis and integration of biostratigraphy. Large-scale architectures are restored using a well-to-well correlation technique, after the well-log markers of the relevant surfaces of sequence stratigraphy are identified. This identification is achieved by comparing well-log signatures to lithological and sedimentological columns of nearby exposed sections. The subsurface dataset consists of 19 wells arranged in two east-west profiles, 341 km and 332 km long.

The Jurassic sequence in Interior Oman shows a general easterly thinning wedge and includes two hiatuses with marked age-gaps. Three major depositional episodes are identified: (1) a Pliensbachian-Toarcian coastal encroachment in a southward direction, represented by the dominantly clastic deposition of the Lower Mafraq Formation upon the Permian carbonates; (2) a general late Bajocian marine flooding (hybrid facies of marginal-marine environments of the Upper Mafraq Formation), followed through the Bathonian-Callovian by the carbonate Dhruma-Tuwaiq System which evolved through time from a low-angle, homoclinal ramp dipping in a (north) westwards direction, to a purely aggradational, flat-topped platform (upper Dhruma and Tuwaiq Mountain formations); (3) a Kimmeridgian-Tithonian onlap in an eastwards direction of fine-grained limestones (Jubaila-Rayda) upon the post-Tuwaiq unconformity. Depositional hiatuses in the early Liassic and at the Early-Middle Jurassic transition are likely to reflect major eustatic sea-level lowstands. In contrast, subsurface correlations of the MFSs through the Dhruma-Tuwaiq indicate that the post-Tuwaiq unconformity is a low-angle (0.001 degrees) angular unconformity associated with tilting and truncation of the underlying sequences. Oxfordian sequences were probably never deposited in Interior Oman because of a lack of accommodation space and prolonged subaerial exposure. It is here proposed that the Upper/Middle Jurassic angular unconformity in Interior Oman was planed-off by subaerial carbonate dissolution during a steady, tectonically-driven uplift of the whole eastern Arabian shelf edge.

The proposed geological model has several implications for the petroleum systems of Interior Oman. The geometric model predicts the distribution of the sedimentary facies, including source rocks, clastic and carbonate reservoirs, and seal facies. The occurrence of isolated Upper Mafraq-producing reservoir sands (i.e. Sayh Rawl field) are believed to be restricted to central and eastern Interior Oman. There are two other reservoir/ seals combinations, both related to the Upper/Middle Jurassic unconformity: (1) truncation traps of the Dhruma-Tuwaiq below the unconformity (i.e. Hadriya and Uwainat reservoirs); (2) updip pinch-out trap of the Hanifa above the unconformity. Finally, it is believed that the early Late Jurassic general uplift and truncation of eastern Oman may have caused local remobilisation, updip migration, and loss to the surface of oil in reservoirs, initially generated from the prolific Al Huqf source rocks of Late Precambrian-Early Cambrian age.

INTRODUCTION

The Jurassic sequence of the Arabian Gulf contains some of the most important reservoirs in the world and includes many of the giant oil fields of the Arabian Gulf (Al-Husseini, 1997). In the Sultanate of Oman, many hydrocarbon shows have been reported from the clastic and carbonate reservoirs of the
Jurassic Sahtan Group, and oil is currently produced from the clastic Mafraq Formation at Sayh Rawl field. Several lithostratigraphic and biostratigraphic investigations of the Jurassic platform sequence have been made in outcrops in northern and eastern Oman (Glennie et al., 1974; Pratt and Smewing, 1990; Rousseau et al., 2005). These studies also include the regional mapping of outcrops by the BRGM on behalf of the government of the Sultanate of Oman. However, no study that is specifically dedicated to the Jurassic of the subsurface in Interior Oman has been published to date. The present work is the first to tie outcrop and subsurface data for the Jurassic sequence of Oman.

This paper provides a geometric model for the Jurassic platform of Interior Oman that is based on two west-east regional well-log correlation transects. Prior to any subsurface correlation, a comparison has been made between wells and nearby outcrops to calibrate the well-log responses in terms of lithology and sedimentology. After the geometric model is drawn, available biostratigraphic data are integrated in order to test and date the model. Finally, we propose a chronostratigraphic diagram for the Jurassic Period in Interior Oman.

Our technical objectives are the following:
(1) to clarify the lithostratigraphic scheme currently used for the Jurassic sequence by tying surface and subsurface data;
(2) to determine large-scale depositional geometries by using regional wireline-log correlation, and thus assist interpretation of the stratal-termination patterns of the Jurassic sequence seen on seismic lines;
(3) to distinguish the controlling factors on the Jurassic carbonate platform system of Oman through regional comparisons (Arabian Shelf and southwestern Neo-Tethys realm): regional changes (sea level, climate) versus local palaeogeography and geodynamics; and
(4) to provide a stratigraphic model which improves the understanding of the petroleum systems of Oman: deposition of source rocks, burial/thermal history, and distribution and entrapment styles of the Jurassic hydrocarbon reservoirs.

STRATIGRAPHIC BACKGROUND

The Sahtan Group was defined by Glennie et al. (1974) in the Oman Mountains outcrops to cover the shallow-marine carbonate Jurassic rocks lying between the Triassic dolomites of the Mahil Formation and the overlying fine-grained limestones and marls forming the lower part of the Kahmah Group. The Jurassic sequence was further divided into several lithostratigraphic units by Hughes Clarke (1988) from a survey of the oil-producing areas of Interior Oman (Figure 1).

The Mafraq Formation, Late Triassic to Middle Jurassic Bajocian in age, was defined in well Mafraq-1 in eastern Interior Oman. The formation is 63 m thick and is composed of a siliciclastic continental unit (i.e. Lower Mafraq), overlain by a mixed siliciclastic-carbonate lithology reflecting the onset of the Jurassic marine transgression (i.e. Upper Mafraq). The overlying Dhurma, Tuwaiq Mountain, Hanifa, and Jubaila formations are exclusively carbonate units, which originally were defined in Saudi Arabia by Steineke (1937, in Powers, 1968). The reference section for the Dhruma Formation in Oman is located in well Yibal-85, central Interior Oman. The section is 218 m thick, and is composed of a mudstone overlain by a slightly dolomitic, porous, grain-supported limestone.

The reference section in Oman for the Tuwaiq Mountain, Hanifa, and Jubaila formations is in well Abu Butabul-1, western Interior Oman. The Tuwaiq Mountain Formation (128 m thick) displays a single sequence evolving upwards from deep-shelf lime mudstones to shallow-marine porous pack-grainstones. According to Hughes Clarke (1988), this formation is probably mainly Oxfordian in age. The 63 m drilled thickness of the Hanifa Formation (probably early Kimmeridgian in age) is an argillaceous, fine-grained limestone at the base, passing up into a porous, grain-supported limestone. Finally, the Jubaila (79 m thick) consists of a slightly argillaceous, generally fine-grained limestone, for which the palynological assemblages indicate an early Tithonian age.

The upper surface that bounds the Jubaila Formation is a disconformity overlain by the Kahmah Group, the basal unit of which, the Rayda Formation, consisting of thin-bedded, porcellaneous limestones (lime mudstones) with fine-grained argillaceous intervals and levels of flints (Connally and Scott, 1985;
Simmons and Hart, 1987; Scott et al., 1988; Pratt and Smewing, 1990; Rabu et al., 1990; Scott, 1990). In Al Jabal al Akhdar, the lowermost Rayda Formation locally shows beds of crinoidal debris (Wadi Quri; Rousseau et al., 2005) and a “bone-bed” with concentrated fish-teeth, belemnites, ammonites and bone fragments (Béchennec et al., 1992). Calpionellid assemblages found in the Rayda Formation yield a biostratigraphic age spanning the Tithonian-Berriasian Boundary (Rousseau et al., 2005).

