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Jurassic Sequence Stratigraphy of the Western and Southern Arabian Gulf

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ABSTRACT

The Jurassic sequence stratigraphic scheme for Central Saudi Arabia is extrapolated to the formations of the western and southern Arabian Gulf region resulting in a tentative chronostratigraphic framework. The framework is tentaively constrained as follows: (1) Upper Triassic-?Lower Jurassic continental clastics (Minjur and equivalents) and the subsequent pre-Toarcian unconformity indicate regional erosion and non-deposition over the Arabian platform. (2) A Toarcian sequence (Marrat and equivalents) provides a basal Jurassic regional datum, except in Oman. (3) The late Toarcian and Aalenian correspond to a substantial sea- level lowstand and a regional depositional hiatus. (4) The Middle Jurassic Dhruma Formation corresponds to four different sequences with a major intervening hiatus. The Upper Dhruma Member, together with the Tuwaiq Mountain form the topmost sequence. The correlation between the Dhruma, Tuwaiq Mountain, Hanifa and Jubaila formations, to their equivalents in other Arabian Gulf countries, requires clearer definitions. (5) The Arab and Hith Anhydrite formations are Tithonian based on their sequence assignment, while the Sulaiy Formation is Berriasian and straddles the Jurassic-Cretaceous boundary. (6) The four Tithonian Arab carbonates may have been deposited as transgressive and early highstand deposits. The Tithonian Arab, Gotnia and Hith anhydrites may be late highstand deposits which overstep inland "salinas" (Gotnia and western Rub' Al-Khali). Each carbonate and overlying anhydrite sequence appear to correspond to a complete third-order cycle. (7) The equivalents to the Kimmeridgian Jubaila Formation and Tithonian Arab carbonates are absent by non-deposition in Kuwait. In Oman, the Arab and Hith Anhydrite formations are absent by erosion. (8) The Tithonian Hith Anhydrite provides a final Jurassic regional, stratigraphic datum, except in Oman and eastern United Arab Emirates.

INTRODUCTION

The Jurassic formations of the western and southern Arabian Gulf ("Region") constitute one of the most important petroleum systems of the world. This petroleum system includes several regional organic-rich source rocks, stacked reservoirs, multiple seals, and many super-giant oil fields; including the world's largest, Ghawar (Figure 1). Although the Jurassic rocks were deposited on a broad platform (Murris, 1980) and are sometimes characterized as "layer cake", their chronostratigraphic correlation from outcrops to wells, well to well, and from country to country, is not definitive.

Proposed Jurassic correlations for the Middle East have been published in numerous studies (e.g. Powers, 1968; Sugden and Standring, 1975; Schlumberger Monographs, 1975, 1981; Lababidi and Hamdan, 1985; Alsharhan and Kendall, 1986; Beydoun, 1988; Hughes Clarke, 1988). Most of these studies present general correlation charts which assign formations specific ages (e.g. Toarcian, Oxfordian, etc.) or stratigraphic positions (Lower, Middle, Upper).

These age assignments are based on fossil evidence and stratigraphic considerations which are compiled in the Lexicons of Saudi Arabia (Powers, 1968) and Qatar (Sugden and Standring, 1975). The definition and age assignments of the Jurassic formations in Bahrain (Chaube and Al-Samahiji, 1995), Kuwait (Yousif and Nouman, 1997) and the (UAE) United Arab Emirates (Hassan, 1989) are generally based on comparisons with Iran, Iraq, Qatar and Saudi Arabia. The Jurassic formations in Oman were described in lexicon style by Hughes Clark (1988), previously with Petroleum Development Oman.

All the studies refered to above predate or preclude the application of the global eustatic sequence stratigraphic framework introduced by Vail et al., (1977). Grabowski and Norton (1995), presented a

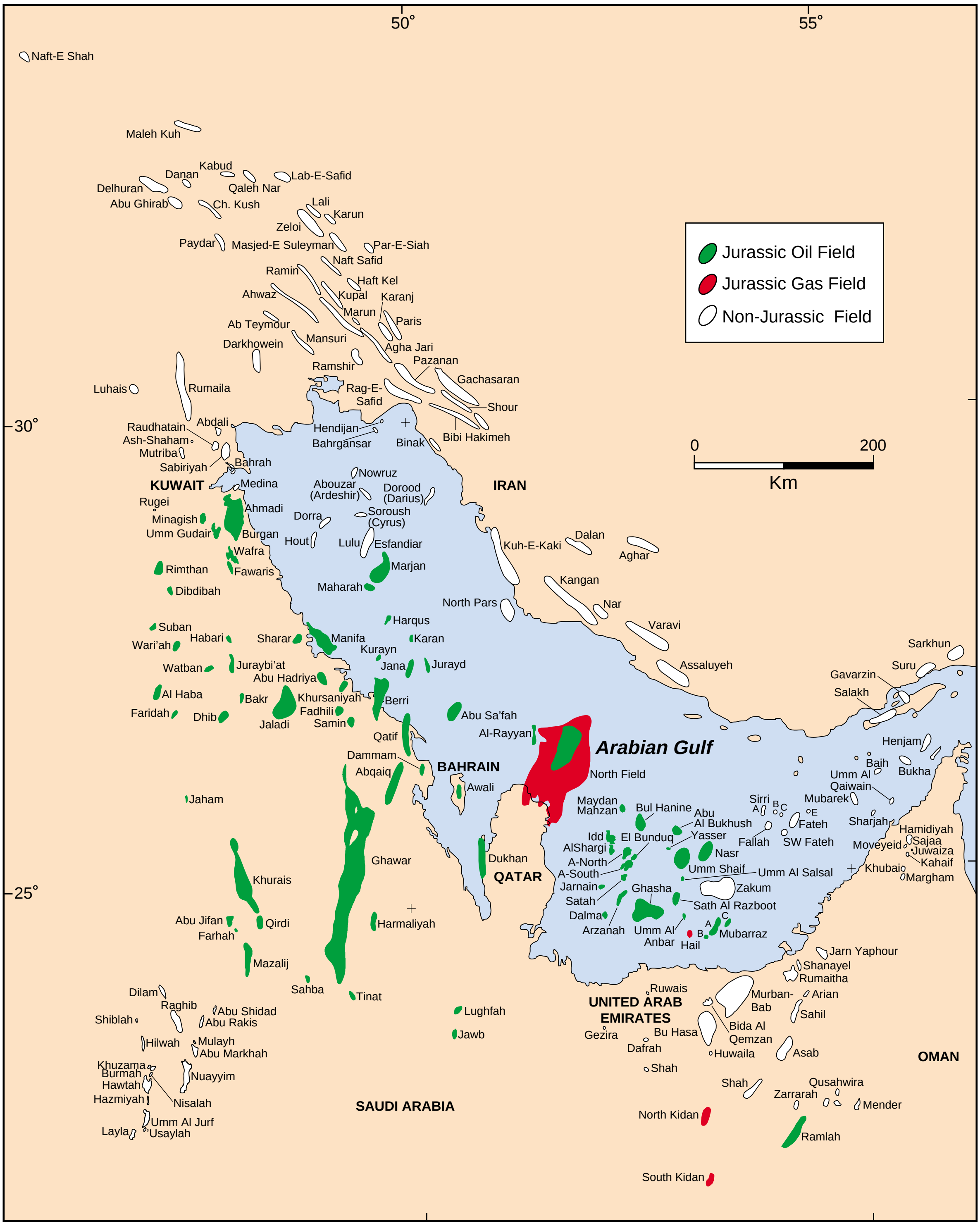


Figure 1: The Jurassic Petroleum System of the Arabian Gulf is one of the most important in the world and includes many of the giant and super giant oil fields of Saudi Arabia, Qatar, eastern United Arab Emirates, Kuwait and Bahrain (Awali Field). The petroleum fields, shown here in color, are interpreted as having Jurassic source rocks, reservoirs and caprocks.

simplified regional tectonic and sequence stratigraphic framework for the whole Arabian Plate. They arranged most of the rock units from the Permian to Recent into sequences which are based on global eustatic cycles (Haq et al., 1988). These authors emphasize that these sequences can be readily correlated with well logs over long distances across the Arabian Platform.

The global eustatic sequence model presented by Grabowski and Norton (1995) provides an ideal framework for the chronostratigraphic correlation of the rock units of the Middle East. Their assignments for Saudi Arabia are similar to those of McGuire et al. (1993) for the Upper Jurassic. These assignments, however, differ substantially from the studies of Le Nindre et al. (1990) and Vaslet et al. (1991).

Le Nindre et al. (1990) and Vaslet et al. (1991), of the Bureau de Recherches Géologiques et Miniéres (BRGM) and the Directorate General for Mineral Resources (DGMR), Ministry of Petroleum and Minerals, Saudi Arabia, submitted their papers simultaneously for publication in 1989. These studies are based on surface data and also assign the Mesozoic formations of Central Arabia to the global eustatic cycles of Haq et al. (1988). Their assignments are based on lithology, depositional environment and biostratigraphic dating. In Figure 2, the results of Le Nindre et al. (1990) and Vaslet et al. (1991) are compared to McGuire et al. (1993), Grabowski and Norton (1995), and the assignments of Powers (1968).

This paper presents a tentative Jurassic sequence stratigraphic framework for the Region. The framework is calibrated from the studies of Le Nindre et al. (1990) and Vaslet et al. (1991) for Central Saudi Arabia (Figure 3). It is then extrapolated to other countries based on regional considerations and existing stratigraphic correlations (Figure 4). The paper highlights regional chronostratigraphic constraints and addresses many unresolved issues.

SEQUENCE STRATIGRAPHY

Van Wagoner et al. (1988) provide an overview of the concepts and definitions of sequence stratigraphy as they apply to siliciclastics; while Sarg (1988) describes sequence stratigraphic models for carbonates. These two papers appeared together with many other important studies on this subject in *Sea level Changes - an Integrated Approach*, Special Publication Number 42 of the Society of Economic Paleontologists and Minerologists (SEPM 42).

