GeoArabia, Vol. 7, No. 4, 2002
Gulf PetroLink, Bahrain

Chronostratigraphy, palynofacies, source-rock potential, and organic thermal maturity of Jurassic rocks from Qatar

Mohamed I. A. Ibrahim[1] and Hamad Al-Saad, University of Qatar
and Suzan E. Kholeif
National Institute of Oceanography and Fisheries, Alexandria

ABSTRACT

Strontium isotope, palynological, and total organic carbon (TOC) analyses were made on core samples from the Izhara, Araej, and Hanifa formations of three wells in onshore Qatar. Eleven samples were analyzed for their $^{87}Sr/^{86}Sr$ ratios. The results gave a chronostratigraphic range of Early Jurassic (Hettangian) to Late Jurassic (Oxfordian), with an overall age range of 202.4 Ma to 157.8 Ma. Maximum flooding surfaces MFS J10 to MFS J50 occur in the Izhara, Araej, and Hanifa formations.

The organic matter in the carbonate sediments of the Izhara, Araej, and Hanifa formations was almost exclusively of marine algal origin dominated by marine microplankton. Organic matter obtained from the Izhara Formation was mature to over-mature kerogen type-III to IV, gas-prone to inert material (mean TOC 0.31%). In the Araej Formation, mature oil-prone and gas-prone kerogen type-II and type-III organic matter occurred in both the lower and upper Araej members (TOC 0.13-0.69%). The stylolitic limestone of the Uwainat member of the Araej Formation has poor potential as a source rock for petroleum (TOC 0.03-0.13%), but is considered to be the main reservoir rock of the Middle Jurassic in Qatar. Mature, highly oil-prone organic matter (type-I and type-II kerogen) was present in black limestone of the Hanifa Formation (mean TOC 0.60%; maximum 0.93%). The limestone is considered to be the most likely petroleum source rock for the underlying and overlying limestone reservoirs of the Uwainat member of the Araej Formation (Bathonian) and the Arab-D member of the Arab Formation (Kimmeridgian) units, respectively.

INTRODUCTION

Qatar is part of the Interior Platform of Arabia over which thick sedimentary sequences have accumulated since the Paleozoic; a thickness estimated to be about 10 km (Alsharhan and Nairn, 1997). The Jurassic rocks in the subsurface of Qatar have attracted the attention of oil companies as they contain most of the hydrocarbon reservoirs and source rocks. Dominguez (1965), Sugden and Standring (1975), Owen (1975), Beydoun (1988), and Alsharhan and Nairn (1994, 1997) summarized the history of hydrocarbon exploration and production in onshore and offshore Qatar.

The aims of our study were as follows: (1) chronostratigraphic determination of the Izhara, Araej and Hanifa formations; (2) palynofacies analyses of the Lower to Middle Jurassic successions; (3) determination of kerogen type and source-rock potential; (4) determination of the degree of organic thermal maturation; and (5) correlating the results with previously obtained data from Qatar and neighboring countries.

Previous Studies

Few Jurassic biostratigraphic studies have been made of Jurassic rocks from Qatar. Smout and Sugden (1961) described some species of the genus *Pfenderina* from the Uwainat member of the Araej Formation. They introduced a new species *(Pfenderina trochoidea)* and placed it in a new family Pfenderinidae. Sugden and Standring (1975) discussed the main stratigraphic and paleontologic characteristics of the Jurassic and Triassic Araej, Izhara, Hamlah, and Gulailah formations in Qatar. They also listed some elements of the faunal contents of these formations of which the genus *Pfenderina* and allied forms are important.

[1] Present address: Department of Environmental Sciences, University of Alexandria, Egypt

Al-Saad et al. (1992) studied the lithofacies and depositional setting of the Araej Formation in the Dukhan oil field. Based on lithologic and microfacies analysis, they recognized 31 microfacies of mainly shallow-water carbonates in the Araej and suggested that it was deposited in a subtidal to shoal setting. Hewaidy and Al-Saad (1993) identified the foraminiferal content of the Araej in the Dukhan field. They divided the Formation into five biostratigraphic zones and assigned it a Bathonian to early Callovian age. They also attempted to correlate their zones with those of the Dhruma Formation in Saudi Arabia.

Hewaidy and Al-Saad (2000) studied the foraminifera of the Lower to Middle Jurassic exposures near Riyadh in central Saudi Arabia, and in ten wells drilled in the Qatar Peninsula. Biostratigraphic schemes were proposed for each area. In central Saudi Arabia, the Middle Jurassic was divided into eight biostratigraphic zones, and into seven zones in Qatar. Important and related studies on the neighboring countries included those of Droste (1990), de Matos et al. (1994), de Matos and Hulstrand (1995), and Al-Suwaidi and Aziz (2002). Recently, Sharland et al. (2001) in their regional work on the sequence stratigraphy of the Arabian Plate defined 10 key maximum flooding surfaces (MFS J10 to J110). These were given ages that ranged from middle Toarcian to middle Tithonian (185–147 Ma), based on lithological, biostratigraphic, sedimentological, sequence stratigraphic, and wireline log criteria.

MATERIALS AND METHODS OF INVESTIGATION

The investigation was based on the analysis of core samples from exploration wells Q-5, Q-8 and Q-9 drilled in western, central and northern Qatar (Figure 1). A total of 83 core samples were taken from the Izhara, Araej and Hanifa formations. The particulars of each well and the number of core samples are shown in Table 1.

Selected samples from the base, middle, and top of each formation were analyzed for their strontium isotope contents (^{86}Sr and ^{87}Sr). The material used had to be unaltered calcite or aragonite from marine