The Jurassic Sahtan Group of the Oman Mountains outcrops is composed of two main lithological units (Rabu, 1987; Le Métour, 1988): (1) a Lower Jurassic, mixed siliciclastic-carbonate unit referred to as Lithiotis Limestones; and (2) a Middle to Upper Jurassic massive carbonate upper unit. An important reduction in thickness of the Jurassic platform series in association with a marked age-gap between the Sahtan and Kahmah groups was previously documented across Al Jabal al Akhdar by Rabu et al. (1990). The Sahtan Group is about 400 m thick in western Al Jabal al Akhdar (e.g. Wadi Sahtan), but is limited to 30 m in the northeastern area (e.g. Wadi Qarah). Recently, Rousseau et al. (2005) have related the eastwards thinning of the Sahtan Group to the truncation of genetic sequences. The angular unconformity at the top of the Sahtan Group is veneered by the Rayda Formation that shows an onlap pattern. The minimal age-gap in the Oman Mountains is middle Callovian-Kimmeridgian. Oxfordian and Kimmeridgian sequences were probably never deposited in this area due to a lack of accommodation space and/or subaerial exposure.

Finally, Sharland et al. (2001) have provided a general sequence-stratigraphic framework for the Arabian Plate on the basis of the identification and codification of several maximum flooding surfaces.

Figure 1: Stratigraphic nomenclature for the Jurassic and Lower Cretaceous of Oman Mountains, Interior Oman and central Saudi Arabia. Geological time scale after Gradstein et al. (2004).
(MFS), interpreted to record eustatic sea-level maxima, which were correlated through the Middle East. As to the Jurassic, eleven MFSs were recognised over the Arabian Plate. The reference sections for these MFSs are spread all over the Middle East: Saudi Arabia for the Early and Middle Jurassic MFSs; and Abu Dhabi, Qatar and Yemen for the Upper Jurassic MFSs. In Interior Oman, the Early to Middle Jurassic MFSs (i.e. J10 to J40), and Late Jurassic MFSs (i.e. J50, J60, J70) have been placed by Sharland et al. (2001) in the well Yibal-85, and well Abu Butabul-1, respectively.

METHODS AND MATERIALS

In Interior Oman, the Jurassic sequence is covered by Cretaceous and Tertiary deposits (Figure 2), and most of the data used in our study come from the subsurface. The seismic-scale architecture of the Jurassic platform is revealed here using a well-to-well correlation technique. The biostratigraphic resolution for the Jurassic of the Middle East is too limited to support any stratigraphic correlations. However, biostratigraphy has been used as much as possible to check and date our stratigraphic model. In this study, the stratigraphic cross-sections have been drawn by correlating the well-log markers of the relevant surfaces of sequence stratigraphy, namely sequence boundaries and maximum flooding surfaces. The sequences are the stratigraphic record of cycles of change in the ratio between accommodation space (A) and sediment influx (S). This approach has found application in Jurassic carbonate platforms, for instance in the Anglo-Paris Basin for which MFSs of third-order sequences have been mapped over tens to hundreds of kilometres (Garcia et al., 1996; Garcia and Dromart, 1997).

For carbonate platforms, a preliminary calibration of the well-log responses in terms of sequence stratigraphy is critical because, for example, some high gamma-ray readings do not correspond to shaley lithologies and some shales do not represent marine inundations (Dromart et al., 1996). The calibration, which consists of checking the sedimentological significance of the well-log patterns (i.e. lithology, depositional facies and environment), is achieved by comparing outcrop sections to the well-log data of the closest well. This procedure leads to the selection of a number of prominent well-log markers including those corresponding to the sequence boundaries and marine-flooding surfaces. Depositional geometries are then reconstructed by a well-to-well correlation of the recurrent markers of these particular surfaces. Because of the fairly flat topography of the Arabian Platform during the Jurassic time, the changes from site to site of the shape of well-log deflections marking those surfaces are limited. However, the final relevance of each stratigraphic surface depends on the possibility of correlating it with confidence over the entire study area.

Two Jurassic sections that crop out on the periphery of Interior Oman were measured, in the Adam Foothills (Jabal al Madar) and the Haushi-Al Huqf areas (Figure 2). The Jabal al Madar Section was correlated with well Jabal Madar-1 located 19 km southeast, whereas the Al Huqf Section was compared to well Shara-1 located 51 km southwest. The subsurface dataset consists of 19 wells that are arranged into two east-west profiles (Figure 2). The transects are 341 and 332 km long, and are tied at well Lekhwair-319. This well was chosen because it yields the most comprehensive Jurassic sequence in Oman (i.e. 1,057 m thick) and biostratigraphic data are available (Millennia, unpublished PDO Report, 1998). As to the 18 other wells, gamma-ray and sonic acoustic-velocity logs, along with neutron-density porosity log overlays, were used for correlation.

The applied methodology can be summarised as follows:

(1) Detailed macroscopic sedimentological and palaeontological description of outcrop sections, and delineation of depositional sequences by environmental interpretation of facies and identification of remarkable surfaces (e.g. subaerial exposure, ravinement, marine flooding).

(2) Calibration of the well-log signatures, i.e. comparison of the well-log data with closest outcrop sections.

(3) Construction of a 2-D to 3-D stratigraphic model by well-log correlation.

(4) Checking and dating the stratigraphic model by biostratigraphic data.

(5) Interpretation of the palaeogeographic and geodynamic frameworks.
Figure 2: Simplified geological map of Interior Oman showing locations of studied outcrops and subsurface transects.
RESULTS

Jabal al Madar Section (22°23′42″N, 58°08′25″E)

A Jurassic sequence is exposed in the core of Jabal al Madar Anticline (Adam Foothills; Figure 3; Geological Map of Nazwa, sheet NF 40-07; Béchennec et al., 1992). The Jurassic sequence in Jabal al Madar is 59 m thick and the top of the Jurassic is truncated. At the base of the Jurassic, above a poorly exposed interval, the section is dominated by shallow-marine limestones interrupted by two major siliciclastic intervals. On the basis of the vertical changes of the faunal content, textures, sedimentary structures and lithological composition, 3 major sequences have been identified. The Sahtan Group is topped by the typical “porcellaneous limestones” of the Rayda Formation. The section is presented below in stratigraphic-ascending order.

Lower unit (Lower Mafraq)

The Triassic Mahil Formation is unconformably overlain by the Jurassic sequence. The unconformity is marked by a ferruginous hardground locally capping a weathered, iron-stained bed. The lower 8 m of the Jurassic sequence are recessive and covered. This interval is overlain by 5 m of fine-grained, variegated limestone, yielding wavy, non-parallel, discontinuous bedding surfaces. The skeletal biota is dominated by thick, paired and elongate bivalve shells composed of fibrous, palisadic calcite, and referred to as Lithiotis. Other bivalves such as small oysters are associated with gastropods in bioclastic lenses. The top of the Lithiotis Limestones consists of a ferruginous hardground. Above, 7 m of the section are covered by scree and capped by a resistant, 6-m-thick, russet sandstone unit of the overlying sequence.

Lower Sequence (Lower Mafraq)

The lowermost 6 m of the sequence are made up of a coarse- to very coarse-grained, clean sandstone showing horizontal planar lamination cut by decimetric scale scours (Figure 3). Above, the general size of the quartz grains decreases. There are large tabular crossbeds associated with shallow scours veneered by lag deposits. Upwards, lenses of fine sandstone are embedded within dm-thick levels of coarser sandstone forming scour-and-fill structures. The upper half-cycle of the sequence includes two horizons of very fine sandstone showing a typical alternation of red and white layers with incipient nodular fabric (Figure 3). The uppermost horizon shows traces of roots, and this is taken as evidence of subaerial exposure. The overall facies assemblage of the sequence is composed of a multi-storey sheet sand-body overlain by abandonment deposits, and is interpreted as a flood-plain facies tract.

Middle Sequence (Upper Mafraq)

The 11 m of the middle sequence are made up of a fine- to very fine-grained bioclastic limestone showing wavy and discontinuous bedding. Diffuse bioturbation has effaced most of the sedimentary structures. The transgressive lower 4 m are composed of a fine-grained bioclastic limestone with a skeletal biota dominated by tiny bivalves (small-sized oysters), fragments of gastropods, echinoderms, and small-sized brachiopods. Higher up, a series of marl-limestone interbeds is capped by a massive dolomitic level. The regressive half-cycle is characterised by a fine- to medium-grained limestone showing amalgamation of lenses of bioclasts. The fine-grained matrix contains small-sized (i.e. 0.1 to 0.5 mm) ferruginous ooids. The top interval of the sequence corresponds to a siliciclastic horizon that consists of a fine- to medium-grained sandstone yielding current- and wave-ripple bedding, and swaley cross-stratification.