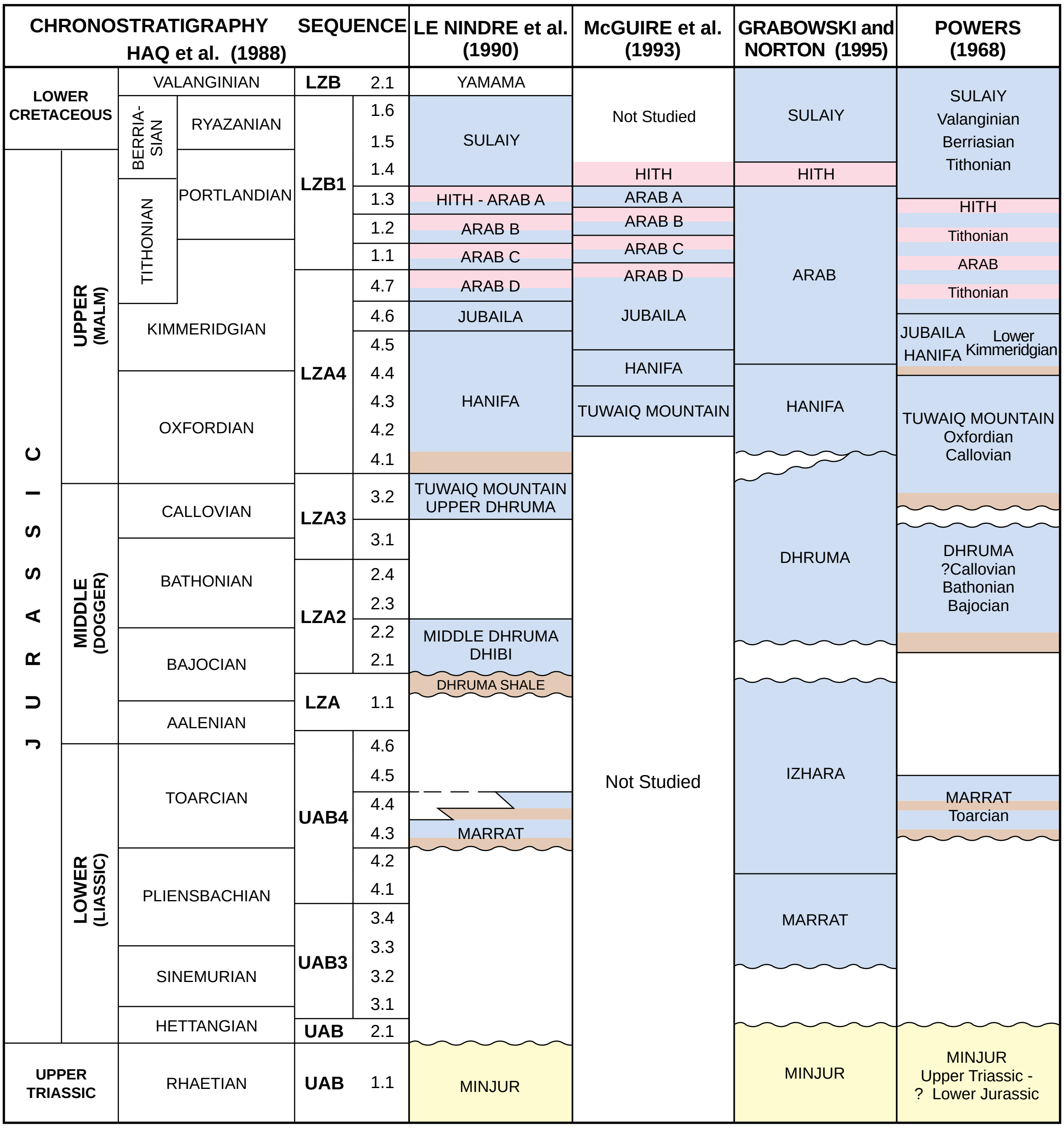
In the recent book *Sequence Stratigraphy*, edited by Emery and Myers (1996), an historical up-to-date perspective summarizes the development of this sub-discipline of stratigraphy. In this book, SEPM 42 is credited for opening up the subject of sequence stratigraphy to a broader geological community beyond industrial seismic interpreters.

Sequence stratigraphy, unlike lithostratigraphy, provides a chronostratigraphic framework for the correlation and mapping of syndepositional facies. It is also useful for predicting stratigraphic and geometric relationships and facies distribution which is important in exploration and reservoir characterization. Sequence stratigraphy is based on seismic stratigraphy, biostratigraphy, chronostratigraphy and sedimentology, but not necessarily on lithostratigraphy (Emery and Myers, 1996).

Tha main "building block" of sequence stratigraphy is the *sequence*. A sequence consists of genetic packages bounded by unconformities and their correlative conformities. It consists of three system tracts: (1) a lower lowstand wedge (LSW) or shelf margin wedge (SMW); (2) middle transgressive deposits (TR); and (3) upper highstand deposits (HS). The boundary between the transgressive and highstand deposits corresponds to the Maximum Flooding Surface (MFS).

Sequences are associated with stratigraphic cycles which last 500 thousand to 3 million years and are primarily controlled by glacio-eustasy (Vail et al., 1991). These are known as third-order cycles.

The other orders of stratigraphic cycles are described by Duval et al. (1992) in Emery and Myers (1996). First-order cycles are tectono-eustatic and exceed 50 million years. They are related to ocean basin volume changes caused by plate tectonic cycles. Second-order cycles last between 3 and 50 million years and correspond to stages of basin evolution.



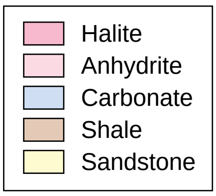
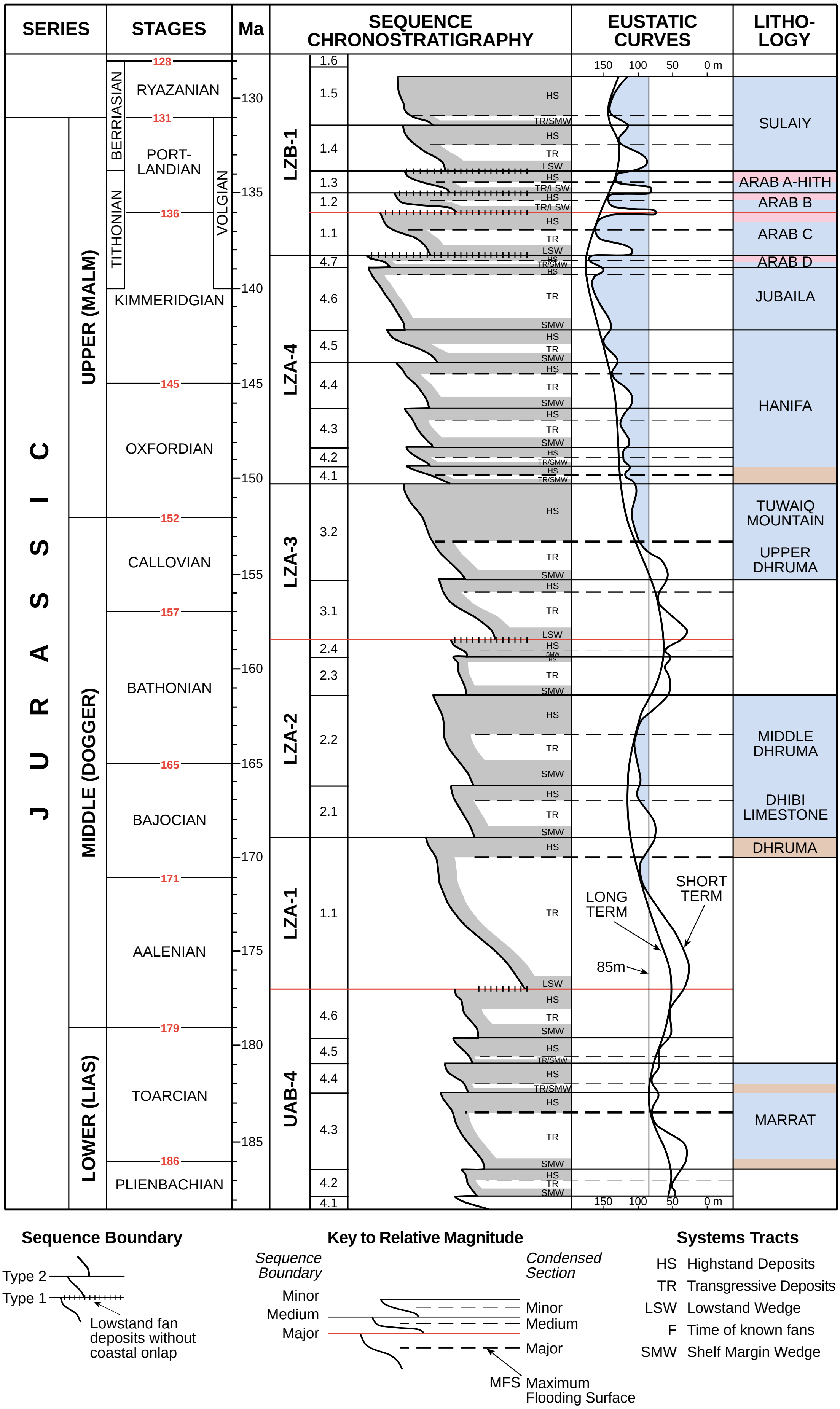


Figure 2: Comparison of sequence stratigraphic assignments for Central Saudi Arabia by Le Nindre et al. (1990; same as Vaslet et al., 1991), McGuire et al. (1993) and Grabowski and Norton (1995). The age assignments of Powers (1968) are also shown. The assignments of Le Nindre et al. (1990) and Vaslet et al. (1991), which are identical, are adopted in this paper (Figures 3, 4 and 12).

Figure 3 (facing page): The sequence stratigraphic framework for the formations and members of Central Saudi Arabia as interpreted by Le Nindre et al. (1990) and Vaslet et al. (1991). The two papers were submitted for publication at the same time. Sequence assignments are based on lithological, depositional and biostratigraphic considerations. The sea-level and coastal onlap curves are from Haq et al. (1988). Periods of non-deposition correspond closely to sea-level lowstands of approximately 75-85 meters or less. The chart is truncated below the Marrat as the Minjur is considered Triassic in the study (Figure 2).


SERIES
STAGES
Ma
SEQUENCE CHRONOSTRATIGRAPHY
EUSTATIC CURVES
LITHO-LOGY
J U R A S S I C
UPPER (MALM)
MIDDLE (DOGGER)
LOWER (LIAS)
BERRIASIAN
TITHONIAN
VOLGIAN
RYAZANIAN
PORT-LANDIAN
KIMMERIDGIAN
OXFORDIAN
CALLOVIAN
BATHONIAN
BAJOCIAN
AALENIAN
TOARCIAN
PLIENBACHIAN
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LZA-3
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LZA-1
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1.6
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LONG TERM
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SULAIY
ARAB A-HITH
ARAB B
ARAB C
ARAB D
JUBAILA
HANIFA
TUWAIQ MOUNTAIN
UPPER DHRUMA
MIDDLE DHRUMA
DHIBI LIMESTONE
DHRUMA
MARRAT
Sequence Boundary
Type 2
Type 1
Lowstand fan deposits without coastal onlap
Key to Relative Magnitude
Sequence Boundary
Minor
Medium
Major
Condensed Section
Minor
Medium
Major
MFS Maximum Flooding Surface
Systems Tracts
HS Highstand Deposits
TR Transgressive Deposits
LSW Lowstand Wedge
F Time of known fans
SMW Shelf Margin Wedge