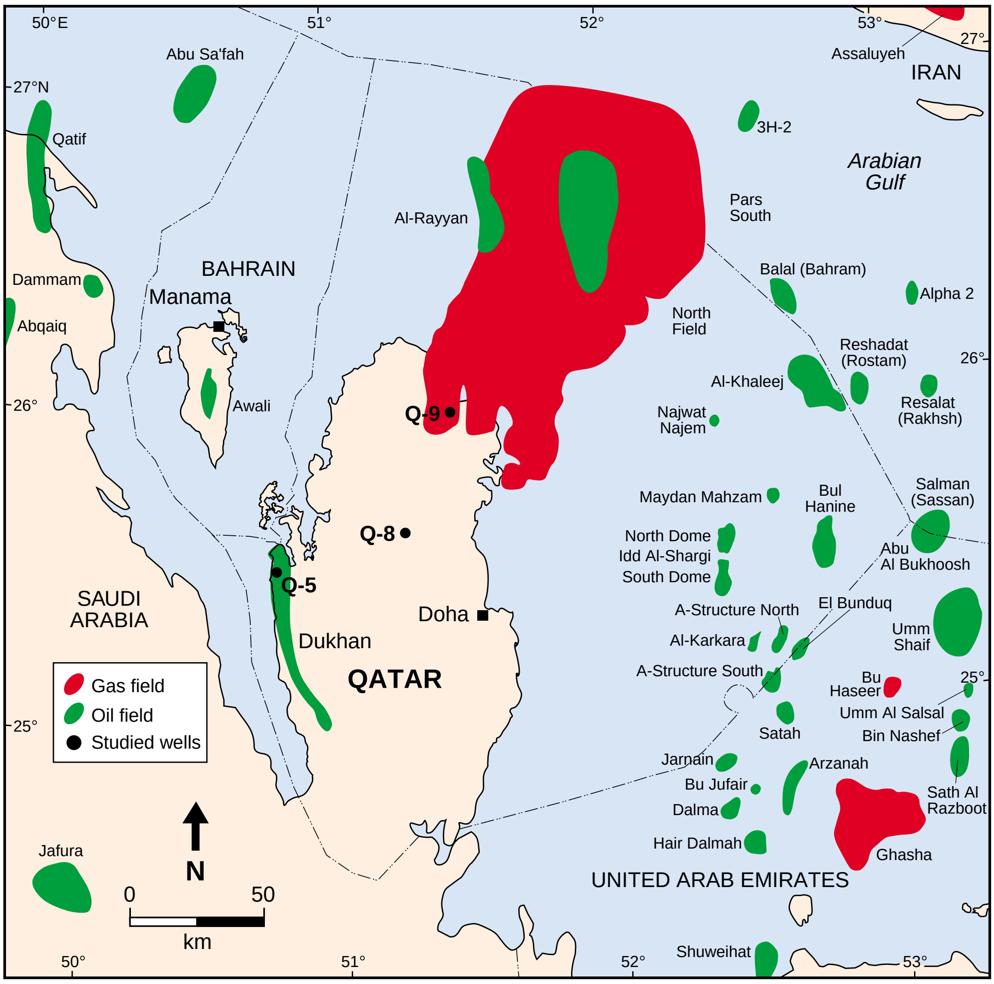


Figure 1: Location map of Qatar showing wells Q-5, Q-8 and Q-9.

Table 1
Number of samples and corresponding formations

Well	Number of Core Samples	Formation	Location
Q-5	31	Izhara and Araej	Dukhan anticline, western Qatar
Q-8	45	Izhara, Araej and Hanifa	Kharaib, central Qatar
Q-9	7	Araej and Hanifa	Ra's Qirtas area, northern Qatar

fossils that incorporated Sr during life. The ^{87}Sr content was determined by its rate of decay from radioactive ^{87}Rb, and the $^{87}Sr/^{86}Sr$ ratio compared with the global seawater Sr curve (database of Howarth and McArthur, 1997). The total organic carbon (TOC) content of 41 samples was also analyzed using the modified Walkley-Black titration method of Gaudette et al. (1974).

In addition, all 83 core samples were processed using standard palynological techniques. The samples were treated with dilute HCl, HF, and concentrated HCl acids to remove carbonates, silicates, and fluorides respectively. The residues were then split into two portions–-one was used to prepare kerogen slides, and the other was filtered using wet sieving with 15 µm polyester sieves. Epoxy resin was used as the mounting medium for the slides. All slides were microscopically examined and at least two slides of each sample were examined in detail. The first 200 palynomorphs were counted for statistical analysis. Species of interest were photographed using an Olympus microscope. The palynological analysis consisted of qualitative and quantitative analysis of organic particles, assessment of palynofacies type, assessment of kerogen type, and determination of spore color and thermal alteration index (TAI).

STRATIGRAPHIC SETTING

The Izhara, Araej, and Hanifa formations in the three wells (Figures 2 and 3) represent the Jurassic sequence from base to top.

Izhara Formation

Sugden introduced the Formation name from a locality near Kharaib in central Qatar in an unpublished report. Sugden and Standring (1975) described the Formation, the type section of which is in the Kharaib-1 well in central Qatar. The overall thickness of the Izhara Formation in central Qatar ranges from 180 to 468 ft, whereas in the Dukhan field (Khatiyah sector) it is from 402 to 468 ft thick (Al-Saad, 1996).

Lithologically, the Formation consists of dark-gray to black argillaceous limestone in its upper and lower parts, and dolomitic limestone in the middle. Generally, the limestone is intercalated with thin lamina of dark-gray shale, marl, claystone, and anhydrite in its lower part. Petrographic analysis of thin sections showed that the Formation is dominated by wackestone / packstone that are intercalated with thin beds of silt in the basal and topmost units. Grainstones are well developed at the middle of the Formation. The grainstone facies are mainly oncoidal with some pyritic remains.

The Formation was assigned an age range of Bajocian to possibly early Bathonian (Middle Jurassic) (Sugden and Standring, 1975; Al-Husseini, 1997; Alsharhan and Nairn, 1997; Hewaidy and Al-Saad, 2000), and was regarded as being equivalent to the lower Dhruma Formation of Saudi Arabia. However, we consider the Lower Jurassic Marrat Formation in Saudi Arabia and Bahrain as being equivalent to the lower part of the Izhara Formation (Figures 2 and 4), as was concluded by de Matos et al. (1994) in their study of the subsurface biostratigraphy from Abu Dhabi to Qatar. Accordingly, the Izhara Formation is assigned an age range of Early to Middle Jurassic. A major hiatus occurred in the middle part of the Izhara Formation (Al-Husseini, 1997, p. 366, Figure 4). It unconformably overlies the Gulailah Formation and the Hamlah Formation in central and western Qatar respectively, and is conformably overlain by the Araej Formation (Figure 4).