The sequence was laid down in a fully-marine environment, passing upwards from upper offshore to (?middle) shoreface. The maximum flooding surface is interpreted to correspond to the recessive shaly horizon, localised in the middle of the sequence (MFS are essentially arbitrarily placed within the shaly horizons). The top boundary of the sequence, i.e. regressive to transgressive turnaround surface, is localised in the middle of the upper siliciclastic interval (Figure 3).
Figure 3: Lithological and sedimentological composite log of the Jabal al Madar Section and sequence stratigraphic interpretation. Details of the distinct clastic facies of the Mafraq Formation: (a) shoreface (clean sandstone with planar and hummocky crossbedding) deposits; (b) floodplain (sheet-flood layering); and (c) channel (scour-and-fill structures).
Upper Sequence (Dhruma)

The uppermost sequence of the Sahtan Group at Al Jabal al Madar is composed of interbedded shales and bioclastic wackestones to grainstones. Both are affected by diffuse bioturbation. The skeletal biota, dominated by tiny oysters and gastropods, is generally arranged in thin, graded bioclastic storm layers. Oolites are a subordinate grain component, though their proportion increases upwards. The uppermost interval is a coarse oolitic grainstone composed of amalgamated bioclastic storm layers and capped by a ferruginous hardground.

This upper sequence shows a vertical stacking of similar facies. The facies assemblage is interpreted to reflect a somewhat protected marine environment because: (1) the storm layers are thin and do not show deep erosional furrows; and (2) the skeletal biota is not diverse.

Jabal al Madar Section – Jabal Madar-1 (JBM-1) Well: Comparisons and Differences

Several specific lithologies and stratigraphic surfaces of the Jabal al Madar Section can be recognised on well-log data (gamma ray-sonic and neutron-density; Figure 4).

The Triassic-Jurassic contact that consists in the field of a sharp change from massive dolomite to shale is clearly distinguishable in JBM-1. The recessive overlying interval in the section has a subsurface counterpart yielding very elevated gamma-ray values (i.e. above 150 API) together with a high positive offset of the neutron-density overlay. Higher up, the Lithiotis Limestones can be identified in the well as a porous limestone, showing a fairly blocky pattern for the gamma-ray log, and no offset for the neutron-density log overlay.

The lower sandstone interval is characterised by medium gamma-ray values and the density that exceeds the neutron porosity in a characteristic silica crossover. The large scattering of gamma-ray values from 30–120 API, together with the general barrel-like shape of the gamma-ray curve, is suggestive of a sand bar (c.f. estuary sand bar documented by Reiser, 1999). The overlying shale levels, interpreted as flood-plain deposits in the Jabal al Madar Section, are represented in the subsurface by high gamma-ray values combined with a pronounced offset for the neutron-density porosity log overlay, due to elevated density (c. 2.8 g/cm³). Similar log attributes for flood-plain shales have been previously documented in the Triassic sequence of the Paris Basin by Bourquin et al. (1993), following the evidence that shales deposited in flood plains have much heavier density than their marine counterparts. It is noted that the high gamma-ray reading of shales observed in the Mafraq Formation of JBM-1, is interpreted as a sequence boundary and not as a maximum flooding surface.

The overlying interval (Middle Sequence), corresponding to an offshore environment in the Jabal al Madar Section, is characterised by fairly low gamma-ray values (not exceeding 100 API), and a limited positive neutron-density overlay. The major shale horizon occurring in the middle of this interval, and interpreted as a marine flooding event, is well expressed by the well-logs. The high density reading shown just beneath this level is indicative of dolomite.

The upper siliciclastic interval characterised in the Jabal al Madar Section by fine-grained sandstone (base of the Upper Sequence) deposited in a shoreface environment is clearly distinguishable in JBM-1, on the basis of a neutron-density crossover. The overlying interval, which is predominantly composed of shallow-water limestone in the section, yields a fairly distinct lithological component in the well. Five horizons with silica content are implied by the neutron-density crossover. They are interbedded with dolomitic limestone horizons.

In the Jabal al Madar Section, the Jurassic-Cretaceous contact is a sharp facies change between the pure carbonate deposits of the upper Dhruma Formation and the fine-grained, argillaceous limestone of the Rayda Formation. This passage is marked in well-logs by a sharp increase of positive neutron-density overlay along with a moderate increase of gamma-ray values.
Figure 4: Correlation between Jabal al Madar Section and JBM-1 well. See Figure 2 for location.
The Jurassic sequence crops out in the Al Huqf area (Figure 5) (Geological Maps of Khaluf, sheet NF 40-15; Dubreuilh et al., 1992). The Jurassic section is 105 m thick. Above a poorly exposed interval, the section is dominated by coarse-grained oolitic limestones deposited in a shallow-marine environment. The top of the Jurassic series of the Al Huqf area is truncated. A total of three sequences have been identified throughout the exposed part of the section. The section is presented below following a stratigraphic-ascending order.

**Lower Unit (Lower Mafraq)**

In the Al Huqf area, the Jurassic Sahtan Group unconformably overlies the Upper Permian part of the Khuff Formation and the basal levels consist of a thick laterite palaeosol according to Dubreuilh et al. (1992). In the studied section, the basal levels are not well exposed owing to the shaly nature of the sediments. Pronounced lateral facies variations are common in this interval. A few hundred metres next to the main section, large lenses of very coarse quartz sandstone can be observed directly above the bioclastic marl of the Khuff Formation. These facies are repeated laterally over a few kilometres and are interpreted to be a succession of distributary channels cutting into floodplain shales. In some places, these channel fills are capped by ferruginous crusts with traces of roots. These terrigenous deposits at the base of the Sahtan Group are overlain by a large recessive and covered section.

**Lower Sequence (Upper Mafraq)**

The base of the transgressive half-cycle is composed of a fine-grained sandy dolomite showing planar lamination with angular-base foresets. Laterally, this horizon shows 2–3-m-deep channels, filled with a matrix-supported conglomerate. The nature of the centimetre-sized angular clasts is varied, including dolomite, chert, bioclastic limestone and fragments of corals. The matrix is composed of very coarse sandstone with horizontal and oblique planar lamination. This channel-fill occurrence represents the uppermost major clastic event recorded in the Jurassic sequence in the Al Huqf area. The lateral equivalent of these channels in the Al Huqf Section (Figure 5) is a ferruginous surface at the top of the sandy dolomite lithology. Above, the quartz fraction decreases rapidly. The overlying levels are composed of a medium-grained bioclastic dolomite showing diffuse bioturbation and locally, planar oblique lamination. Storm beds, with echinoderm debris and convex-up valves of bivalves, occur occasionally. The following five metres are made up of a dolomicrite including isolated cherts. This monotonous interval is punctuated by three storm layers with tiny bioclasts. Above, the deposition of a fine- to medium-grained bioclastic dolomite yielding oolites and debris of corals is indicative of a greater marine influence. The overlying shales are inferred to represent the maximum flooding episode of the sequence. Shale levels are abruptly capped by a 7-m-thick, massive package of beds made up of a fauna-rich, coarse-grained oolitic grainstone. Skeletal biota is composed of bivalves, gastropods, corals and echinoids. These components are typical of a wave-agitated marine shoal.

A lagoonal, backshore environment is inferred for most of the thick, transgressive half-cycle. The regressive half-cycle is much thinner, and is composed of shoal facies directly overlying offshore facies. The boundary between the lower and middle sequence, i.e. regressive to transgressive turnaround surface, is localised within the massive oolitic unit.