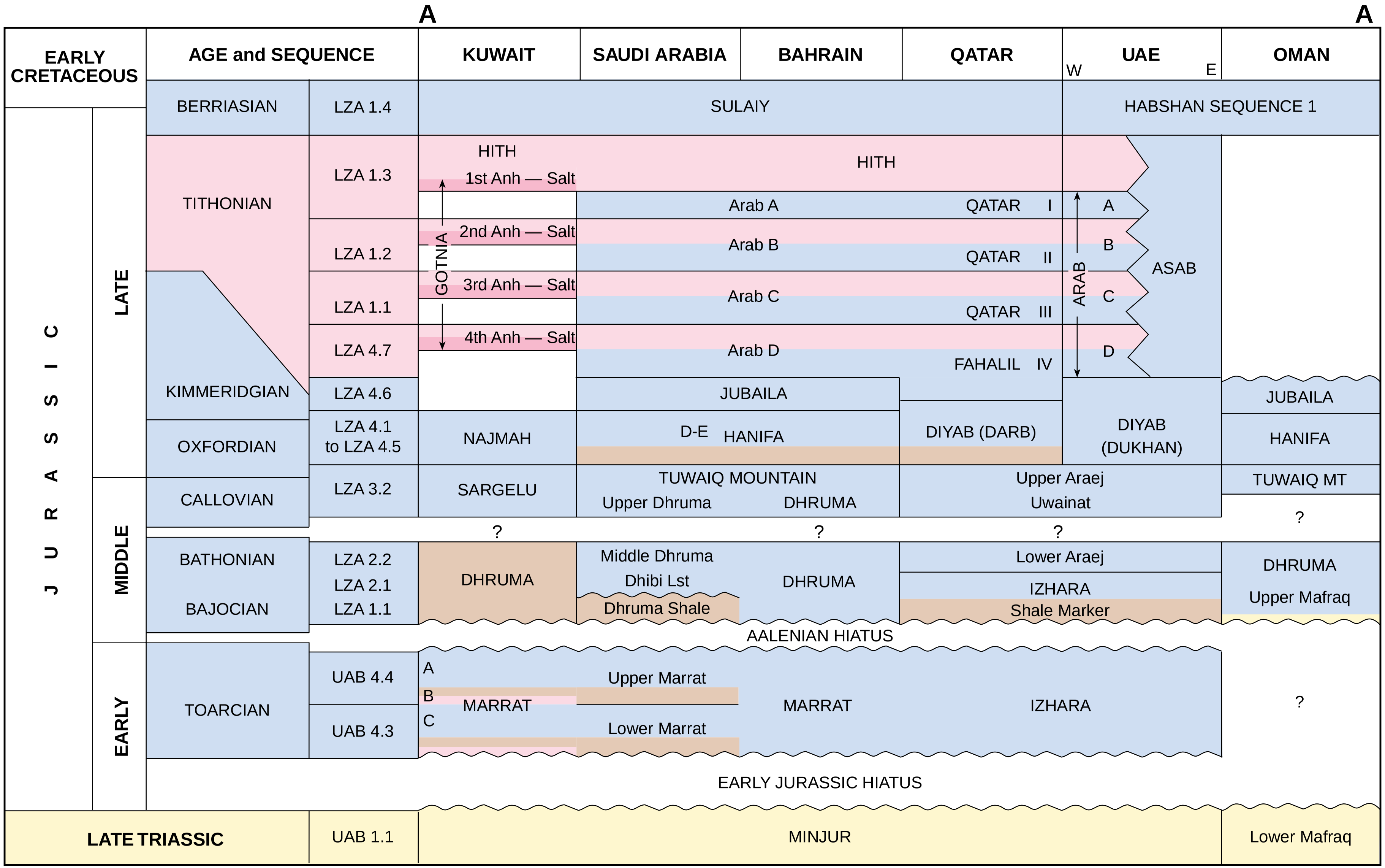

Figure 4: Jurassic sequence stratigraphic framework of the western and southern Arabian Gulf. The chart is based on Le Nindre et al. (1990) and Vaslet et al. (1991) for Saudi Arabia. Lateral correlations are based on stratigraphic and biostratigraphic considerations. For location see Figure 1 and traverse AA' in Figure 7.

Fourth-order cycles last 100 to 500 thousand years and correspond to parasequences. They represent shallowing-upward facies cycles bounded by surfaces of abrupt deepening (Emery and Myers, 1996). Fourth-order cycles may be vital for interpreting the diagenetic imprint on carbonates due to their control of pluvial and non-pluvial events.

The most widely used Sequence Chronostratigraphic Chart for the Mesozoic and Cenozoic was published by Haq et al. (1988) in SEPM 42. This chart is partly reproduced in Figure 3 and it shows the correspondence between second- and third-order cycles and rock units in Saudi Arabia. For example, second-order cycle LZA4 includes the Hanifa and Jubaila formations, and the Arab-D Member; while third-order sequence LZA4.6 corresponds to the Jubaila Formation.

Ongoing research in the relationship between orbital forcing and eustasy may result in further refinements to the Haq et al. (1988) curve (Emery and Myers, 1996; R.K. Mathews, personal communication, 1997).

EARLY JURASSIC HIATUS

The global sequence stratigraphic framework of Haq et al. (1988) cannot be applied without qualifications to the Arabian platform. Alsharhan and Kendall (1991) and Kendall et al. (1991), in their sequence stratigraphic analysis of the Cretaceous rocks of Abu Dhabi, point out important considerations in this regard. The sequence stratigraphic model must simultaneously take into account eustasy, tectonic movements and rates of sedimentation. While eustatic events can be identified by their world-wide distribution, their effect and size may be affected by the other two factors. In particular the sediment fill is controlled by the accomodation volume available due to the combination of local tectonic subsidence and eustatic position.

The interaction of eustasy, tectonics and sedimentary supply is important for the pre-Jurassic period in the Arabian Gulf. Tectonic uplift, erosion and non-deposition dominated the southern and western parts of the Arabian Plate starting in the Carboniferous, and throughout the Permian and Triassic. The Permian-Carboniferous uplift of southern Arabia and Oman is attributed to the development of a rift system between India and Arabia (Figure 5, Marcoux et al., 1993). Al-Belushi et al. (1996) attribute the Permian-Carboniferous glaciation of Oman to this uplift.

During the Late Triassic and Jurassic the Arabian Gulf region was a stable interior platform located at an equatorial latitude. An oceanic spreading system extended parallel to the present-day Zagros-Taurus Mountains along the margins of the Tethys Ocean (Figure 5). The Late Triassic paleoenvironment, depicted in Figure 5, represents the Late Norian period between 215-212 million years ago (Ma) and shows most of Arabia as an exposed continent. The corresponding formations consist of barren largely continental and shallow marine clastics: Minjur Sandstone in Abu Dhabi, Bahrain, Kuwait, Qatar and Saudi Arabia; and the Lower Mafraq Member in Oman (Figure 4). All these formations are tentatively shown to extend into the Lower Jurassic (Powers, 1968; Hughes Clark, 1968; Hassan, 1989).

Le Nindre et al. (1990) and Vaslet et al. (1991), however, show the Minjur as completely Triassic (Figures 2 and 4). The Early Jurassic hiatus (Figures 2 and 4) may be the result of a pronounced long term sea-level lowstand which prevailed from the Hettangian to the Pliensbachian (Figures 4 and 6). This period of non-deposition was briefly interrupted during the Toarcian as evidenced by the Marrat clastics and carbonates. During the late Toarcian and Aalenian, sea-level again dropped resulting in another period of non-deposition (Figures 4 and 6).

TOARCIAN TRANSGRESSION

During the Early Jurassic, Toarcian, a widespread marine transgression covered the Arabian shelf. The depositional environment was arid and varied from non-deposition and erosion in southern Arabia to a clastic platform in the west. A shallow marine, mostly carbonate, platform developed to the north and east (Figures 7a and 8).

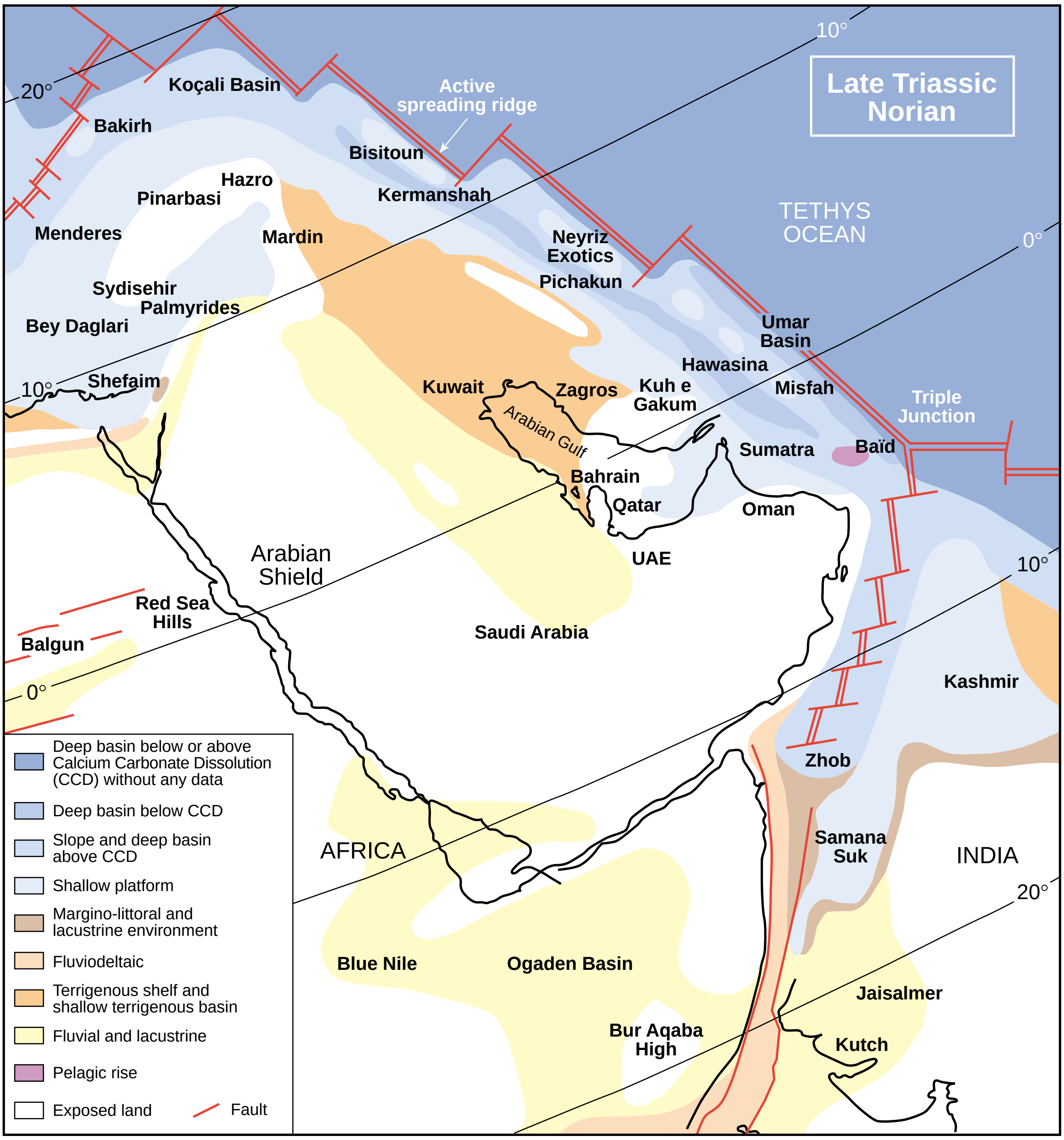

Figure 5: During the Late Triassic (Late Norian, 215-212 Ma) the Arabian Plate formed the outer rim of the Gondwana Continent. This map was compiled for the Tethys region by Marcoux et al. in the Tethys Atlas (Dercourt, 1993) based on the work of LeNindre et al. (1987). The Arabian Gulf region was equatorial and isolated from the Tethys Ocean. A sea-floor spreading system, consisting of rifts and transforms, ran parallel to the margin of the Arabian and Indian plates. A triple-junction, located in the Tethys Ocean (east of present-day Oman), included a rift branch which separated the Arabian and Indian plates. The triple junction may have originated in the Carboniferous and caused the uplift and glaciation of southern Arabia and Oman (Al-Belushi, 1996). During the Late Triassic-Carboniferous Arabia was an uplifted exposed landmass where barren sandstones were deposited (Figures 4 and 6).