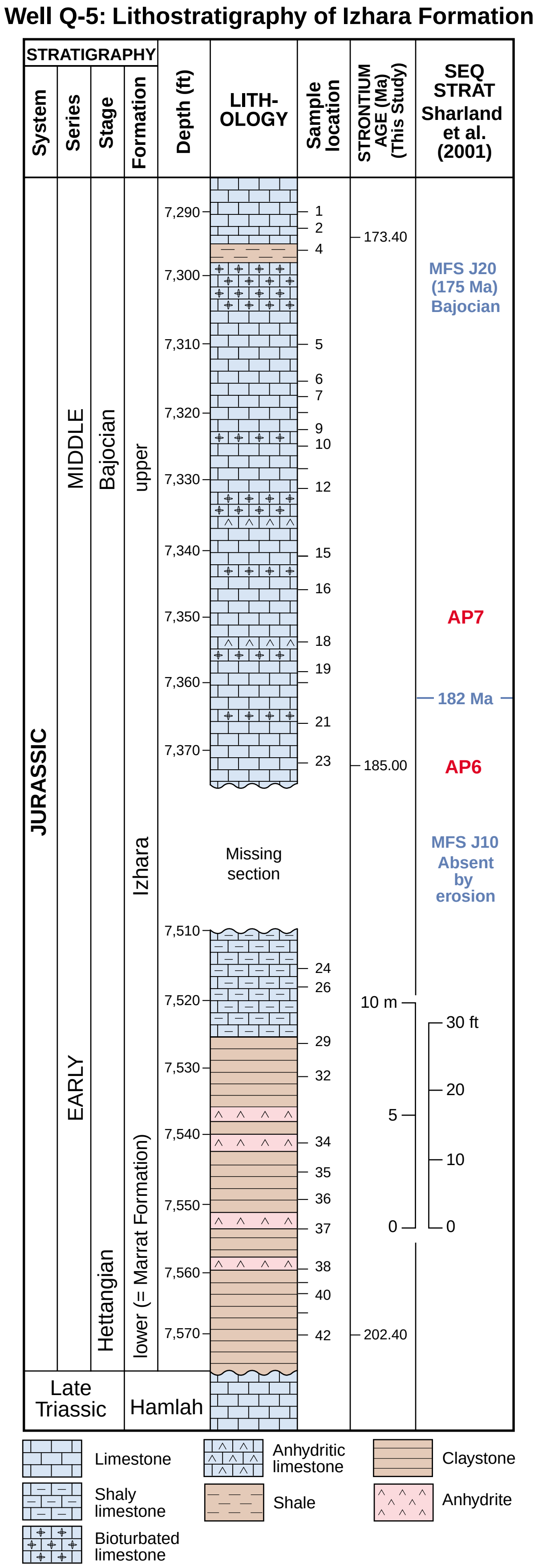


Figure 2: Lithostratigraphy of Izhara Formation in well Q-5 with sample locations, ages from strontium isotope measurements, and correlation with the sequence stratigraphy of Sharland et al. (2001). MFS = Maximum Flooding Surface.

Araej Formation

The Formation was introduced by Sugden (cited in Sugden and Standring, 1975) and takes its name from Jebel Araej in central Qatar. The type section (590 ft thick) was established in the Kharaib-1 well, between the drilled depths of 7,010 and 7,600 ft. In other wells, the Araej has a thickness of between 590 and 656 ft. It is composed of a succession of tight argillaceous limestone in its upper and lower parts, and a middle part that consists of mainly clean limestones. These facies are associated with nodules of anhydrite and numerous stylolitic streaks.

It is divided into three members (Sugden and Standring, 1975; Al-Saad, 1996; Alsharhan and Nairn, 1997) from top to bottom as follows:

Upper Araej member

This member is composed of dark-gray to black or dark-reddish pyritic shaly / argillaceous limestone. Texturally, it is characterized by wackestone interbedded with thin units of packstone / grainstone. In the upper part of the member, these facies gradually change into dense lime mudstone containing small amounts of terrigenous material, including detrital quartz and clay. The upper Araej member is the thinnest member in the Araej Formation, and ranges in thickness from 95 to 250 ft. The contact between the dark shaly limestone of the upper Araej member and the olive limestone of the underlying Uwainat member is sharp and clear.

Uwainat member

The Uwainat member took its name from a locality near the Dukhan oil field. This middle member of the Araej Formation is composed of gray or olive-colored, oil-stained, compact stylolitic fossiliferous limestone. It is characterized by its light color, as compared with the members above and below. Based on the dominant facies, the upper part of the member is composed of wackestone interbedded with thin beds of packstone containing foraminifera and bivalves and rare stylolites. The middle part of the member is characterized by fining-upward facies that are organic-rich and formed of bituminous grainstone / wackestone, whereas the lower part of the member is mainly shaley wackestone. The Uwainat member is from 162 to 195 ft thick.

Lower Araej member

This is the thickest member of the Araej Formation being from 310 to 385 ft thick. It is composed of dark-gray, black and dark-red pyritic and argillaceous limestone. Texturally, the lower Araej