**Middle Sequence (Dhruma)**

This sequence is 34 m thick and characterised by dominantly carbonate sedimentation under fully marine conditions. The base and top of this unit is composed of a chalky oolitic grainstone to rudstone, yielding a very varied skeletal macrofauna dominated by different coral forms (Figure 5). The bulk rock is composed of oolites with a size varying from 0.25 to 2 millimetres. Additional components of the fauna are large bivalves, including oysters, echinoderms, large brachiopods (e.g. Burmirhynchia), and large gastropods. The oolitic grainstone shows planar and oblique lamination, storm-generated furrows, and wavy lamination. These sedimentary structures are indicative of high-energy conditions. Several surfaces of non-deposition, including the top surface of this interval, are encrusted by corals and thick-shelled oysters.
Figure 5: Lithological and sedimentological composite log of the Al Huqf Section and sequence stratigraphic interpretation. Views showing different aspects of the depositional facies of the Dhruma Formation: (a) well-bedded pattern of the upper oolitic facies; (b) chalky oolitic facies enclosing large-sized cherts; and (c) horn-shaped coral.
The Middle Sequence displays a relative symmetrical pattern in terms of hemi-cycle thickness and facies composition. This sequence is bounded by mixed oolitic and coral shoals subjected to permanent wave agitation. The 10-metre-thick, middle interval probably corresponds to a more distal, open-marine environment, only disturbed by storms reworking oolites from the shallower upper-offshore environment.

**Upper Sequence (Dhruma)**
The Upper Sequence consists of interbedded shales and very fine-grained bioclastic dolomites. Noticeable sedimentary structures are planar crossbeds, undulatory laminae, thin storm coquina beds with typical convex-up bivalves, and bird-eye fenestrae, all suggestive of shallow-water environments. The poorly diversified skeletal biota is composed mainly of bivalves, mostly oysters, and corals with few gastropods near the top only. The top of the sequence consists of a thin level of oolitic grainstone with bioclasts.

The Upper Sequence shows a vertical stacking of fairly similar facies indicative of a restricted, shallow-water environment protected by an oolitic barrier. The maximum flooding surface of the sequence corresponds to the maximum palaeobathymetry.

**Al Huqf Section – Shara-1 (SH-1) Well: Comparisons and Differences**
The four intervals, including the three fully-developed sequences of the Al Huqf Section can be recognised from the well-log patterns of Shara-1 (SH-1; gamma ray-sonic and neutron-density; Figure 6). The Khuff-Sahtan contact in SH-1 consists of a reciprocal and sharp change of gamma-ray and sonic values. The overlying shaly interval that represents the lower interval of the outcrop section is apparently 3 m thinner in SH-1.

Above, the sharp shift from shale to sandstone, interpreted in the field section to be a sequence boundary, can unmistakably be pinpointed in the well. The overlying sandstone is characterised in SH-1 by low gamma-ray values and a very moderate positive offset of the neutron-density overlay. The Lower Sequence shows a similar composition and thickness in the well and outcrop section. Distinctively, dolomitic levels are thinner in the well, and the occurrence of an upper shaly sandstone interval is restricted to the well. The pronounced lithological contrast marked by the sharp shift of sonic, density and neutron-porosity logs at the top of the interval, and corresponding to the Mafraq-Dhruma transition, can be correlated with the marked change of facies, at the sole of the lower oolitic horizon of the section.

The composition (shaly carbonates) and thickness (c. 25 m) of the Middle Sequence are very comparable in the well and section. The repeated high gamma-ray readings can be interpreted as maximum flooding surfaces. The upper, well-bedded oolitic limestone at the top of the interval is clearly distinguishable in the well (porosity of about 10%).

The Upper Sequence that corresponds to a restricted marine environment in the Al Huqf Section, is made up of a large spectrum of lithologies in the well: shales, shaly carbonates, a sandy limestone, and a shaly dolomite at the top. Such a lithological assemblage is consistent with a restricted marine environment as well. The significant positive neutron-density overlay, noticed throughout this interval, is due to the presence of shales. The gamma-ray values decrease towards the top. A much thicker part of this Upper Sequence is preserved in SH-1 in comparison to the outcrop section (50 m versus 25 m).

The Jurassic-Cretaceous contact in SH-1 has been placed at the base of a porous limestone unit (Lekhwair Formation).

**REGIONAL EAST-WEST CORRELATIONS**
The northern east-west wireline-log correlation extends from well Jabal Madar-1 (JBM-1) to well Lekhwair (L-319) (Figure 2). The well spacing varies from 16 to 61 km. The southern east-west correlation is 350 km long and extends from SH-1 to L-319. The well spacing varies from 8 to 82 km.
Figure 6: Correlation between Al Huqf Section and Shara-1 well.
The datum of both transects is more or less the boundary between the Dhruma and Tuwaiq Mountain formations.

Both transects (Figures 7 to 10) show the following salient features:
(1) The Mafraq and Dhruma formations both thicken considerably in a westward direction.
(2) The Tuwaiq Mountain Limestone has a constant thickness and shows a sheet-like depositional geometry.
(3) There is a very marked unconformity at the top of the Dhruma-Tuwaiq system, cutting down into the Tuwaiq Mountain and Dhruma formations in an eastward direction.
(4) The post-Tuwaiq unconformity is overlain by distinct lithological units, i.e. formations are younger in age as we move eastwards.

Figure 7: West-east regional well-log correlation for the Jurassic sequence in Interior Oman, northern transect (Figure 2). The datum is the MFS right above the Uwainat Member, i.e. Bathonian-Callovian transition.
The Mafrag System

Two transects have been drawn for the Mafrag (Figures 11 and 12). The datum is the subaerial exposure surface (i.e. sequence boundary) identified in outcrops at the base of the Lower Sequence and Middle Sequence in the Al Huqf and Jabal al Madar sections, respectively. This surface separates the Lower Mafrag from the Upper Mafrag (sensu Hughes Clarke, 1988).

The total thickness of the Lower Mafrag increases tenfold in a westward direction, i.e. from 20–30 m to 280 m. The Lower Mafrag approximately doubles in thickness between AH-48 and MTL-1 in the southern transect, and between FSW-305 and ARS-1 in the northern transect. The depositional geometries, restored by the well-log correlations suggest, a typical onlapping stratal termination pattern for the Lower Mafrag. Deposits lap onto the Permian-Triassic succession towards the E-SE.

The log signatures show that most of the lowermost Mafrag consists of flood-plain shales enclosing lignite (e.g. L-319) and sandstone occurrences (e.g. L-319, MZON-1, ARS-1, FSW-305). The sandstones cannot be correlated from well to well and probably represent amalgamated and single fluvial-channel fills. Two remarkable limestone marker units can be distinguished in the Lower Mafrag: (1) the Lithiotis Limestones, restricted to the eastern section of the northern transect (i.e. JBM-1 to MMR-1); and (2) a unit, labelled as “Lower Mafrag Limestone Marker” that can be traced along the entire length of the northern transect and down to Y-440 in the southern transect. Above this limestone marker, the uppermost Lower Mafrag is composed of a widespread, fairly flat and aggrading unit. The continental deposits of this unit are predominantly shales in the western area (L-319, MZON-1, ARS-1, FSW-305, N-82, and MTL-1, Y-440, AH-48) and pass in an eastward direction to a diversified and laterally variable assemblage of dolomites, shales and sandstones. The lower interval of the Al Huqf Section can be related to this interval (uppermost Lower Mafrag), as well as the interval referred to as “Minjur Formation” by Dubreuilh et al. (1992) in the Al Haushi area and north of Jabal Tharay. This basal interval, up to 15 m in thickness, is composed of variegated shales and sandstones with common root traces, and locally, lenses of kaolinitic clay and ferruginous crusts.