Saudi Arabia and Bahrain

Powers (1968) describes the oldest-dated Jurassic Marrat Formation in terms of two sequences: (1) Lower Marrat consisting of barren, non-marine, basal shales, sandy shales and calcareous sandstones (21.5 m) and an upper limestone (15 m) which is confidently dated as early Toarcian (Arkell, 1952, in Powers, 1968); and (2) Middle Marrat (41.8 m) consisting mostly of shales and sandy shales which

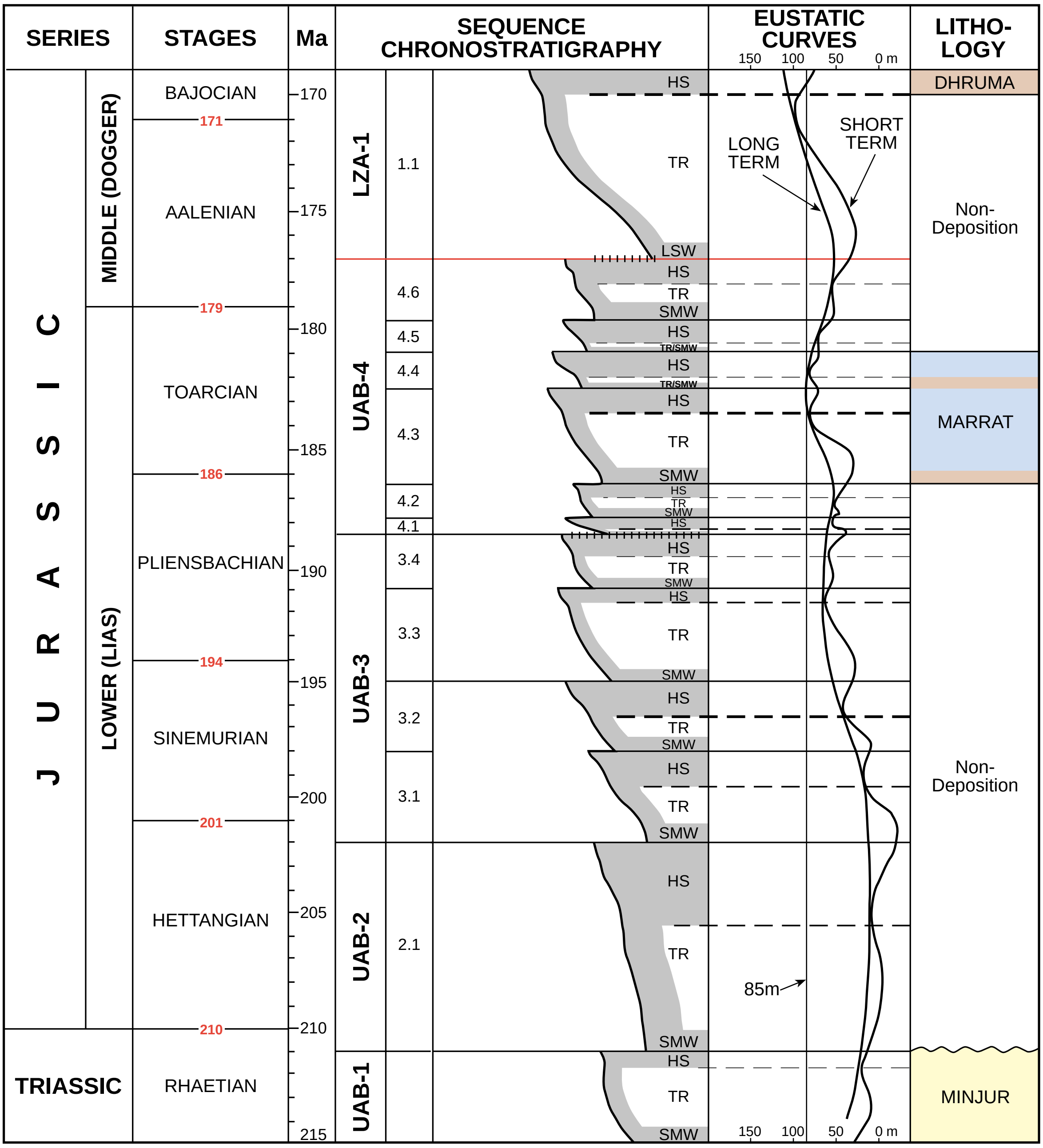

Figure 6: The two periods of non-deposition in Central Arabia occur from the earliest Jurassic, Hettangian to Pliensbachian, and from the late Toarcian, Aalenian to early Bajocian. These periods correspond to sea-level lowstands when the average level was less than approximately 75-85 meters. The close correspondence between sea-level and deposition indicates that global eustasy, and not tectonic factors, was the main factor in determining accomodation volume.

appear to be non-marine and represent flood plain and tidal flat deposits; and the Upper Marrat (24.2 m), which is a shallow marine limestone dated as early late Toarcian.

Grabowski and Norton (1995) incorrectly assign the Marrat to the Pliensbachian which is inconsistent with the fossil record in Saudi Arabia (Powers, 1968; Figure 2). The Marrat is considered a single sequence UAB4.3 by Le Nindre et al. (1990). This is the main Toarcian transgressive sequence of Supercycle UAB4, and corresponds to both the short and long term sea-level rise (Figures 3 and 6). The evidence for two consecutive and distinct trangressive sequences as described by Powers (1968) suggests that the Marrat corresponds to sequences UAB4.3 and UAB4.4 (Figures 3 and 4), which fits closely with the early and early late Toarcian.

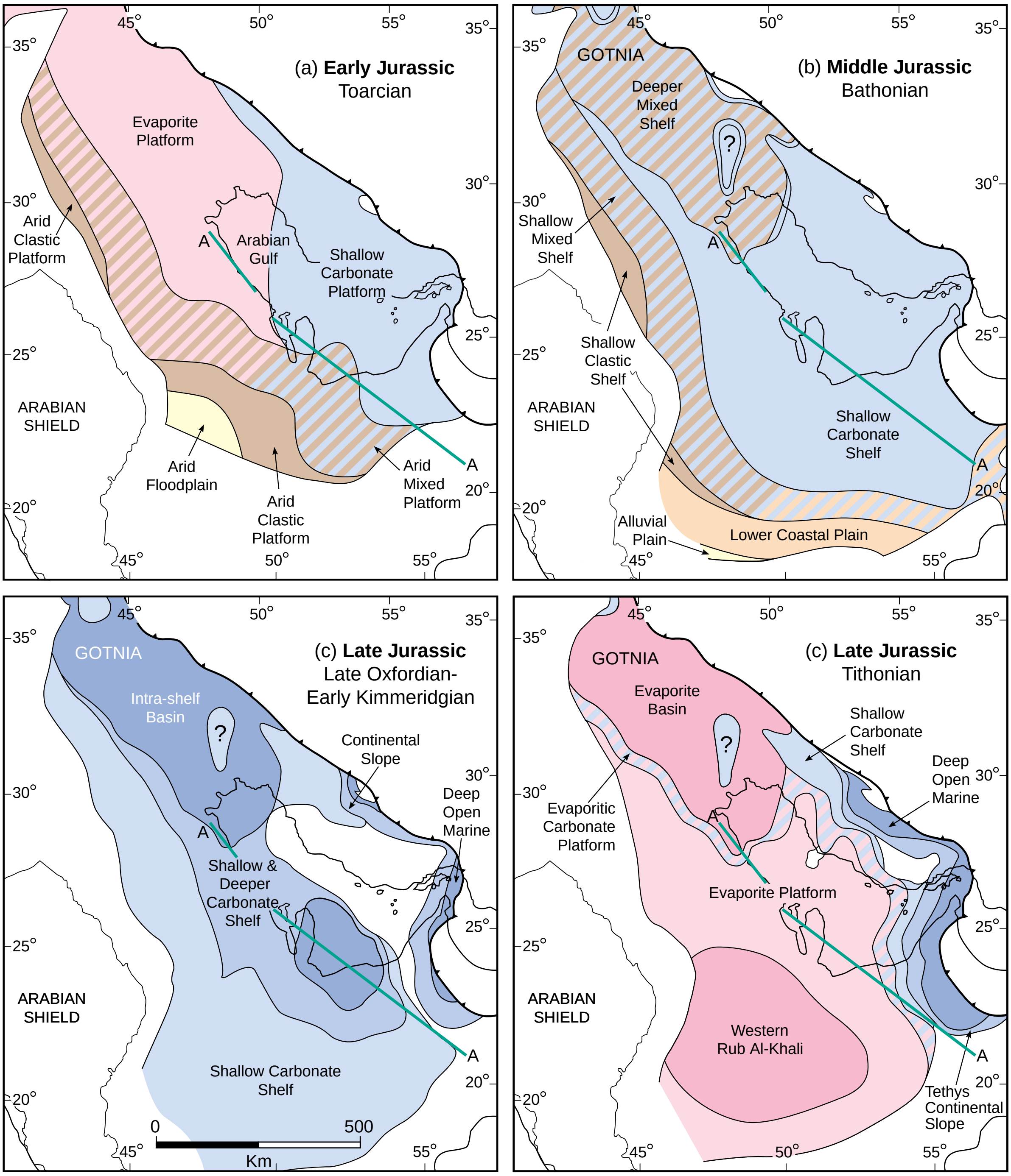

Figure 7: Jurassic environments of deposition in the Middle East (Murris, 1980). (a) After a depositional hiatus which spanned most of the Early Jurassic, a Toarcian transgression flooded the Arabian Peninsula. (b) A second depositional hiatus during the initial Aalenian phase of the Middle Jurassic was followed by a second transgression in Bajocian-Bathonian time. (c) During the Late Jurassic (Oxfordian and early Kimmeridgian) source rocks (Hanifa and equivalents) were deposited in broad intra-shelf basins. (d) In the Late Jurassic Tithonian the deposition of four carbonate-anhydrite cycles constituted the dominant regional reservoirs and caprocks (Arab carbonates and Arab and Hith anhydrites). The western Rub' Al-Khali and Gotnia basins were inland salt lakes (salinas). In Figures 8 to 11, the paleoenvironments of the Middle Toarcian (Bassoullet et al., 1993), Callovian (Enay et al., 1993), Early Kimmeridgian (Cecca et al., 1993) and Late Tithonian (Fourcade, 1993) are shown together with the corresponding tectonic reconstructions. The environments, in Figures 8 to 11, for the Arabian platform are based on Le Nindre et al. (1987) and compiled in the Tethys Atlas (Dercourt et al., 1993). The traverse AA' corresponds to the sequence depicted in Figures 4 and 12.