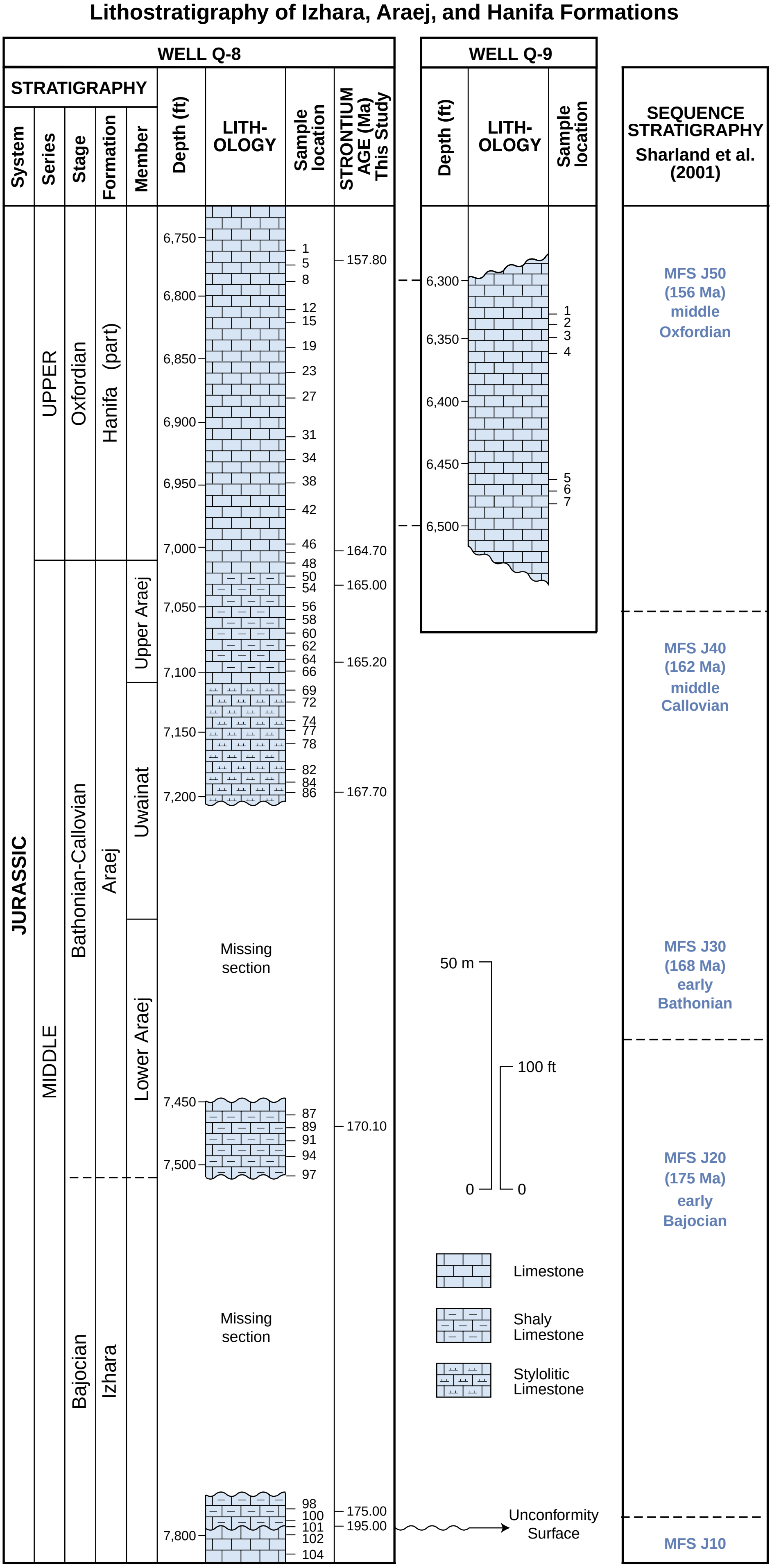


Figure 3: Lithostratigraphy of the Izhara, Araej, and Hanifa formations in wells Q-8 and Q-9 with location of samples, ages from strontium isotope measurements, and correlation with the sequence stratigraphy of Sharland et al. (2001). A disconformity was detected between sample 101 (195 Ma) and 99 (175 Ma) of the lower and upper Izhara Formation in well Q-8, shown by the absence of rocks of Pliensbachian, Toarcian, and Aalenian age. MFS = Maximum Flooding Surface.

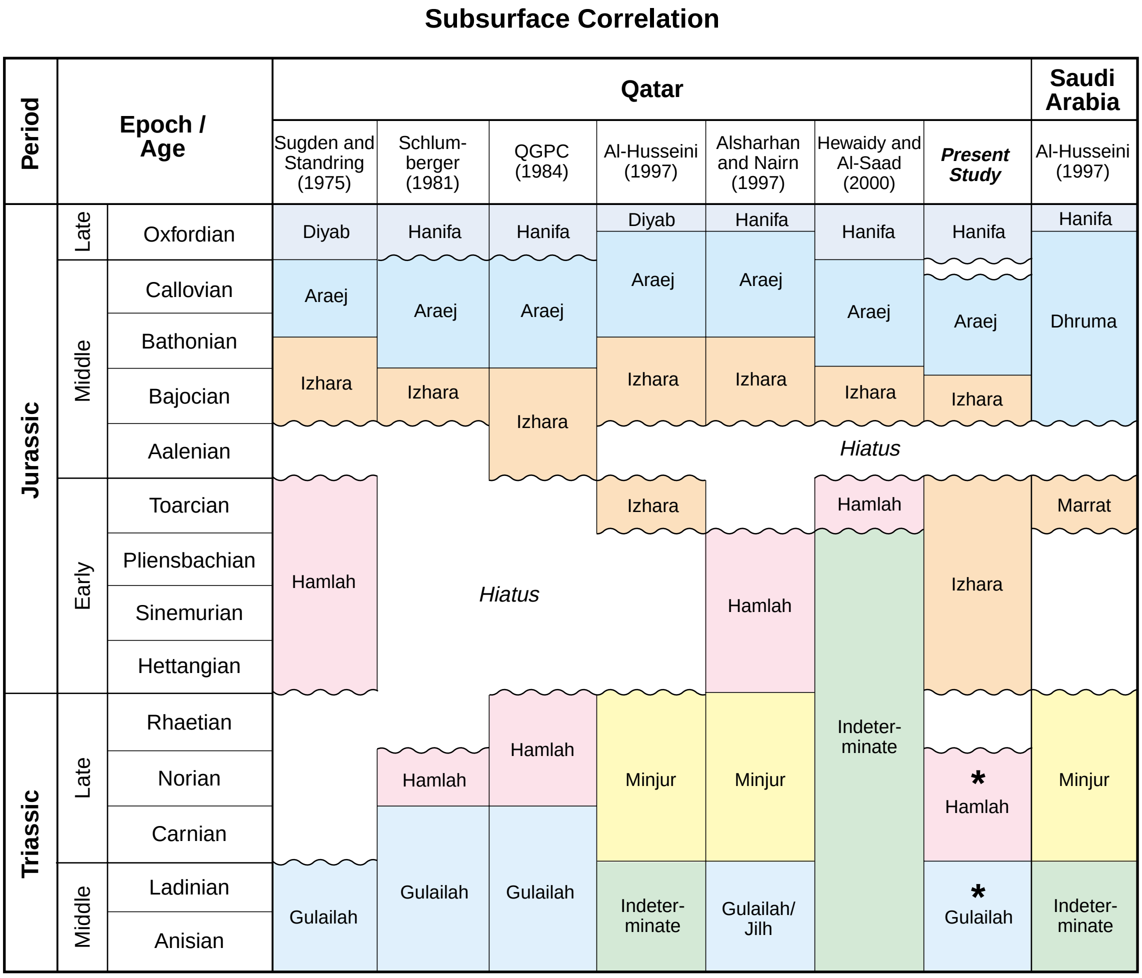


Figure 4: Subsurface correlation of the Middle Triassic to Late Jurassic formations of Qatar and Saudi Arabia (asterisk refers to the work of Ibrahim, in press).

consists of silty wackestone / packstone interbedded in places with pelletal grainstone. It has a well-defined contact with the overlying olive-colored limestone of the Uwainat member.