Biostratigraphic data are limited for the Lower Mafrag in Oman. However, in the northeastern area of study (e.g. Jabal al Madar Section), the Lithiotis Limestones contain the benthic foraminifer Orbitopsella praecursor in Al Jabal al Akdhar (Rabu, 1987), diagnostic of a late Carixian (i.e. early Pliensbachian) age (Bassoullet, 1997a). This dating is consistent with the middle-late Carixian age recently proposed by Elmi et al. (2003) for the Lithiotis Limestones of western Algeria, on the basis of associated brachiopod marker beds. Above, the presence of the dinocyst Nannoceratopsis gracilis, just below the “Lower Mafrag Limestone Marker” in well Y-440 (Figure 12), indicates a late Pliensbachian-Bathonian age (Courtinat, oral communication, 2004). The well-log correlations make it possible to consider that there are no deposits of Triassic age within the Lower Mafrag in eastern Interior Oman. Accordingly, the reassignment by Dubreuilh et al. (1992) and Roger et al. (1992) of the Lower Mafrag to the (Triassic) Minjur Formation in the Haushi-Al Huqf area because of facies comparisons should be abandoned.

The Upper Mafrag, which records the early transgression of the Jurassic over Interior Oman (Hughes Clarke, 1988), consists of a typical aggrading system (i.e. sheet-like overall geometry; Figures 9–11. Although the thickness variation of the Upper Mafrag is relatively subtle (20–30 m over the study area, 23 m in well Mafrag-1), the log signatures show evidence of complex lateral variations of facies (shales, silty shales, sandstones, dolomitic sandstones, dolomites, limestones). This high lateral variability is well-illustrated by the distinct facies association encountered in the time-equivalent Middle Sequence of the Jabal al Madar Section (12 m, Figure 3) and Lower Sequence of the Al Huqf Section (27 m, Figure 5). The lateral variability is partly due to the development in some places of incised valleys on the Lower Mafrag. These valleys would have been variably filled during the early transgression. In well MBR-4, for example, the filling section is composed of basal ferruginous oolites (possibly reworked pisolites from laterite crusts) and silty, dolomitic shales, possibly representative of estuarine environments.

The upper boundary of the Mafrag is placed at the top of the interval with significant clastic content (Hughes Clarke, 1988). So in the far-western area (e.g. L-319), the Upper Mafrag is restricted to the...
Figure 8: Detailed correlations of the Jurassic sequence in Interior Oman, northern transect presented in Figure 7.
lower part of the transgressive hemicycle, whereby in most of the wells and in the Al Huqf Section, the Upper Mafraq covers the full transgressive hemicycle. Conversely, in northeastern Interior Oman (e.g. Middle Sequence of the Jabal al Madar area), there is also a clastic phase in the regressive part of the first cycle so that the Upper Mafraq composes a full depositional cycle.

Only one direct biostratigraphic data point has been established for the Upper Mafraq in Oman. Molds of the ammonite *Thambites cf. planus* were found at the base of the Upper Mafraq in the Haushi-Al Huqf area (Roger et al., 1992). *Thambites cf. planus* is characteristic of the D3 unit of the Dhruma Formation in Saudi Arabia (late Bajocian to earliest Bathonian; Enay et al., 1987a). Independently, *Thambites* has been dated in the Parkinsoni Zone (late Bajocian) in Morocco (Enay et al., 1987b). This late Bajocian age for the Upper Mafraq that can be derived from the Al Huqf Section, is consistent with the late Bajocian-Bathonian age of the lower Dhruma given by the dinocyst assemblages in L-319.

The Dhruma-Tuwaiq System

The stratigraphy of the Dhruma and Tuwaiq Mountain formations has been interpreted by correlating 6 maximum flooding surfaces (Figures 7–10). The Dhruma-Tuwaiq System shows a substantial and regular thickening (e.g. 60 to 550 m for the Dhruma) in a (north) westwards direction prior to erosion. The maximum flooding surfaces delineate the geometries which evolved through time from a low-angle, homocinal ramp dipping in a (north) westwards direction, to a pure aggradational, flat-topped platform (upper Dhruma and Tuwaiq Mountain). This overall stratal pattern of the Dhruma-Tuwaiq carbonate platform is consistent with the general “shallowing-up” trend inferred in the wells from the vertical decrease of the gamma-ray values.

The well-log signatures suggest the Dhruma-Tuwaiq System is made up of porous and non-porous limestones and shales. We have no control on the complexity of the lateral-facies substitution. However, it should be noted that a porous horizon (i.e. Uwainat Member) of the upper Dhruma can apparently be traced over the entire Interior Oman.

According to dinocyst assemblages in L-319, the age of the Dhruma is late Bajocian-Bathonian and that of the lower Tuwaiq is middle Bathonian-early Callovian. The ages of the outcrop sections have been provided in the literature. A Bajocian-Callovian age has been inferred from foraminiferal occurrences for the Dhruma of the Haushi area (Dubreuilh et al., 1992). However, the presence of *Haurania cf. amiji* and *H. deserta* in their list better suggests a Bajocian-Bathonian time-span, according to Bassoullet (1997a). In the Oman Mountains (Al Jabal al Akhdar), a brachiopod-rich level found in the middle Dhruma has yielded an early Bathonian-middle Callovian age (Rousseau et al., 2005). In addition, the comparison of MMR-1 (northern transect) with the Wadi Nakhr Section in western Al Jabal al Akhdar (Rousseau et al., 2005) suggests that the MFS at the Dhruma-Tuwaiq passage in the well can be reliably correlated with the MFS of sequence IV of the outcrop. Sequence IV contains a prolific assemblage of benthic foraminifers typical of the *Pfenderina trochoides* Cenozone that corresponds to the Atash Member of the Upper Dhruma Formation in Saudi Arabia (Bassoullet, in Rousseau et al., 2005). The Atash Member marks the Bathonian-Callovian transition on the western Arabian shelf (Enay et al., 1987a). This independent age assignment for the Dhruma/Tuwaiq boundary in MMR-1 is in total agreement with the biostratigraphic information available in L-319, supporting the proposed stratigraphic model.

A Bathonian age can thus be considered for the Dhruma in Oman. Following the time scale of Gradstein et al. (2004), the sequences corresponding to the 6 MFSs traced through the Dhruma were deposited during several million years, which suggests that the MFSs are on the third-order scale of Vail et al. (1991). As yet the Bajocian-Bathonian and Bathonian-Callovian boundaries cannot be accurately placed. However it can be seen that the MFSs at the Mafraq-Dhruma and Dhruma-Tuwaiq transitions do not fit in age with the relevant MFSs of Sharland et al. (2001) reported in Y-440. (Figures 9 and 10). Sharland et al. (2001) apparently have misplaced the MFSs middle Toarcian J10 (late Bajocian in Y-440), early Bajocian J20 (late Bajocian in Y-440), and middle Callovian J40 (early Callovian in Y-440). Only the position of the early Bathonian J30 MFS is in agreement with the data presented here.
The thickness of the upper Dhruma and Tuwaiq Mountain formations is reduced by truncation at the top towards the northeast (Figures 7–10). Consistently, evidence of subaerial exposure (i.e. karst features) has been reported for the surface between the Tuwaiq Mountain and Hanifa in L-319 (Badley Ashton and Associates Ltd, unpublished PDO report 99118, Core Sedimentology of Lekhwair Field, 2000). The top erosional surface is widespread and truncates, from west to east, the Tuwaiq Mountain and the Dhruma formations. The truncation is low angle. The average gradient of erosion is about 0.1%; the upper Dhruma and Tuwaiq in the northern transect lose about 250 m in thickness along a 300-km-long distance. The general gradient is lower in the southern transect: 170 m have been removed over a length of 350 km. Enhanced erosion can be detected locally in wells FSW-305, JMM-1 and AH-48.