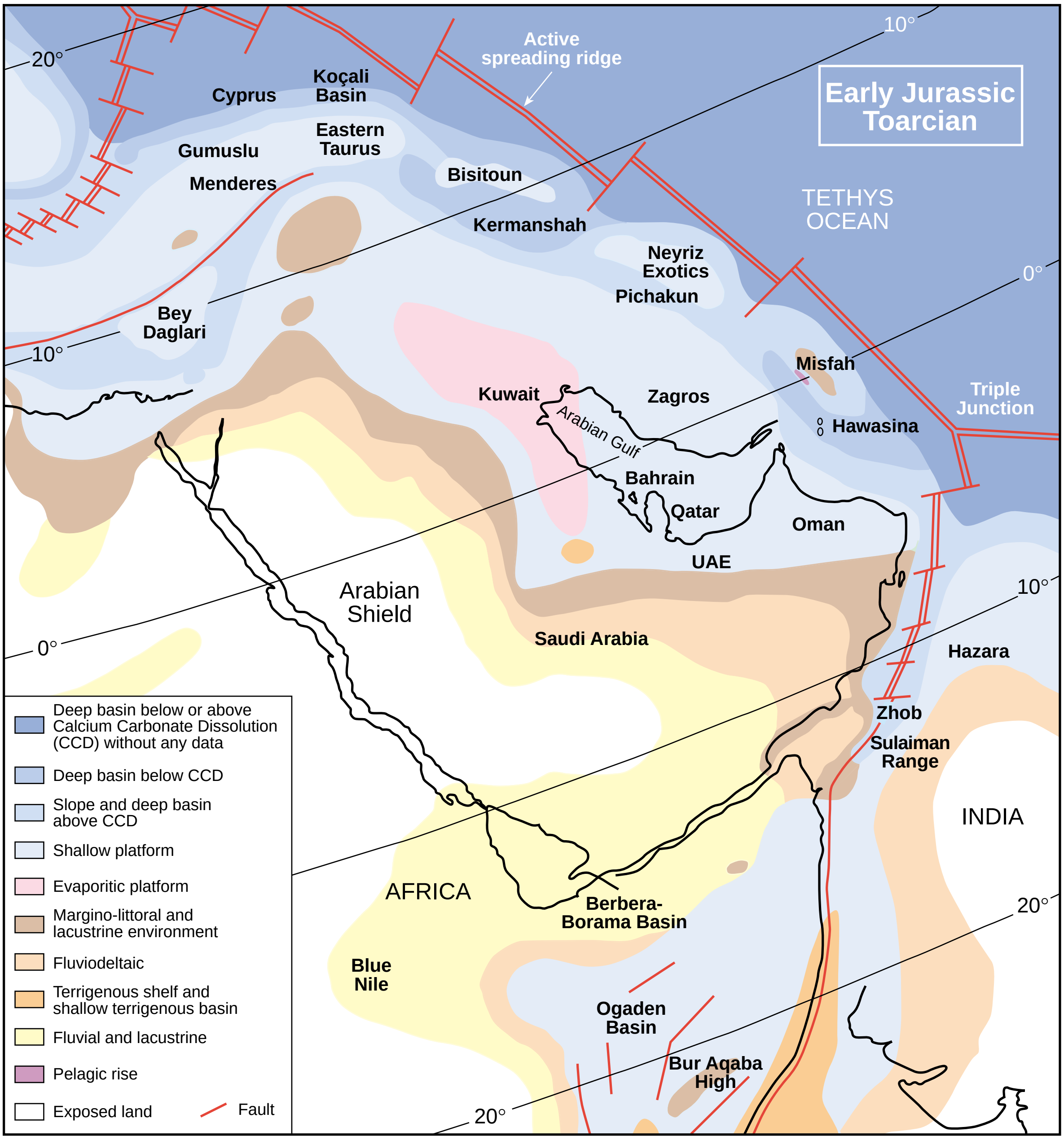

Figure 8: Paleoenvironment and tectonic reconstruction of the Early Jurassic, Middle Toarcian (184-182 Ma), shows the Arabian Gulf flooded by a marine transgression (Le Nindre et al., 1987; Bassoullet et al., 1993). The two bounding periods (Early Jurassic and Aalenian, Figure 4) are associated with non-deposition and correspond to sea-level lowstands (Figures 3 and 6).

In Bahrain the Marrat Formation is a dolomite which is assigned to the Toarcian and Aalenian (Chaube and Al-Samahiji, 1995). The comparable stratigraphy to Saudi Arabia implies an assignment to UAB4.3 and UAB4.4 (Figure 4).

Kuwait

In Kuwait, Yousif and Nouman (1997) divide the Marrat Formation into five regional units, 1,800 feet (ft) thick in type section. The lower two units, E and D, are interbedded lime mudstone, dolomite, anhydrite and shale. The middle unit C is mostly limestone. Unit B is limestone with interbedded shale and streaks of dolomite and shale and Unit A is interbedded limestone, wackestone and calcareous shale. The Marrat E to C units probably corresponds to UAB4.3, and Marrat B and A to UAB4.4 (Figure 4).

Qatar and United Arab Emirates

The Jurassic formations in Qatar are described by Sugden and Standring (1975) and Qatar General

Petroleum Corporation (QGPC) in a Schlumberger Monograph (1981). In Abu Dhabi, similar formations are described by Abu Dhabi Marine Operating Company (ADMA-OPCO), Abu Dhabi Company for Onshore Operations (ADCO) in Schlumberger (1981), and more recently Hassan (1989).

The Hamlah Formation in Qatar consists of two sequences which are each shale at the base, and dolomite with anhydrite streaks at the top. The formation is barren and Sugden and Standring (1975) assign it an Early Jurassic age based on stratigraphic position. In Abu Dhabi, however, Hassan (1989) assigns the Hamlah Formation to the Triassic based on regional stratigraphic correlations of wireline data. He shows that the Triassic Minjur Sandstone, which is absent in Qatar and mostly eroded in Abu Dhabi, overlies the Hamlah Formation.

The overlying Izhara Formation, in Qatar, consists of dolomite, marl and shale (452 ft in Kharaib-1). It is correlated with the Lower Dhruma and assigned a Bajocian and possibly early Bathonian age (Sugden and Standring, 1975).

In the UAE, Hassan (1989) divides the Izhara into five units (682 ft in Ghasha-7) and considers it Lower Jurassic by stratigraphic position. The Izhara consists mostly of limestone except for the basal part of Unit 3 which is a thick shale marker bed. If the lower two units correspond to sequences UAB4.3 and UAB4.4 (Marrat Formation), then the Izhara shale marker bed would correlate with the "Dhruma Shale" in Saudi Arabia (Figure 4).

Oman

In Oman, Hughes Clarke (1988) introduced the Liassic to Bajocian Mafraq Formation and divided it into lower and upper parts. The Lower Mafraq consists of continental clastics with rare palynomorphs which suggest Early Jurassic and Late Triassic to ?Permian ages. The upper part is a shallow marine sequence of latest Liassic to Bajocian age.

Hughes Clarke interprets the Lower Mafraq as an equivalent to the Triassic-?Lower Jurassic Minjur Sandstone in Saudi Arabia and the Upper Mafraq as essentially a clastic basal unit of the Dhruma Formation. This interpretation implies the absence of the Toarcian sequences in Oman.

AALENIAN HIATUS

Following the Toarcian transgression, a depositional hiatus spanned the late Toarcian and Aalenian. Sea-level was nearly 50 m lower in the middle Aalenian relative to the Toarcian (Figures 3 and 6). Le Nindre et al. (1990) indirectly deduce this hiatus (182.5 to 170.5 Ma) and caution its interpretation with a question mark. They tentatively associate a 30-meter thick undated section in the Upper Marrat, consisting of gypsum layers, with the hiatus.

BAJOCIAN-BATHONIAN TRANSGRESSION

Following the Aalenian depositional hiatus, Middle Jurassic (Bajocian-Bathonian) carbonates were deposited over most of the Arabian Peninsula in a shallow, clear, warm-water shelf environment (Figure 7b). In the west and south, clastic input continued, while in the north, a deeper mixed siliciclastic-carbonate shelf existed and the Gotnia Basin developed.

Saudi Arabia and Bahrain

Powers (1968) divides the Dhruma Formation (374.5 meters) into three parts: (1) the Lower "Dhruma Shale" and the overlying Dhibi Limestone Member; (2) the Middle Dhruma Limestone Member; and (3) the Upper Dhruma consisting of the 'Atash Member limestone (also Lower Fadhili Reservoir) and an upper interbedded shale and limestone section, Hisyan Member.

Le Nindre et al. (1990) and Vaslet et al. (1991) also subdivide the Dhruma into lower (D1 and D2), middle (D3 to D6) and upper (D7). The Dhruma Shale corresponds to D1 and the lower part of D2 and is dated from fossils as early Bajocian. These authors assign the Dhruma Shale to the prominant transgressive sequence ZA1.1 (Figure 3). This assignment is consistent with a "Lower Dhruma Unconformity" between the Dhruma Shale and Dhibi Limestone as described by Powers (1968).