Sugden and Standring (1975) assigned a Bathonian to Oxfordian age to the Araej Formation, and thus equated it with the middle and upper parts of the Dhruma Formation in the Tuwayq escarpment of central Saudi Arabia (Al-Husseini, 1997). It is overlain disconformably by the Hanifa / Diyab formations and is conformable on the underlying Izhara Formation (Sugden and Standring, 1975; Al-Saad, 1996; Alsharhan and Nairn, 1997).

Hanifa Formation

The Hanifa Formation in Qatar has a significant lateral variation in both thickness (50 to 300 ft) and lithology. It consists of a basal bituminous, thin-bedded black limestone that grades upward into basin-fill shelf carbonates, capped by anhydrite of the basal Jubaila Formation. The lower part of the Formation is mainly composed of tight limestone that grades into bioturbated wackestone and peloidal packstone in the middle part; the upper part consists of fossiliferous dolomitic packstone. Thin streaks of anhydrite are scattered throughout the Formation.

The Hanifa Formation is equivalent to the Diyab Formation of Sugden and Standring (1975). It was dated as late Oxfordian to possibly early Kimmeridgian (Le Nindre et al., 1990). In Saudi Arabia and Bahrain, the Hanifa Formation consists of shales in the lower and middle part, and limestone in the upper part. The Hanifa shales are the main Jurassic source rocks, and the limestones form the Hanifa reservoir (Ayers et al., 1982).

STRONTIUM ISOTOPE ANALYSIS AND AGE DATING

Strontium (Sr) isotope stratigraphy is a valuable tool to complement biostratigraphic dating or to use where biostratigraphy is absent or is producing broad biozones. However, it is easier to express radiogenic ^{87}Sr (formed from the radioactive decay of ^{87}Rb) by means of its ratio to the stable isotope ^{86}Sr. The amount of radiogenic strontium is principally controlled by its input from continental runoff, exhalations at oceanic ridges, and meteoric waters. Variations between these major factors produces unique $^{87}Sr/^{86}Sr$ values for much of the Phanerozoic. Because strontium has a long residence time in oceanic waters, there is time for it to become thoroughly mixed so as to produce a uniform $^{87}Sr/^{86}Sr$ ratio for a given time slice. However, if water circulation within the basin is restricted, either by an offshore barrier or by the basin being totally enclosed, the strontium isotopes will not be mixed efficiently and the resulting ratios will reflect an internal basin stratigraphy and not the seawater strontium curve. It is then possible to construct a local strontium stratigraphy that can be used for intrabasin correlation.

The main sink for strontium is carbonate-bearing or phosphatic sediments. However, this does not restrict the technique to such sediments as mudstones and sandstones may also contain carbonate or phosphatic fossils. Preferably, the material used should be unaltered marine fossil calcite or aragonite into which radiogenic ^{87}Sr was incorporated during the life of the organism. The $^{87}Sr/^{86}Sr$ ratio is compared to the global seawater strontium curve of Howarth and McArthur (1997), the original database for the strontium curve was by Smalley et al. (1994). There is a 95 percent chance that the true age and the mean relative age are within the time interval designated. The use of fossil material has been standard for all academic work involving strontium isotopes.

Strontium Age Results

A total of 11 core samples were selected for strontium isotope analysis from the Izhara, Araej, and Hanifa formations in wells Q-5 and Q-8. The samples, composed mainly of carbonates, were analyzed for their $^{87}Sr/^{86}Sr$ ratios and the results are given in Table 2. Strontium isotopes do not provide an absolute age, as do true radiometric techniques based on the decay of unstable radioactive isotopes. Rather, the value of the ratio of the two strontium isotopes can be interpreted in terms of a stratigraphic age by comparing the ratio with the published global seawater strontium curve; a numerical age is derived from a corresponding timescale. The strontium isotope values were plotted as Figure 5 and the preferred age profile plotted against depth in Figure 6. The ages are given in terms of the Gradstein et al. (1994, 1995) timescale for the Mesozoic.

Table 2 gives the $^{87}Sr/^{86}Sr$ results in terms of Stages based on the timescales of Gradstein et al. (1994, 1995) and Haq et al. (1988). Significant differences are apparent between the two timescales; for example, the top of the Oxfordian is at 154.1 Ma on the Gradstein scale but at 152 Ma on the Haq scale. The age of the top of the Bathonian / base Callovian is 164.4 Ma according to Gradstein but 157 Ma on the Haq scale. Similarly, the top of the Bajocian is at 169.2 Ma on the Gradstein scale but 165 Ma on the Haq scale.

Age Conclusions

The well samples ranged in age from Late Jurassic (Oxfordian) at KB4 (6,773 ft) to Early Jurassic (Hettangian) at IZ42 (7,569 ft). Numerical ages were from 157.8 Ma to 202.4 Ma. The age breakdown is as follows:

Mid-Hanifa Formation (well Q-8)

One sample was dated as Oxfordian at 6,773 ft (157.8 Ma). Sharland et al. (2001) assigned a middle Oxfordian age to MFS J50 of the "condensed organic-rich limestones within the lower Hanifa Formation and Diyab Formation (Droste, 1990; Alsharhan and Nairn, 1997)", and dated it at 156 Ma based on the timescale of Gradstein and Ogg (1996). Al-Suwaidi and Aziz (2002) dated the Hanifa Formation in well-J of offshore Abu Dhabi as Oxfordian (154.9 Ma, Depositional Sequence Jurassic 50-DS J50) based on strontium isotopes.

Araej Formation (well Q-8)

Upper Araej member: Bathonian / Callovian (164.70 Ma, sample depth 7,005 ft) and late Bathonian (165.0–165.2 Ma, sample depths 7,029 and 7,095 ft). However, Sharland et al. (2001) placed MFS J40 in the "shale at the base of the upper Araej Formation (Murris, 1980; Alsharhan and Nairn, 1997)", and dated it as middle Callovian at 162 Ma based on the timescale of Gradstein and Ogg (1996).

Table 2
Sample data and corresponding strontium isotope ratios, chronostratigraphic stage, and absolute age; dinoflagellate age after Ibrahim et al. (in press); maximum flooding surface (MFS) based on Sharland et al. (2001); and ammonite zones after Le Nindre et al. (1990) and Enay and Mangold (1994).