The erosional unconformity visible at the top of the Tuwaiq-Dhruma System is variably overlain by the porous carbonates of the Hanifa Formation in the west (L-319), the fine-grained limestones of the Jubaila-Rayda System in DM-3, the typical Rayda Formation (northern transect, exclusive of ARS-1...
Rousseau et al. (2005): 
S_{TV} MFS: Bathonian / Callovian 
S_{III} MFS: M. Bathonian-M. Callovian

BIOSTRATIGRAPHY:
1 Late Tithonian-Early Valanginian
2 Late Kimmeridgian-Early Berriasian
3 Middle Bathonian-Early Callovian
4 Late Bajocian-Bathonian
5 Late Pliensbachian-Bathonian

Hanifa Formation 
Mafraq Sequence Boundary 
Top of “Lower Mafraq Limestone Marker” 
Maximum Flooding Surfaces

Jurassic Sequence, Interior Oman

Northwest

SOUTHERN TRAVERSE

Lekhwair-319 (L-319)

Muwaythil-1 (MTL-1)

Yibal-440 (Y-440)

Al Huwaisah-48 (AH-48)
and MZON-1, and BK-5 to MTL-1 in the southern transect), and by the Lekhwair Formation in the southeast (FA-1 to BA-5 and SH-1). According to Hughes Clarke (1988), the Hanifa Formation is early Kimmeridgian in age in western Oman. Above, the occurrence of *Clypeina jurassica* in the lowermost Jubaila-Rayda of L-319 indicates a latest Kimmeridgian to Tithonian age (Bassoullet, 1997b).

On the basis of the microfossil (calpionellid association) and macrofossil (ammonite) content, the Rayda Formation has been assigned to the uppermost Tithonian-Berriasian in Al Jabal al Akdhar (Rousseau et al., 2005). Finally, the Lekhwair Formation has been dated as Hauterivian (Hughes Clarke, 1988). This implies that a highly variable age gap between the Sahtan and the Kahmah groups is developed in Interior Oman. The ages of the rocks beneath and above the unconformity do not vary independently. The older the underlying rocks, the younger the overlying rocks are, so that the hiatus increases considerably from west-northwest to east-southeast: early-middle Callovian to early Kimmeridgian in L-319; Bathonian to Berriasian in JBM-1; and Bathonian to Hauterivian in SH-1.
Figure 11: West-east regional well-log correlation for the Mafraq Formation in Interior Oman, northern transect (Figure 2). The datum is the subaerial-exposure surface separating the Lower and Upper Mafraq.
DISCUSSION

Control on the Stratal Termination Pattern

The stratal-termination pattern of rock units is controlled by the variations of accommodation (i.e. creation and removal of space for sediments to fill) through time and space. Tectonics and eustasy, both responsible for accommodation changes, can theoretically be distinguished since subsidence and uplift is a function of both space and time, whereas sea level rises and falls uniformly through time. The depositional and erosional history of the Jurassic rock units of Interior Oman are discussed below in stratigraphic ascending order.

Early Jurassic Liassic Coastal Onlaps

Considerable peneplanation must have taken place prior to deposition of the Jurassic Sequence, as the basal Sahtan shows evidence of a palaeorelief (Figure 11). The Lower Mafraq in Interior Oman is a wedge of floodplain deposits that onlaps to the east and southeast. The middle Liassic unit represented by the Lithiotis Limestones is interpreted by us as having been the first Jurassic marine deposit that overstepped the Permian succession in a southwards direction. These marginal-marine...
Figure 12: West-east regional well-log correlation for the Mafraq Formation in Interior Oman, southern transect (Figure 2). The datum is the subaerial-exposure surface separating the Lower and Upper Mafraq.

Facies (Catenacci, 1976; Frazer, 2001) are restricted in our study area to the eastern part of the northern transect, and are well-developed farther north in Oman Mountains outcrops (Rabu, 1987; Rousseau et al., 2005). The Lithiotis Limestones are not encountered in the interior of the Arabian shelf but are widespread over the eastern edge of the Arabian Plate, as they have been documented in the Musandam Peninsula (Hudson and Chatton, 1959) and in the Fars Province of Iran (Gollesstaneh, 1965; Setudehnia, 1978). These nearshore, transgressive deposits in northern Oman are thought to reflect the Carixian (Pliensbachian) eustatic rise, recorded in the southern Neo-Tethys, in particular in the Betic Cordillera in southern Spain (Ruiz-Ortiz et al., 2004), and on the northwestern Saharan basement (Elmi et al., 1998). Deposition is believed to have ceased abruptly in Interior Oman after this flooding episode. Evidence of marked subaerial exposure (i.e. karstic vugs) observed at the top of the Lithiotis Limestones in the Oman Mountains outcrops (e.g. Wadi Muaydin, Al Jabal al Akdhar) supports this interpretation.

Aggradation and onlap of continental clastics (channel-fill sandstones and floodplain shales) resumed in western Interior Oman, presumably in response to gentle down-warping of this area. Above, the major and transverse overstepping feature produced by the “Lower Mafraq Limestone Marker” in a southwards direction (Figures 11 and 12), is suggestive of the occurrence of a significant eustatic rise. We have neither depositional facies control nor macrofossil documentation that could substantiate...
this. However, the “Lower Mafraq Limestone Marker” can be compared to the limestone unit at the Lower-Middle Marrat transition in central Saudi Arabia, the top of which is confidently dated, on the basis of ammonite biostratigraphy, as early Toarcian (Arkell, 1956; Enay et al., 1987a). The microfossil content in Interior Oman (i.e. dinocysts in Y-440) is consistent with a Toarcian age. This transgressive feature in the Lower Mafraq of Interior Oman is interpreted by us as reflecting the early Toarcian marine flooding that covered most of the Arabian shelf (Le Nindre et al., 1990; Al-Husseini, 1997). The overlying, purely aggrading continental to marginal-marine unit bounded upwards by a subaerial-exposure surface (e.g. Lower Sequence in the Jabal al Madar Section) is interpreted as being a typical highstand wedge. There is no direct dating available for the deposition of this unit.

**Early-Middle Jurassic Depositional Hiatus**

Following the Toarcian transgression and aggradation, a major depositional hiatus developed in eastern Interior Oman prior to the late Bajocian marine flooding. Apparently little topography was created during this subaerial exposure. Incised valleys are presumed to have developed in MBR-4 and FA-1 of the southern transect. No significant upwarping affected the underlying reference level that is the “Lower Mafraq Limestone Marker” (Figures 11 and 12) suggesting that the main factor responsible for this regional subaerial-exposure surface in Interior Oman is a sea-level lowstand. Similarly, the Jurassic sequence of central Arabia lacks upper Toarcian and Aalenian deposits (Enay et al, 1987a). A substantial sea-level fall (i.e. about 50 m) was proposed by Al-Husseini (1997) to explain this major depositional hiatus recorded all over the western and southern Arabian Gulf.

**Late Bajocian Marine Flooding**

The combination of the geometric control and the vertical facies evolution observed in outcrops suggests that the Upper Mafraq Formation in Interior Oman, dated as late Bajocian, was deposited during a transgression over a land surface with some minor relief. Mobilisation of coarse-grained clastics during early transgression (i.e. transgressive half-cycle) was widespread over the study area. In detail, the basal Upper Mafraq is presumably diachronous because of the presence of some incised valleys. Conversely, clastic deposition during the following highstand phase was restricted to near-shore environments in the northeastern area, probably nearer exposed siliciclastic sources, so that the Upper Mafraq-Dhruma transition is likely to be diachronous as well.

Transgressive conditions prevailed during the Bajocian all over the Arabian shelf (Enay et al., 1987a; Al-Husseini, 1997). The maximum overstepping of Bajocian marine deposits onto the Arabian Shield corresponds to the lower Middle Dhruma D3 unit (Parkinsoni Zone) (Le Nindre et al., 1990), the time-equivalent unit of the Upper Mafraq in Interior Oman. The Upper Mafraq is thus interpreted to represent a typical transgressive systems tract of a second-order, eustatic-controlled marine flooding.

**Bathonian-Callovian Carbonate Platform**

Correlations in the Dhruma-Tuwaiq carbonate system in Interior Oman suggest minimal relief and an aggrading geometry. The geometry, together with the facies composition, reveals that the Interior Oman shelf was permanently flooded under shallow-marine waters, and marginal siliciclastic sources were no longer exposed. We see evidence for a predominantly tectonic control for the lower and middle Dhruma related to downwarping of the western area, whereby little accommodation was created in eastern Oman, presumable by a concomitant slow rise in sea-level.