The Lower Dhruma Dhibi Limestone and the Middle Dhruma (upper part of D2 to D6) together correspond to ZA2.1 and ZA2.2 (Figures 2, 3 and 4). The basal Middle Dhruma unit D3 is dated as late

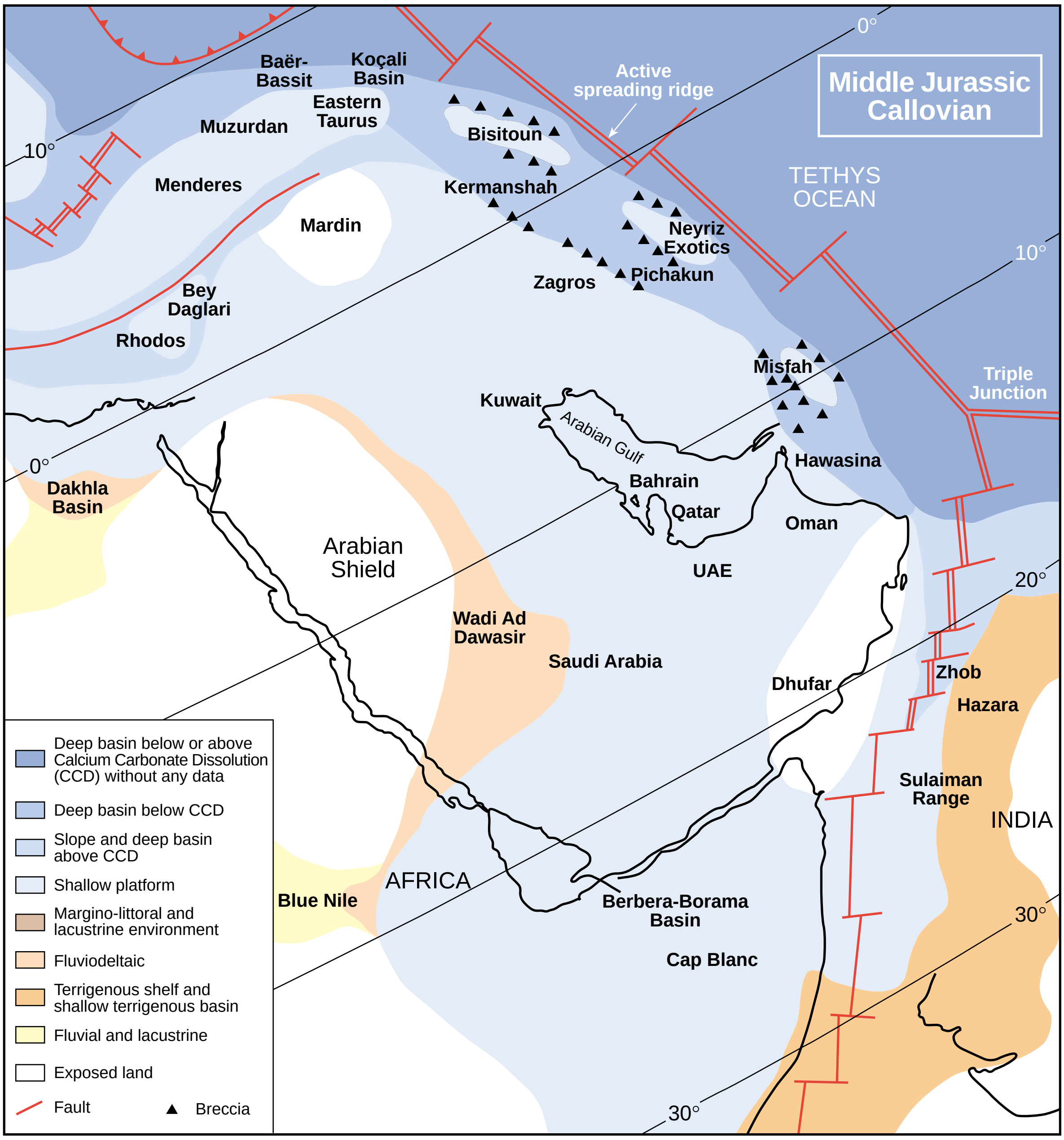

Figure 9: Paleoenvironment and tectonic reconstruction of the Middle Jurassic, Callovian (162-158 Ma), shows tha Arabian Plate flooded by a marine transgression (Le Nindre et al., 1987; Enay et al., 1993). During the Callovian the Upper Dhruma and Tuwaiq Mountain were deposited. The period from the Middle Callovian through the end of the Jurassic represents continued deposition in warm equatorial latitudes (see also Figures 8, 10 and 11). This period corresponds to a sustained global sea-level highstand (Figure 3).

Bajocian and early Bathonian, while the D5 unit is correlated with the highstand at 163.5 Ma. The top unit D6 of the Middle Dhruma is the highstand deposit of ZA2.2.

Le Nindre et al. (1987, 1990) assign the biostratigraphically-dated middle Callovian Upper Dhruma and Tuwaiq Mountain Limestone to a single sequence ZA3.2 (Figures 3 and 9). This assignment implies a depositional hiatus of nearly 6 million years between ZA2.2 and ZA3.2 which corresponds to a marked sea-level lowstand (Figure 3).

In Bahrain the Dhruma Formation was deposited in a shallow carbonate shelf setting (Figure 7b) and is mainly limestone with some calcareous shale near the base (Chaube and Al-Samahiji, 1995). It would appear to correspond to cycles ZA1.1 to ZA2.2 (Figure 4).

Kuwait

During the Middle Jurassic, Kuwait was part of the deeper mixed shelf (Figure 7b). Yousif and Nouman (1997) describe the Dhruma as a calcareous shale with minor limestone laminations which varies in thickness from 100 to 200 ft. The Dhruma in Kuwait probably corresponds to the Lower and Middle Dhruma in Saudi Arabia and sequences ZA1.1 to ZA2.2 (Figure 4).

Qatar and United Arab Emirates

As noted earlier, the Izhara shale marker bed (Unit 3 of Hassan, 1989) may correlate with the Lower Dhruma Shale. Besides their lithological similarity the Izhara is considered Bajocian and possibly early Bathonian by Sugden and Standring (1975). The upper limestones of the Izhara (upper unit 3 to unit 5) would then correlate to the Dhibi Limestone Member of the Lower Dhruma.

The overlying Bathonian-Callovian Araej Formation (Sugden and Standring 1975) reflects a deeper-marine environment. The Lower Araej Member consists of lime mudstones with lime packstones towards the top. The middle Uwainat Member (also Uwainat Reservoir) is a chalky lime mud wackestone and the Upper Araej Member is a lime mudstone.

The Araej Formation in the UAE (ADMA-OPCO and ADCO in Schlumberger, 1981) is also divided into three members: (1) the Lower Araej Member consists of packstone, grainstone and lime mudstone (307 to 391 ft); (2) the middle Uwainat Member is a wackestone and packstone with minor grainstones (130 to 179 ft) and (3) the Upper Araej Member is an argillaceous limestone overlain by grainstones and packstones (128 to 335 ft).

The Araej Formation in Qatar and the UAE is correlated to the Middle and Upper Dhruma of Saudi Arabia (Sugden and Standring, 1975). These correlations imply that the Izhara from Unit 3 (Shale Marker) to Unit 5, and the Lower Araej correspond to sequences ZA1.1 to ZA2.2, while the Uwainat and Upper Araej members correspond to sequence ZA3.2.

Oman

Hughes Clark (1988) describes the Dhruma in Oman (714 ft) as a complete cycle of sedimentation. The lower and middle limestone are mud-supported while the upper part is dominantly grain-supported. The Dhruma in Oman is Middle to Late Jurassic based on microfossils and subsurface correlations with Saudi Arabia (Figure 4). The Upper Mafraq, described earlier as a clastic basal unit of the Dhruma, together with the Dhruma, may correspond to sequences ZA1.1 to ZA2.2. The equivalent to the Upper Dhruma of Saudi Arabia may be absent in Oman.

CALLOVIAN-KIMERIDGIAN SEQUENCES AND THE TITHONIAN CARBONATE-EVAPORITE CYCLES

During the early Late Jurassic an intra-shelf basin developed over most of Arabia (Figures 7c and 10). This basin was the depocenter of the main Jurassic source rocks as well as several important reservoirs. The Tithonian stage of the Upper Jurassic was dominated by evaporites and shallow marine carbonates which correspond to the Arab reservoirs and Arab, Hith and Gotnia evaporites (Figure 4). Two evaporite / salt inland "salinas" (salt lakes) developed in the western Rub' Al-Khali and Gotnia Basin (Figure 7d).

Saudi Arabia and Bahrain

As noted earlier, Le Nindre et al. (1987, 1990) assign the Upper Dhruma and Tuwaiq Mountain Limestone to a single sequence ZA3.2 which straddles the Callovian-Oxfordian boundary. Powers (1968) describes the contact between the Tuwaiq and Dhruma as disconformable. In the type section the Tuwaiq is a 203 m thick limestone which is marly in the lower 35-40 m. The lower marly facies are a source rock; the base and top sections correspond to the Upper Fadhili and Hadriya reservoirs.

Above the Tuwaiq Mountain, the Hanifa Formation (113.3 m in type section) consists of shales in the lower and middle part, and limestones in the upper part. The Hanifa shales are the main Jurassic source rocks and the limestones are the Hanifa Reservoir (Ayers et al., 1982).

In Figures 2 and 3, Le Nindre et al. (1990) and Vaslet et al. (1991) assign the Hanifa to ZA4.1 to ZA4.5 based on fossil evidence which indicate early, middle and late Oxfordian ages. They associate patch