Sample/ Depth (ft)	Well	Formation/ Member	$^{87}Sr/^{86}Sr$	Analytical Error	Age (Ma)	Stage (Gradstein et al., 1994). Ages are for top	Stage (Haq et al., 1998). Ages are for top	Stage based on dinoflagellate biostratigraphy (Ibrahim et al., in press)	Sequence Stratigraphy (MFS) and Ammonite Zone
KB4/6,773	Q-8	Mid Hanifa	0.706852	0.000022	157.80	Oxfordian 154.1	Oxfordian/ Callovian	Early Oxfordian	MFS J50 Perisphinctes plicatilis
KB47/7,005	Q-8	Upper Araej member	0.706960	0.000022	164.70	Bathonian/ Callovian 164.4 Ma	Bathonian 157 Ma	Late Bathonian-early Callovian	MFS J40 Erymnocers coronatum
KB53/7,029	Q-8	Upper Araej member	0.706959	0.000018	165.00	Bathonian 164.4 Ma	Bathonian 157 Ma	Late Bathonian-early Callovian	
KB65/7,095	Q-8	Upper Araej member	0.706964	0.000020	165.20	Bathonian 164.4 Ma	Bathonian/ Bajocian	Late Bathonian-early Callovian	
KB86/7,200	Q-8	Mid Araej Uwainat member	0.707059	0.000020	167.70	Bathonian 164.4 Ma	Bajocian 165 Ma	Bathonian	-
KB90+89/ 7,470-75	Q-8	Lower Araej member	0.707083	0.000025	170.10	Bathonian/ Bajocian	Bajocian 165 Ma	Bathonian	MFS J30 Zigzagoceras zigzag
KB99/7,785	Q-8	Top Izhara	0.707268	0.000022	175.00	Bajocian 169.2 Ma	Aalenian 171 Ma	Bajocian	MFS J20 Witchellia laeviuscula
KB101/7,795	Q-8	Mid Izhara	0.707426	0.000017	195.60	Sinemurian 195.3 Ma	Sinemurian 194 Ma	Undetermined	MFS J10 Hildocera bifrons
IZ3/7,296	Q-5	Top Izhara	0.707185	0.000020	173.40	Bajocian 169.2 Ma	Bajocian 165 Ma	Late Bajocian	MFS J20 Witchellia laeviuscula
IZ23/7,372	Q-5	Mid Izhara	0.707162	0.000020	185.00	Toarcian 180.1 Ma	Toarcian 179 Ma	Early Bajocian	MFS J10 Hildocera bifrons
IZ42/7,7569	Q-5	Mid Izhara (=Marrat Formation)	0.707682	0.000020	202.40	Hettangian 201.9 Ma	Hettangian 201 Ma	Hettengian-Toarcian	

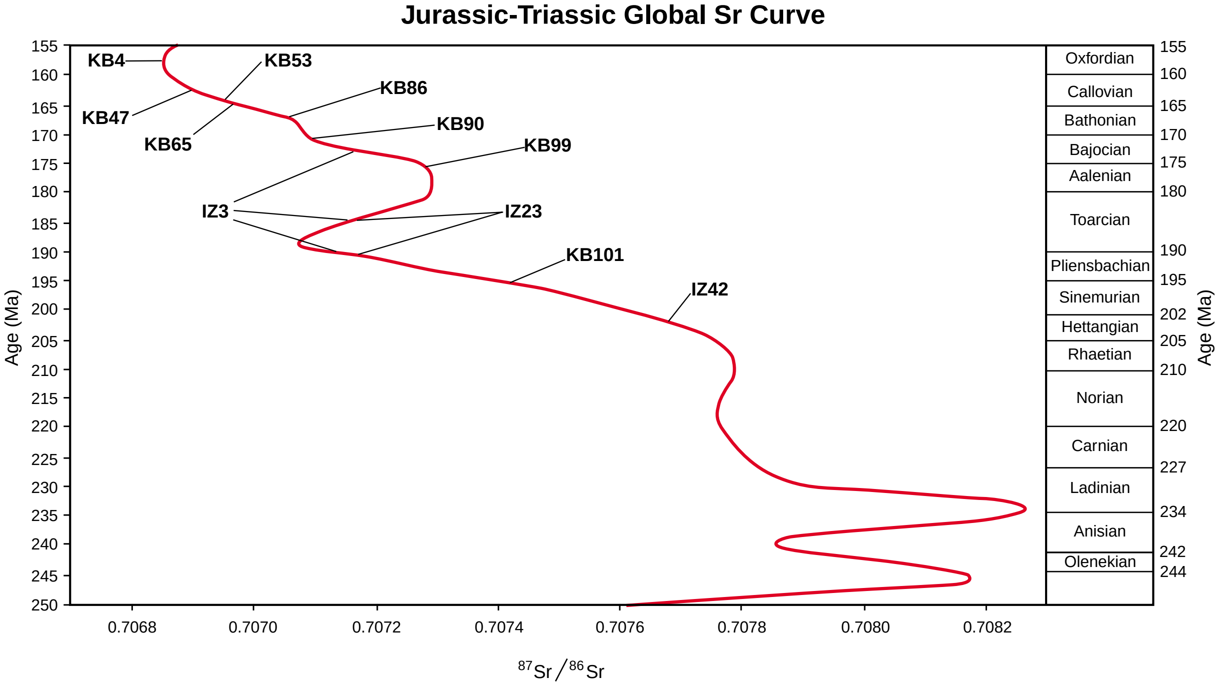


Figure 5: Strontium isotope results plotted on the Triassic-Jurassic global strontium isotope curve (red) against age (Gradstein et al., 1994). See Table 2 for sample data.