Equal thickness of the Upper Dhruma and Tuwaiq Mountain strata (prior to erosion) over the entire study area suggests that differential subsidence ceased to the benefit of a eustatic-controlled and steady rise in relative sea level. The Upper Dhruma and Tuwaiq Mountain formations can be seen as a typical flat-topped, aggrading carbonate platform referred to as “keep up” type by Sarg (1988). The late Bathonian-middle Callovian depositional time for the Upper Dhruma and Tuwaiq Mountain formations was a period of general transgression over the Arabian shelf (Al-Husseini, 1997), presumably related to a global sea-level rise.
Late Jurassic Subaerial Peneplanation

The post-Tuwaiq unconformity in Interior Oman presumably is a composite feature, including the widespread Middle-Upper Jurassic unconformity that has been recognised all over the Arabian Peninsula (Murris, 1980). There is no record of the uppermost Callovian-lower Oxfordian between the Tuwaiq Mountain and Hanifa formations in central Saudi Arabia (Enay et al., 1987a; Hirsch et al., 1998). This major hiatus has been recently related to a general lowstand of sea level in association with the formation of high-latitude continental ice sheets (Dromart et al., 2003). Whereby marine conditions resumed during the middle Oxfordian over most of the Arabian Peninsula (i.e. original Hanifa Formation; Enay et al., 1987a), the Sahtan Group of Interior Oman was presumably maintained under subaerial exposure throughout the Oxfordian-Kimmeridgian (Rousseau et al., 2005). Necessarily, this relatively high elevation would have been tectonically created because the Late Jurassic was a time of high global sea level (Hallam, 1988). The general low-angle topography of the surface at the top of the Sahtan Group suggests that erosion mainly involved subaerial dissolution, promoted and kept going by gentle upwarping of the carbonate-platform edge. If we assume that the thickness of the upper Dhruma-Tuwaiq was constant across the area before erosion, it can be inferred that a carbonate pile, up to 200 m in height, may have been removed in eastern Interior Oman prior to latest Jurassic-Cretaceous deposition.

A possible mechanism for the differential uplift across Interior Oman is a general compressive buckling of the lithosphere. Such a view is supported by the fact that the exhumation and peneplanation described for the Upper Jurassic in Interior Oman is conspicuous over the 2,000-km-long, entire eastern edge of the Arabian Plate (e.g. eastern Abu Dhabi, Al-Suwaidi and Aziz, 2002; Fars Province of Iran, Gollesstaneh, 1965). Consistently, several contemporaneous intrashelf basins were differentiated over the Arabian shelf (Murris, 1980; Ayers et al., 1982; Beydoun, 1988; Sharland et al., 2001), including the Abu Dhabi intrashelf basin adjacent to Interior Oman (Al-Suwaidi and Aziz, 2002).

Late Jurassic-Early Cretaceous Onlap

In Interior Oman, the erosional Jurassic unconformity is overlain successively in an eastwards direction by the Hanifa, above which the Jubaila-Rayda, the Rayda, and the Lekhwair formations lap onto progressively older Jurassic rocks. A short episode of subaerial exposure followed deposition of the Hanifa (early Kimmeridgian) and preceded deposition of the Jubaila-Rayda (latest Kimmeridgian to Tithonian).

In outcrops of the Central Oman Mountains, the Sahtan-Kahmah unconformity is sealed by an opposite (i.e. westward-directed) onlap of the Rayda Formation. The lowermost Rayda, which shows a typical deepening-upward sequence, has been dated as Tithonian from the occurrence of crinoidal sands, including saccocoma-type debris, and ammonites (Rousseau et al., 2005). In northern Oman, the offshore Triassic carbonate plateau of Jabal Kawr is overlain sharply by pelagic, saccoecomid-rich deposits (Béchennec et al., 1992), typically of an early Tithonian age in the western Neo-Tethys (Dromart and Atrops, 1988). A similar reset of marine conditions can also be documented in the Interior Fars province of Iran (Gollesstaneh, 1965). In outermost shelf sections of the High Zagros (e.g. Kameh Kat and Kuh-e Gadvan sections), fine-grained and thin-bedded limestones, bearing latest Kimmeridgian-early Tithonian ammonites (i.e. Lithoceras and Torquatisphinctes), directly overlie Middle Jurassic strata (Gollesstaneh, 1965).

So apparently, the whole eastern edge of the Arabian shelf was subjected to a marine flooding during the latest Kimmeridgian and Tithonian. A similar and contemporaneous transgression has been documented, in very distinct geodynamic settings, over western Neo-Tethys carbonate platforms including the Dinarids (Slovenia) and the Jura (eastern France) (Strohmenger et al., 1991), northern Algeria and Morocco (Atrops and Benest, 1984; Cattaneo, 1991), and central Italy (Umbria; Centamore et al., 1971). This suggests that the aggradational-onlap pattern of latest Jurassic strata around the Arabian shelf edge was primarily induced by a long-term eustatic sea-level rise (i.e. second-order).
IMPLICATIONS FOR THE JURASSIC PETROLEUM SYSTEM IN INTERIOR OMAN

The following discussion aims to: (1) evaluate how the Jurassic geological history of Interior Oman may have controlled the deposition of organic-rich rocks, remigration of hydrocarbons, and the development of traps; and (2) show how depositional environments may have influenced the localisation, and some of the attributes of the Jurassic reservoirs.

Source Rocks

Lignite beds have been encountered in the Lower Mafraq Formation in a number of wells in Interior Oman (e.g. Lekhwair, Mafraq). However, these intervals are too thin and discontinuous to offer any notable source-rock potential.

Middle Oxfordian (i.e. DS J50) organic-rich mudstones (i.e. Hanifa) were deposited in the western offshore area of the Abu Dhabi Emirate in the United Arab Emirates (Al-Suwaidi and Aziz, 2002), and their extent to northwestern Oman might be a possibility. The deposition and preservation of these source rocks in the western intrashelf basin was favoured by the uplift of eastern Interior Oman during the early Late Jurassic because it formed a restricted basin on the shelf.

According to Terken et al. (2001), the oil-generation rate of the Jurassic oils significantly increased during the Late Cretaceous. In northwestern Oman these oils may have migrated laterally from source rocks in the west, up-section and updip to the east into the Hanifa reservoir.

Burial, Thermal Histories and Remigration

The Jurassic sequence in Oman shows a general easterly thinning wedge and large hiatuses (Figure 13). The depositional gap of the lowermost Jurassic is associated with a long-term lowstand of the sea level. The Early-Middle Jurassic hiatus is a widespread depositional gap due to major, eustatically-induced, withdrawals of the sea. Conversely, the Middle-Upper Jurassic unconformity, mainly due to erosion related to the progressive tilting of the east flank of Interior Oman, shows missing overburden at this period. Any modelling of the burial and thermal history of the area should take account of this feature.

The early Late Jurassic uplift of the east flank of Interior Oman caused general tilting of the underlying formations. The large-scale geometries across Interior Oman (Figures 7–10) show related erosion cutting into the Dhroma Formation. Erosion reached the Lithiotis Limestones in the outcrops of the northwestern Oman Mountains (Rousseau et al., 2005). Finally, the occurrence of large-sized carbonate lithoclasts coming from the Akhdar Group (Permian) within the upper Guwaysa Formation (Upper Jurassic; eastern flank of Al Jabal al Akhdar, Jabal Safrah and Hamrat Duru Range; Rousseau and Dromart, personal observations) shows that the early Late Jurassic erosion reached Upper Palaeozoic formations. We believe that the early Late Jurassic general uplift truncation of eastern Oman may have triggered remobilisation, updip migration, and loss to the surface of oil in reservoirs, initially generated from the prolific Al Huqf source rocks of Late Precambrian-Early Cambrian age (Al Huqf and Q oils; Terken et al., 2001).

Entrapment Style and Trap Timing

Three types of stratigraphic traps (i.e. reservoir/seal combinations) can be identified in the Jurassic sequence of Interior Oman (Figures 13 and 14): (1) isolated reservoir sands of the Lower and Upper Mafraq; (2) truncation traps of the Dhroma-Tuwaiq below the pre-Jubaila-Rayda unconformity; and (3) updip pinch-out trap of the Hanifa above the pre-Jubaila-Rayda unconformity.