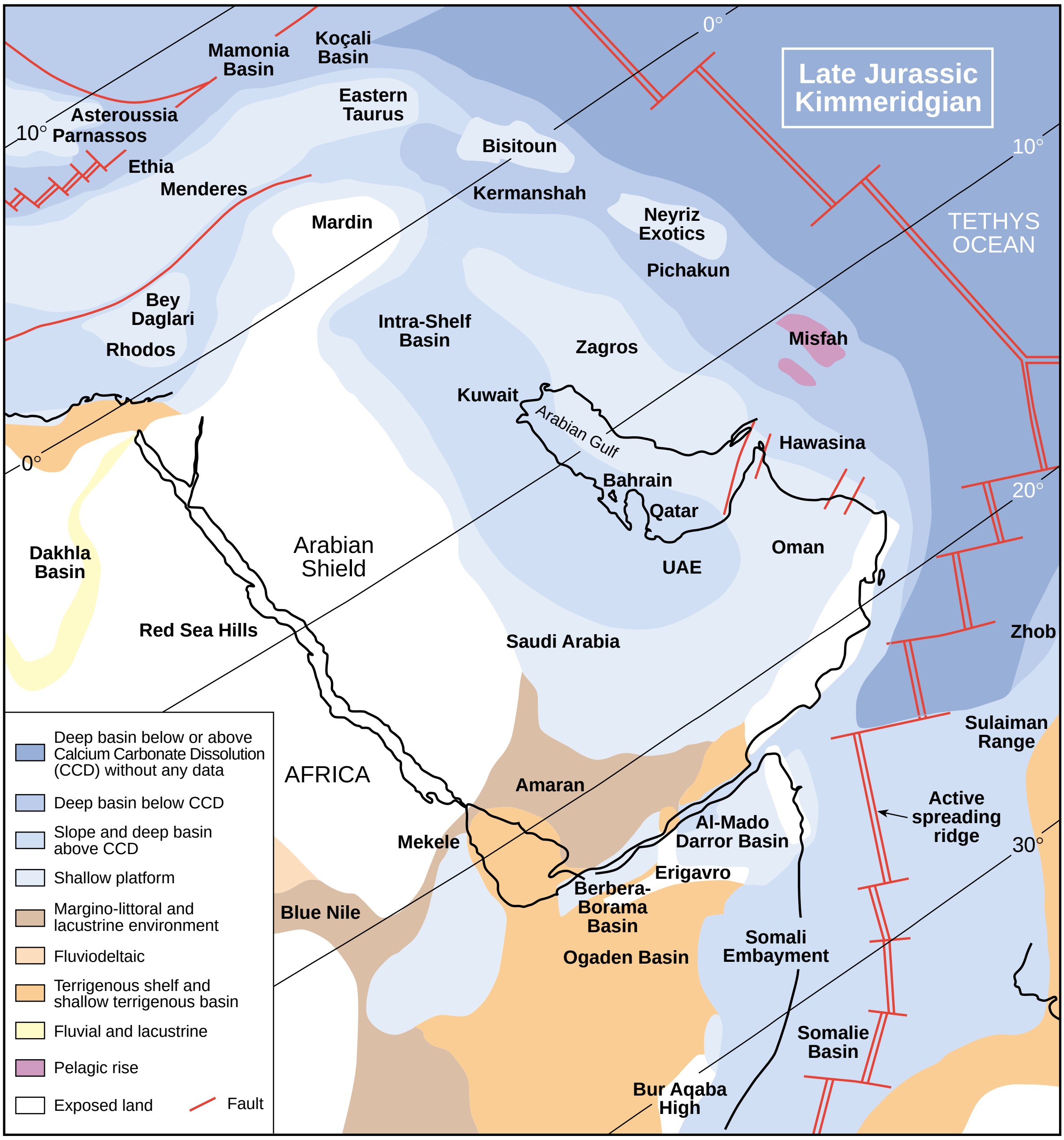

Figure 10: Paleoenvironment and tectonic reconstruction of the Late Jurassic, Early Kimmeridgian (138-135 Ma, modified after Le Nindre et al.,1987; Cecca et al. 1993). The intra-shelf basin centered in Kuwait, is shown as a margino-littoral and lacustrine environment by Cecca et al. (1993). This is inconsistent with Murris (1980; see Figure 7c) and Le Nindre et al. (1987) which show an intra-shelf basin. The rift system between Arabia/Africa and India became well developed by this time.

reefs, in the upper part of the Hanifa, to the highstand of ZA4.5 (143 to 142 Ma). The overlying Jubaila Limestone is early Kimmeridgian and corresponds to ZA4.6. It is 118.3 m thick in the type section and consists of partially dolomitized aphanitic limestones in the lower 85 m and calcarenitic limestones in the upper 33 m (Powers, 1968).

Above the Jubaila, the Arab Formation consists of four members: Arab-D, C and B, each consisting of a lower carbonate unit and an upper anhydrite unit; and the Arab A carbonate. The Arab A carbonate is capped by the Hith Anhydrite.

McGuire et al. (1993), in a study of the Berri field in Saudi Arabia, assign the Arab Formation to sequences ZA4.7 to ZB1.3 (Figure 3). They correlate the Arab anhydrites to lowstand wedges and transgressive

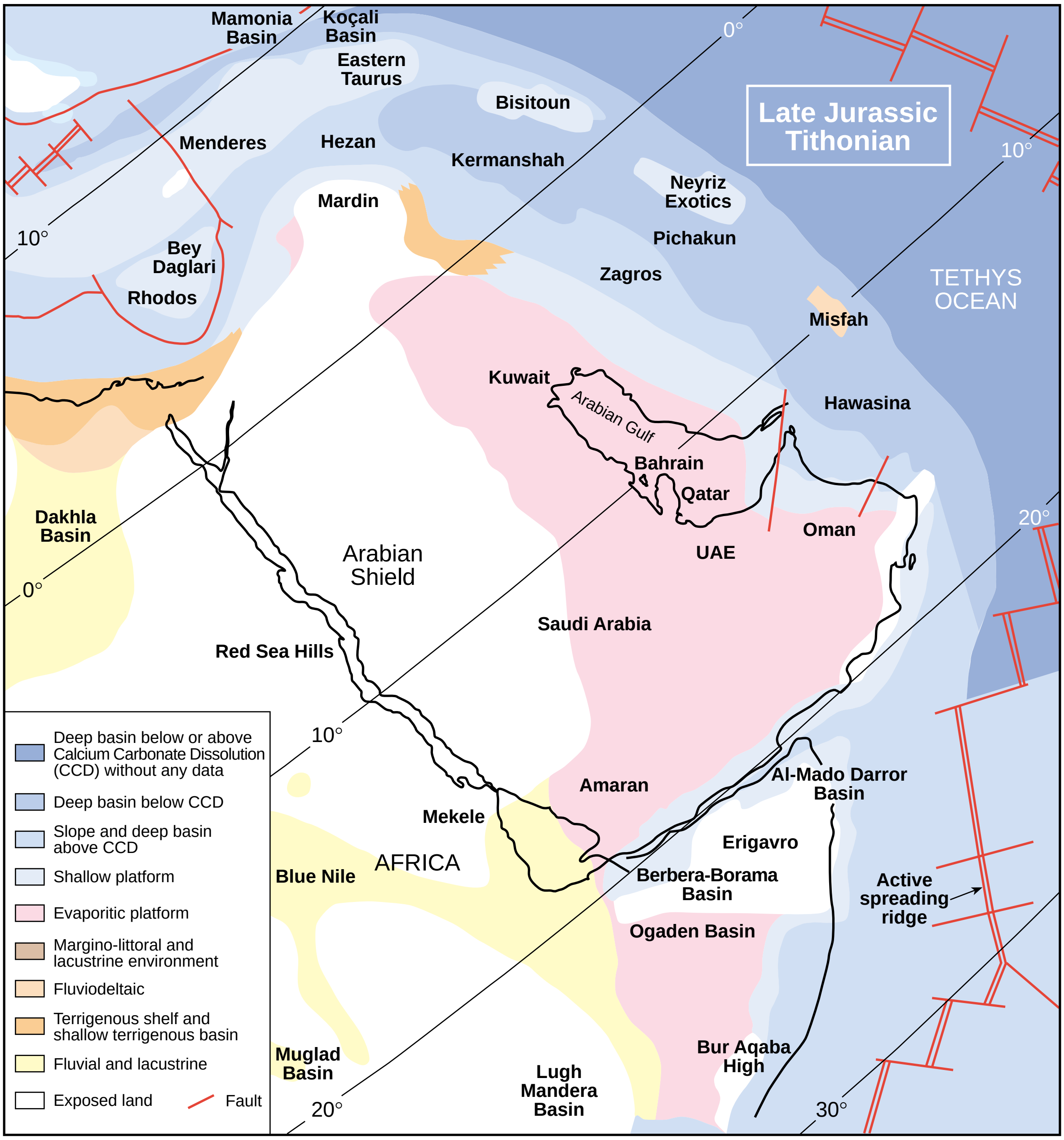

Figure 11: Paleoenvironment and tectonic reconstruction of the Late Jurassic, Late Tithonian (146-144 Ma, after Le Nindre et al., 1987; Fourcade et al., 1993).

deposits, and the carbonates to the highstand deposits. This interpretation would assign the Tithonian Hith Formation to the Berriasian sequence ZB1.4.

Le Nindre et al. (1990), on the other hand, assign the Arab D Member to sequence ZB4.7; Arab C and B to ZB1.1 and ZB1.2, respectively; and Arab A and Hith to the Tithonian sequence ZB1.3 (Figure 3). Their interpretation shows the three Arab and Hith anhydrites corresponding to the highstand deposits of these 4 sequences, which is the complete opposite of the interpretation by McGuire et al. (1993). Le Nindre et al. (1990) and Vaslet et al. (1991) place the Sulaiy Formation in sequence ZB1.4 which is consistent with its Berriasian age and its correlation with the Habshan Sequence I, also ZB1.4, in Abu Dhabi and Oman (Aziz and El Sattar, 1997; Alsharhan and Kendall, 1991; Kendall et al., 1991).

Sarg (1988) presented a sequence stratigraphic model for carbonates and evaporites. He indicates that evaporites can occur as (1) onlapping lowstand or shelf margin wedges; (2) onlapping and retrogradational units of the transgressive deposits; and (3) as lagoonal/sabkha facies in platform interior settings of the highstand deposits.

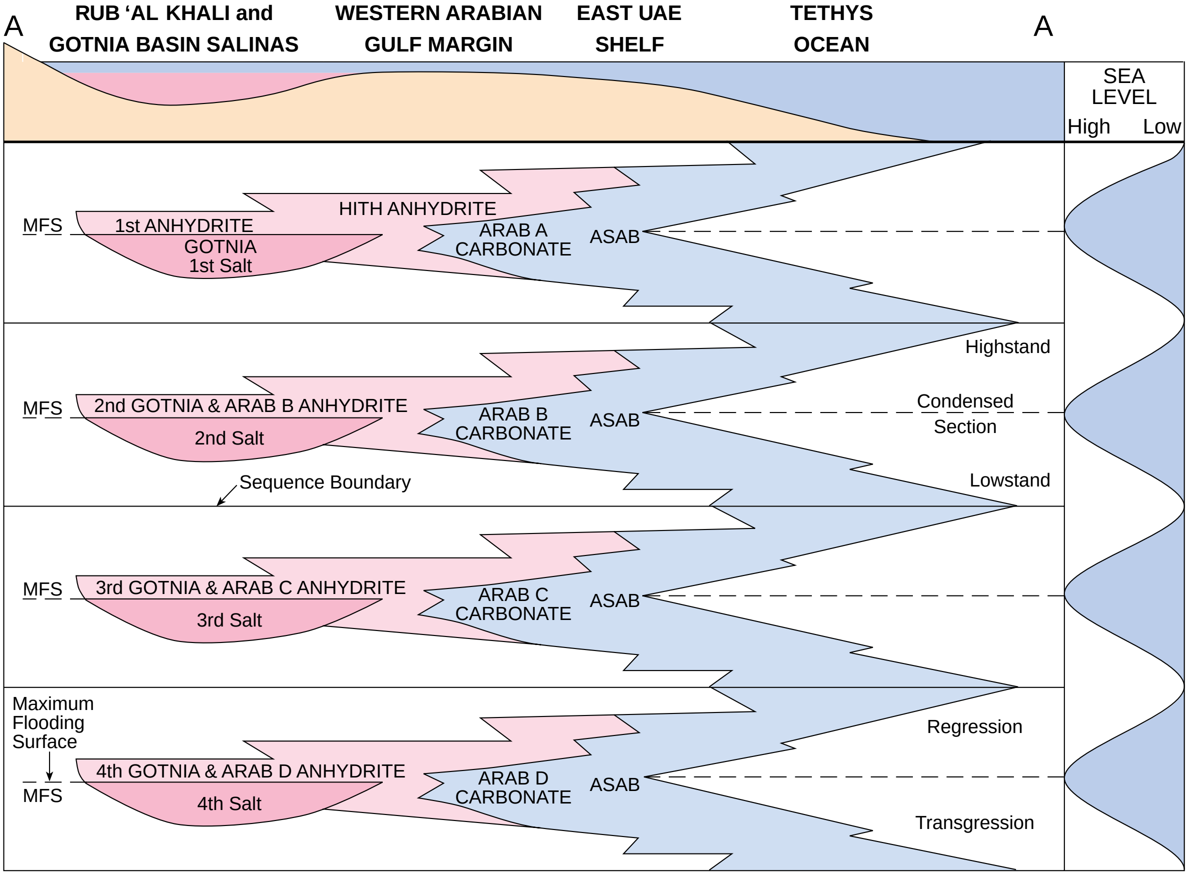

Figure 12: A complete Arab sequence (top of underlying anhydrite to top of main overlying anhydrite) consists of (1) shallowing-upward, shoal grainstone (transgressive deposits); (2) bedded lagoonal mud/wackestone (maximum flooding surface); (3) coarse bioclastic grainstone capped by algal laminates (early highstand); (4) and culminate into anhydrites (later highstand). During the cycles the Gotnia and western Rub' Al-Khali were "cut off" hypersaline lakes (salina). The colors correspond to lithology as shown in Figure 2 and blank areas correspond to non-deposition. Location of AA' is shown in Figure 7.