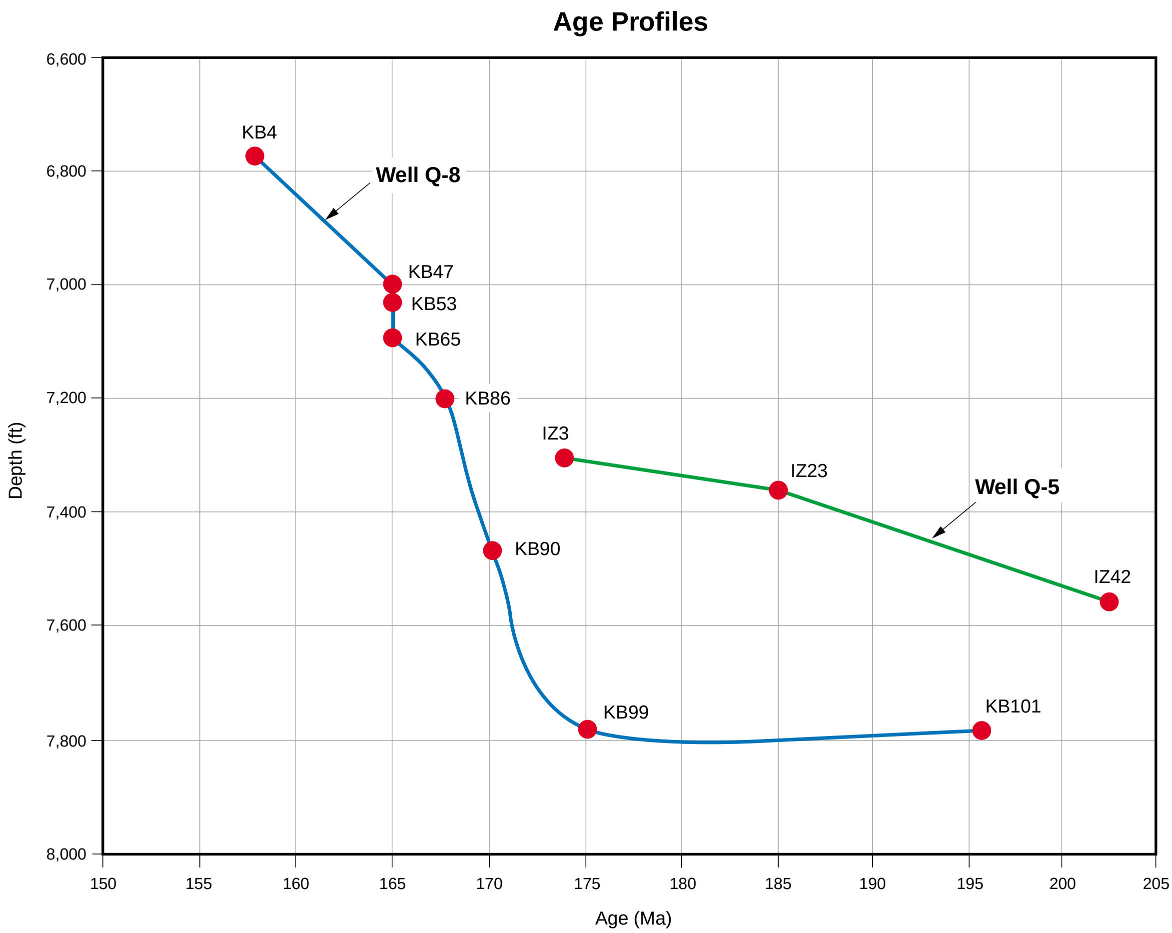


Figure 6: Plot of the favored age profile against depth: well Q-8 (blue line); well Q-5 (green line). See Table 2 for sample data.

Uwainat member: Bathonian (167.7 Ma, sample depth 7,200 ft).

Lower Araej member: Bajocian/lower Bathonian (170.1 Ma, sample depth 7,470 ft). Sharland et al. (2001) placed MFS J30 in the "argillaceous limestone within the lower Araej Formation (Alsharhan and Nairn, 1997)", and dated it as early Bathonian at 168 Ma (Gradstein and Ogg, 1996).

Izhara Formation (wells Q-8, Q-5)

The top of the Formation was assigned a Middle Jurassic, Bajocian age (175.0 Ma in well Q-8 and 173.4 Ma in well Q-5), and its base was dated as Sinemurian (195.6 Ma) in well Q-8 and Hettangian (202.4 Ma) in well Q-5. However, according to Grabowski and Norton (1995) the base of the Izhara Formation is Pliensbachian. A disconformity, and the absence of the Pliensbachian, ?Toarcian, and ?Aalenian, was detected between the lower and upper parts of the Formation in well Q-8 between samples 101 (195 Ma) and 99 (175 Ma) (Figure 3). Al-Husseini (1997) interpreted major hiatuses in the middle of the Formation and at its base. Thus, the Izhara Formation has a complex history, and without detailed dating its base could be interpreted as being almost anywhere within the Lower Jurassic.

JURASSIC PALYNOSTRATIGRAPHY

Palynology is widely used in the petroleum industry but there are no publications on this subject concerning the Jurassic of Qatar, and few for the Arabian Peninsula in general. The present investigation represents the first palynological study of the subsurface Izhara, Araej, and Hanifa formations in wells Q-5, Q-8, and Q-9.

The stratigraphic distribution and occurrence of the palynomorphs led us to propose five dinoflagellate cyst zones and one barren zone within the Hettangian to Oxfordian interval. Detailed biozonation is beyond the scope of the present paper and the results will be published separately (Ibrahim et al., in press). Table 3 summarizes the dinoflagellate biozones.

Most of the 83 samples analyzed yielded moderately rich and well-preserved, but not always diversified, dinoflagellate cyst assemblages. This was particularly so for the Araej Formation, whereas poor preservation and a scarcity of palynomorphs was a characteristic feature of samples from the upper Izhara and Hanifa formations in wells Q-5 and Q-8, respectively. Spores and pollen were determined quantitatively to the specific level but were present only rarely in the studied intervals. Seventy dinoflagellate cyst species belonging to 32 genera, 4 acritarch taxa, and 18 miospore species related to 13 genera, were identified (see Appendix); some of the dinoflagellate species are shown in plates 1 and 2.

Table 3
Dinoflagellate biozones

Stage	Formation/ member		Dinoflagellate Zone	Well/Depth (ft)
Early Oxfordian	Hanifa Formation		Zone V *Systematophora areola-Liesbergia liesbergensis* Assemblage Zone	Q-9/6,333-6,484 Q-8/6,765-6,991
Late Bathonian-early Callovian	Araej Formation	Upper Araej member	Zone IV *Chlyamydophorella ectotabulata-Rhynchodiniopsis cladophora-Lithodinia jurassica-Mendicodinium groenlandicum* Assemblage Zone	Q-8/6,991-7,100
Bathonian	Araej Formation	Uwainat member	Zone III *Ctenidodinium continuum-Dichadogonyaulax sellwoodii Korystocysta kettonensis/gochtii* Assemblage Zone	Q-8/6,115-7,470
Late Bajocian	Araej Formation	Lower Araej member	Zone II *Gonyaulacysta pectinigera-Escharisphaeridia pocockii* Assemblage Zone	Q-8/7,470-7,508
Early Bajocian	Izhara Formation		Zone I *Nannoceratopsis gracilis-Mancodinium semitabulatum Rhyncodiniopsis? regalis-Pareodinia ceratophora* Assemblage Zone	Q-5/7,290-7,370 Q-5/7,508-7,795
Hettangian -Toarchian	Lower Izhara (Marrat Fm)		Barren Zone	Q-5/7,370-7,570 Q-5/7,795-7,810

Plate 1 (facing page): Miospores (a–c) and dinoflagellate cysts (d–o) of the Izhara and Araej formations; sample number, slide designation, and England Finder reference (EF) are given sequentially for each illustrated specimen. All magnifications x 600.