Hydrocarbon shows have been reported from sandstones of the Lower Mafraq Formation, i.e. Lekhwair and Al Huwaisah fields (Figures 1, 13 and 14). Those clastic units correspond to fluvial channel fills totally encased in impermeable shales and siltstones. The location of such occurrences in
the subsurface remains unpredictable, and they are generally too thin, (i.e. only a few metres thick) to be detectable on seismic data. Oil currently is produced from sandstones of the Upper Mafraq in Sail Rawl field. Three clastic units are present and seals are provided by intra-formational shales and argillaceous lime mudstones (S.G. Corbin, unpublished PDO, 1984). The possible gas effect in the uppermost clastic level of the Upper Mafraq in JBM-1 (i.e. high displacement of density-porosity relative to neutron; Figure 4) confirms stratigraphic-trap potential of the Upper Mafraq in eastern Interior Oman. These well-sorted, clean sandstones are thought to owe their reservoir quality to the shoreface environment in which they were deposited. They should exhibit a much greater lateral continuity and volume than their Lower Mafraq counterparts. Conversely, the apparent genetic connection of the Upper Mafraq clastic reservoirs to a shoreface depositional environment suggests that they are not present in the western area of the study area (characterised by distal marine environments).

Habiba and Fushaigah fields are example of the second type of stratigraphic trap where the Uwainat reservoir of the Upper Dhruma is truncated towards the east and is sealed by the tight fine-grained limestones of the Rayda Formation (Figures 6-8). A similar reservoir/seal combination is available farther west, e.g. Dhulaima field, where the Hadriya Limestone of the Tuwa’iq Mountain Limestone is cut by the unconformity and capped by fine-grained limestones of the Jubaila Formation.

The third type of stratigraphic trap is restricted to the most western area where the typical association comprises porous limestone of the Hanifa Formation that laps onto the post-Tuwa’iq unconformity and is sealed by aphanitic limestones of the Jubaila Formation. The Hanifa reservoir has proved prolific in Abu Dhabi but not yet in northwestern Oman.

![Figure 13: Schematic regional chronostratigraphy for the Jurassic and earliest Cretaceous through Interior Oman. The diagram shows hydrocarbon occurrences in the Jurassic sequence.](http://pubs.geoscienceworld.org/geoarabia/article-pdf/11/1/17/5442661/rousseau.pdf)
The combination of the geological history and the timing of the trap formation implies that the Jurassic reservoirs of the Dhruma, Tuwaiq Mountain and Mafraq formations were probably (re)charged during the Late Cretaceous and Tertiary compression, from the remobilisation of hydrocarbons initially generated from source rocks of the Al Huqf system (Terken et al., 2001).

CONCLUSIONS

A geological model for the Jurassic Period in Interior Oman is proposed. This model is predictive with respect to the regional distribution of the sedimentary facies (carbonate versus clastic) and stratigraphic traps for hydrocarbons. The salient conclusions of this study are summarised below.

The Lower Mafraq Formation is very likely to be Toarcian in age, and thereby is a lateral equivalent of the Marrat Formation and not of the continental sands of the Minjur Formation of Saudi Arabia. The Upper Mafraq Formation, late Bajocian in age, is a clastic unit genetically attached to the Dhruma Formation. A major depositional hiatus, related to a general subaerial exposure, separates the Lower and Upper Mafraq clastics, and explains why those sub-units vary in thickness and facies independently.

The Jurassic depositional history of Interior Oman shows a predominant control of the major regional (southwestern Neo-Tethys) sea-level cycles: (1) early Pliensbachian (Carixian), Toarcian, late Bajocian, late Bathonian-middle Callovian, latest Kimmeridgian-Tithonian transgressions; and (2) late Pliensbachian, Toarcian-Aalenian, latest Callovian-early Oxfordian, late Kimmeridgian regressions. The Jurassic Sahtan Group displays an easterly thinning wedge, indicative of a tectonic influence. Two types of geological scenarios have contributed to this general geometric pattern: (1) a syndepositional downwarping apparently occurred during the deposition of the lower Upper Mafraq (?early Toarcian) and lower Dhruma (Bajocian-Bathonian transition); (2) towards the east, the

Figure 14: Schematic stratigraphic organisation of the Jurassic sequence of Interior Oman showing three types of potential stratigraphic traps (PST): Type 1 are isolated reservoir sands of the Lower and Upper Mafraq; Type 2 are truncation traps of the Uwainat and Hadriya limestones below the Hanifa and Jubaila-Raydah formations; and Type 3 traps are updip pinch-outs of the Hanifa Formation.
unconformity at the top of the Sahtan Group cuts into increasingly older formations and the Kahmah (uppermost Jurassic-lowermost Cretaceous) laps onto the unconformity. This stratal-termination pattern indicates differential uplift occurred during the early Late Jurassic across Interior Oman.

The early Late Jurassic uplift of the east flank of Interior Oman has several implications on the petroleum system: (1) the topographic high favoured the adjacent deposition of the Hanifa source rocks in the western province; (2) the associated tilting and erosion may have caused remobilisation, updip migration, and loss to the surface of previously stored oil; and (3) truncation stratigraphic traps of the upper Dhruma and Tuwaiq were formed, and (re)charged during the Late Cretaceous-Tertiary.

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ABOUT THE AUTHORS

Mathieu Rousseau obtained an MSc in Sedimentology in 2000, and defended his PhD in December 2004 at the University of Lyon, France. He spent six months at the JVR Centre for Carbonate Studies at Sultan Qaboos University, Oman, working on outcrops and well data of the Jurassic of Interior Oman. Mathieu also participated in a field study (conducted by the French “Marges Continentales” program) of the carbonate turbiditic system of the Jurassic Guwaysa in the Oman Mountains. He is particularly interested in the application and development of GIS to budget ancient sediment transfers from platforms to basins.

Gilles Dromart is Professor of Geology at the Laboratoire des Sciences de la Terre, Université de Lyon and Ecole normale supérieure de Lyon. He was a doctoral fellow with the Geological Survey of Canada, Eastern Petroleum Subdivision, Dartmouth, between 1984-1985. Gilles was appointed Professor of Geology at the University of Lyon in 1996. His main fields of interest are carbonate sedimentology, tectonics and sedimentation, numerical simulation of carbonate depositional systems, mass transfers at the Earth surface (Carbonate Cycle). He has been involved in extensive research on Jurassic carbonate platforms in the Scotian shelf (Canada), North Africa (Algeria), Subalpine and Paris basins. Gilles has also worked on several industrial projects with Elf-E.P, Gaz de France, and ANDRA (Agency for Nuclear Waste Repository). He is an active member of the American Association of Petroleum Geologists since 1989.
Henk Droste is Geoscience Advisor for the JVR Centre for Carbonate Studies at Sultan Qaboos University, Oman. He is also a member of the Carbonate Development Team with Shell Exploration and Production Technology in Rijswijk. Henk has an MSc in Geology from the University of Amsterdam, The Netherlands. He was previously employed by Petroleum Development Oman as a Sedimentologist in the Exploration Laboratory, a Geologist/Seismic Interpreter in Exploration, a Production Geologist, and Team Leader of the Regional Studies and Geological Services Team. Henk has also worked as a Carbonate Geologist with Shell Research in The Netherlands and as a Sedimentologist in the Regional Studies Team of Shell Explo in London.

Henk.Droste@shell.com

Peter Homewood is Professor of Carbonate Geology and Director of the JVR Centre for Carbonate Studies at Sultan Qaboos University, Oman. He has a PhD from the University of Lausanne, Switzerland. He was previously Senior Advisor for Sedimentology at Elf-EP and then TotalFinaElf. He taught at universities of Zurich and Fribourg in Switzerland. Peter served as Editor of Sedimentology (1986-1990), International Association of Sedimentologists Publications secretary (1990-1994), and AAPG European Distinghuised Lecturer (1998-1999), and he received the Elf Science Prize (1995) and the TotalFinaElf communications award (2000).

Homewood@squ.edu.om

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