Azer and Peebles (1995) describe an evaporite model in which the highstand portion of the depositional cycle eventually consumes its vertical accomodation space. It then progrades seaward leaving a "cut off" basin that receives ever diminishing supplies of marine recharge and becomes increasingly evaporative. The basin then evolves into a hypersaline lake (salina) and finally a sabkha before the end of the depositional sequence.

In Figure 12, a simplified model shows the application of eustatic cycles corresponding to the Arab to Hith Anhydrite formations. The cross-section (AA' in Figures 4 and 7) shows an intrashelf basin corresponding to either the Gotnia or Rub' Al-Khali basins, a margin area corresponding to the western and southern Arabian Gulf (Eastern Province of Saudi Arabia, Bahrain, Qatar and western UAE), and an open basin corresponding to the eastern Arabian Gulf (eastern UAE).

The late highstand interpretation of the Arab, Hith and Gotnia evaporites, shown as the Western Arabian Gulf Margin in Figure 12, is consistent with the assignments of Le Nindre et al. (1990). However, the exact correspondence between the carbonates and anhydrites of the Arab members and Hith Anhydrite Formation with specific systems tracts (lowstand, transgressive or highstand) is a subject which deserves more detailed higher resolution modeling.

Understanding the depositional environment and sequence stratigraphic architecture of the Arab and Hith formations is important. These sequences contain four of the most prolific carbonate reservoirs in the World: Arab D Reservoir (Arab D carbonate and upper Jubaila), and Arab A to C reservoirs (Arab A to C carbonates). The Arab D reservoir accounts for most of the Jurassic oil in the Arabian Gulf. The reasons for its predominance are two-fold. Firstly, it occurs directly above the Hanifa source rock and is regionally sealed by the Arab D anhydrite. Secondly, it is the main reservoir in the world's largest oil field, Ghawar.

The Upper Jurassic sequences in Bahrain and Saudi Arabia are similar. The Arab reservoirs in Bahrain's Awali field contain both oil (Arab C and A) and gas (Arab D and B) which is sourced from the Hanifa Formation (Chaube and Al-Samahiji, 1995).

Kuwait

During the Late Jurassic, Kuwait was part of a deep marine basin in which the Sargelu and Najmah formations were deposited. The Sargelu Formation is an interbedded wackestone, mudstone and grainstone and the Najmah Formation an interbedded grainstone and argillaceous limestone. Each formation is approximately 200 ft thick (Yousif and Nouman, 1997) and these probably correspond to the cycles ZA3.2 through ZA4.5.

Above the Najmah Formation, the Gotnia Formation consists of 4 salt and 3 anhydrite layers, followed by the Hith first anhydrite (Yousif and Nouman, 1997). The contact between the Gotnia and Najmah formations is an unconformity which is consistent with the absence of the Jubaila Formation and Arab D carbonate in Kuwait.

The relationship between the rocksalt and anhydrite layers of the intrashelf Gotnia basin (Figure 7d) to the carbonates and anhydrites of the Arab and Hith formations is seen in Figures 4 and 12. In this model the Gotnia Formation of Kuwait (except for the first Salt unit) is equivalent to the Arab Formation. The first Gotnia salt unit and Hith (first anhydrite unit) are together equivalent to the Hith Formation in Saudi Arabia.

Qatar

In Qatar, Sugden and Standring (1975) tentatively show the Diyab and Darb formations as equivalent to the ?Tuwaiq Mountain, Hanifa and Jubaila formations (Figure 4). They remark that the Diyab-Araej contact could represent a considerable break in sedimentation, spanning the Oxfordian-?Callovian, which resulted from uplift over the Qatar Arch.

In Qatar, the Diyab Formation consists of black, fetid, bituminous argillaceous mudstones and shales (325 ft, Sugden and Standring, 1975; Schlumberger, 1981) and the lower part may correlate with the Hanifa Formation. The Darb consists of argillaceous lime wacke / mudstones which shoal upward into higher energy grain-supported carbonates.

The upper Jubaila and Arab D carbonate of Saudi Arabia are correlated to the Fahalil Formation (also Limestone IV) in Qatar. The Arab A to C members are equivalent to the Qatar Formation which consists of Limestones 1 to 3 onshore, or Arab I to III offshore (Sugden and Standring, 1975; QGPC in Schlumberger, 1981). Finally, the Hith Anhydrite Formation is equivalently defined in both countries.

United Arab Emirates

(Esteve) de Matos and Hulstrand (1995) studied the Middle to Upper Jurassic Diyab Formation of offshore Abu Dhabi using cores and thin sections from 40 wells. They show the Diyab Formation, in offshore Abu Dhabi, as equivalent to the Tuwaiq Mountain, Hanifa and lower part of the Jubaila formations for onshore Abu Dhabi.

They conclude that a ?Callovian / Oxfordian rapid sea-level rise followed the deposition of the Upper Araej. During the initial rapid rise, waves and currents ripped up and reworked some clasts. Subsequently the transgression flooded the basin causing sedimentary starvation in offshore Abu Dhabi. They consider the boundary between the Upper Araej and the Tuwaiq Mountain as a drowning unconformity, rather than an erosional one. This interpretation is consistent with the assignment of the Upper Araej and Tuwaiq Mountain to a single sequence (Figure 4) with the latter corresponding to the main transgressive deposits of ZA3.2, as in Saudi Arabia (Le Nindre et al., 1990)

Above the Tuwaiq Mountain, de Matos and Hulstrand (1995) recognize a Type-2 sequence boundary of Oxfordian age. This would correspond to the top of ZA3.2 (Figure 4). A Type-2 sequence boundary forms when basin subsidence at the depositional-shoreline break exceeds the rate of eustatic sea-level fall. As a result no relative sea fall occurs. The boundary is marked by subaerial exposure without erosion associated with stream rejuvenation. Coastal onlap is shifted landward of the depositional-shoreline break and facies are shifted basinward (van Wagoner et al., 1988).

A second Type-2 sequence boundary is placed above the Hanifa Formation (de Matos and Hulstrand, 1995). They assign the Hanifa Formation an early Kimmeridgian age. This sequence boundary would correspond to the top of the ZA4.6 sequence (Figure 4).

Above the Diyab (also Dukhan), the Arab and Hith formations are similar to Saudi Arabia (Al-Silwadi et al., 1996). Further east, however, the anhydrite passes laterally into outer-shelf grainstones of the Asab Formation (Figure 4).

Oman

In Oman the Tuwaiq Mountain (410 ft in type well) consists of a single sequence grading from deeper-shelf lime mudstone to porous pack-grainstone (Hughes Clarke, 1988). Conformably overlying the Tuwaiq Mountain, the Hanifa Formation (208 ft thick in the type well) passes from argillaceous fine-carbonates below to porous grain-supported carbonates above. The overlying Jubaila Formation (260 ft) is generally a fine-grained limestone. In Oman the Hith and Arab formations are missing by erosion or non-deposition.

DISCUSSION

The sequence stratigraphic framework depicted in Figure 3 (after Le Nindre et al., 1990; Vaslet et al., 1991) and its extrapolation to the western and southern Arabian Gulf (Figure 4) raises important regional considerations for stratigraphic assignments and correlations. Many new constraints and insights, which were not previously fully recognized, stand out more clearly.

1. The Upper Triassic-?Lower Jurassic barren continental clastics and the subsequent Early Jurassic hiatus indicate regional erosion and non-deposition over the Arabian platform. This period corresponds to a sea-level lowstand.

2. The early and early late Toarcian transgression closely corresponds to the biostratigraphic age of the Marrat Formation. This formation and its equivalents provide a basal regional, stratigraphic datum, except in Oman where the Lower Jurassic may be missing. Pre-Aalenian Jurassic rocks are not known in the region, except possibly for the barren Triassic-?Upper Jurassic sandstones. The Marrat and Izhara correspond to sequence UAB4.3 (Le Nindre et al., 1990), and also UAB4.4 as suggested here.

3. The latest Toarcian and Aalenian correspond to a substantial sea-level lowstand (75 to 85 m or less) and a regional depositional hiatus.

4. The Middle Jurassic Dhruma Formation in Saudi Arabia corresponds to several sequences which are separated by significant unconformities (Powers, 1968; LeNindre et al., 1990). The Lower Dhruma Shale is a separate sequence. The Upper Dhruma together with the Tuwaiq Mountain Limestone is interpreted by LeNindre et al. (1987, 1990) as a single Callovian-Oxfordian sequence. In the UAE the equivalent Upper Araej and Tuwaiq Mountain (lower Diyab) may also correspond to one sequence.

5. The correlation of the Oxfordian-Kimmeridgian Hanifa from Saudi Arabia, which is the main Jurassic source rock in the Region, to other countries is confusing due to variable nomenclature. It appears to correlate to the Najmah in Kuwait, Diyab in Qatar, Diyab-Dukhan in the UAE and Hanifa in Bahrain and Oman.

6. The equivalents to the Jubaila Formation and Arab carbonates are absent in Kuwait. The upper Jubaila and Arab D carbonate, together, constitute the Arab D Reservoir in Saudi Arabia, Bahrain and the UAE. In Qatar they are equivalent to the Fahalil Formation or Limestone IV. In Oman the Arab and Hith formations are absent.

7. The Arab, Gotnia and Hith anhydrites are tentatively considered as late highstand deposits which cap the Arab sequences. An Arab sequence may consist of a lower section of carbonates corresponding to the margin shelf wedge, transgressive and early highstand deposits. The upper section is mainly evaporites deposited as later highstand deposits.

8. The Hith anhydrite provides a final Jurassic regional, stratigraphic datum, except in Oman and eastern UAE where it is absent. The Arab and Hith formations are Tithonian based on their sequence assignment (Haq et al., 1988). The Sulaiy Formation is Berriasian which straddles the Jurassic-Cretaceous boundary.

RECOMMENDATIONS

Sequence stratigraphy provides a regional chronostratigraphic framework for further refining correlations which are based on lithology and biostratigraphy. The framework presented here for the Jurassic places most of the formations of the southern and western Arabian Gulf in a sequence stratigraphic matrix (Figure 4). Further adjustments, refinements, reassignments and perhaps new rock unit definitions are possible with detailed regional multi-disciplinary studies (e.g. Azer and Peebles, 1995; de Matos and Hulstrand, 1995; Aziz and Abd El-Sattar, 1997).

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