(a) *Apiculatasporites* sp. Well Q-8, sample 98, slide 1; EF: E27/3.
(b) *Callialasporites trilobatus* (Balme) Sukh Dev, 1961. Well Q-8, sample 98, slide 1; EF: R31.
(c) *Callialasporites* sp. Well Q-8, sample 102, slide 1; EF: E52/4.
(d) *Pareodinia ceratophora* Deflandre, 1947, emend. Gocht, 1970. Well Q-8, sample 94, slide 1; EF: W28.
(e) *Rhynchodiniopsis*? cf. regalis (Gocht) Jan du Chêne et al., 1985. Well Q-8, sample 98, slide 1; EF: L3/3.
(f) *Mendicodinium* sp. Well Q-8, sample 94, slide 1; EF: U41/3.
(g) *Lithodinia jurassica* Eisenack, 1935, emend. Gocht, 1975. Well Q-8, sample 64, slide 2; EF: V47.
(h) *Sentusidinium* sp. Well Q-8, sample 94, slide 1; EF: D60/1.
(i) *Valensiella ovulum* (Deflandre) Eisenack, 1963, emend. Courtinat, 1989. Well Q-8, sample 97, slide 1; EF: Y44/1.
(j) *Lithodinia* sp. Well Q-8, sample 89, slide 1; EF: T47/2.
(k) *Prolixosphaeridium* sp. Well Q-8, sample 89, slide 1; EF: X33/1.
(l) *Korystocysta gochtii* (Sarjeant) Woollam, 1983. Well Q-8, sample 64, slide 2; EF: C45/3.
(m) *Gonyaulacysta jurassica adecta longicornis* (Deflandre) Downie and Sarjeant, 1965, emend. Sarjeant, 1982. Well Q-8, sample 64, slide 2; EF: B50.
(n) *Chlamydophorella ectotabulata* Smelror, 1989. Well Q-8, sample 87, slide 1; EF: W33/2.
(o) *Ctenidodinium continuum* Gocht, 1970. Well Q-8, sample 87, slide 1; EF: E34/4.

Plate 1

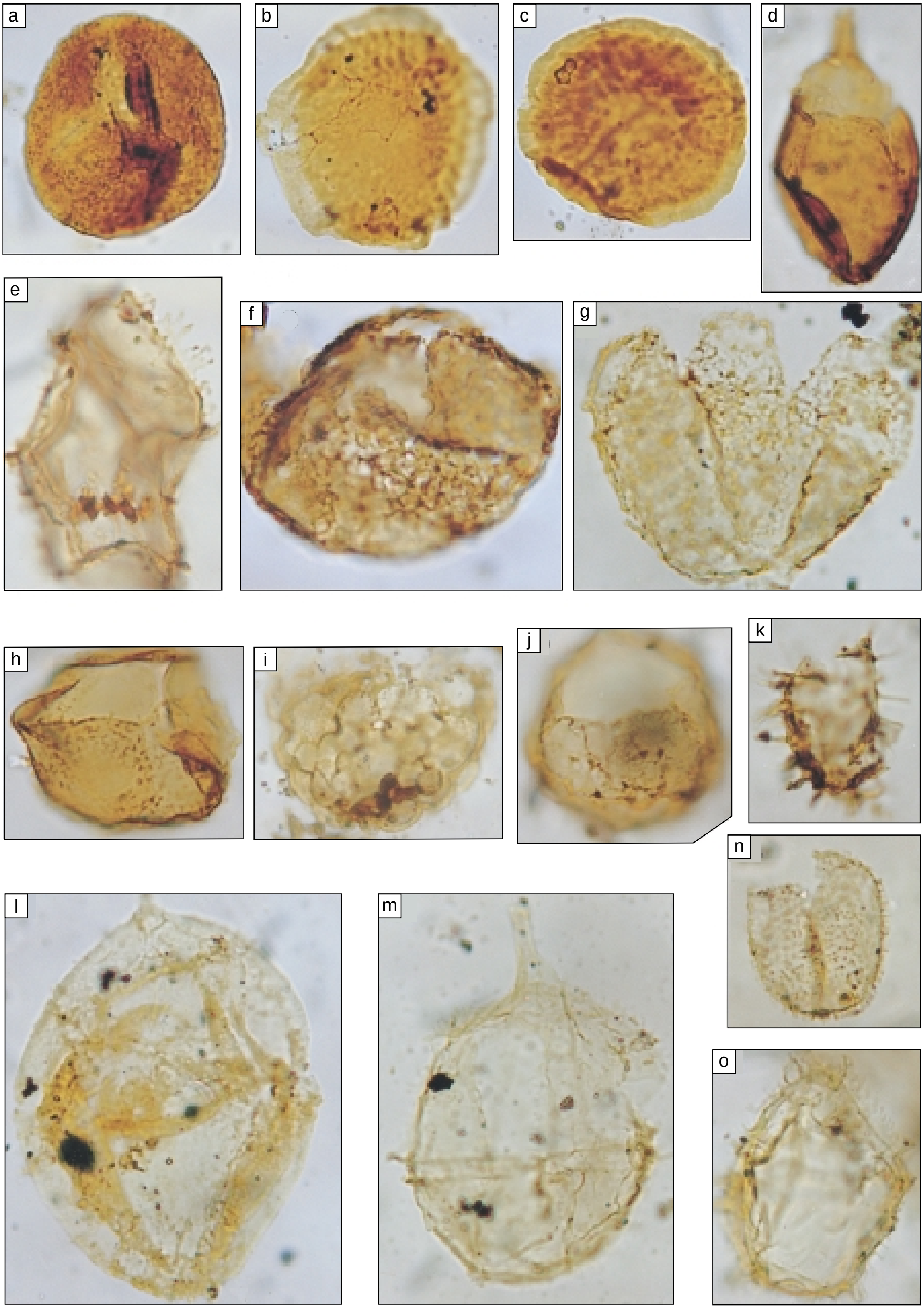
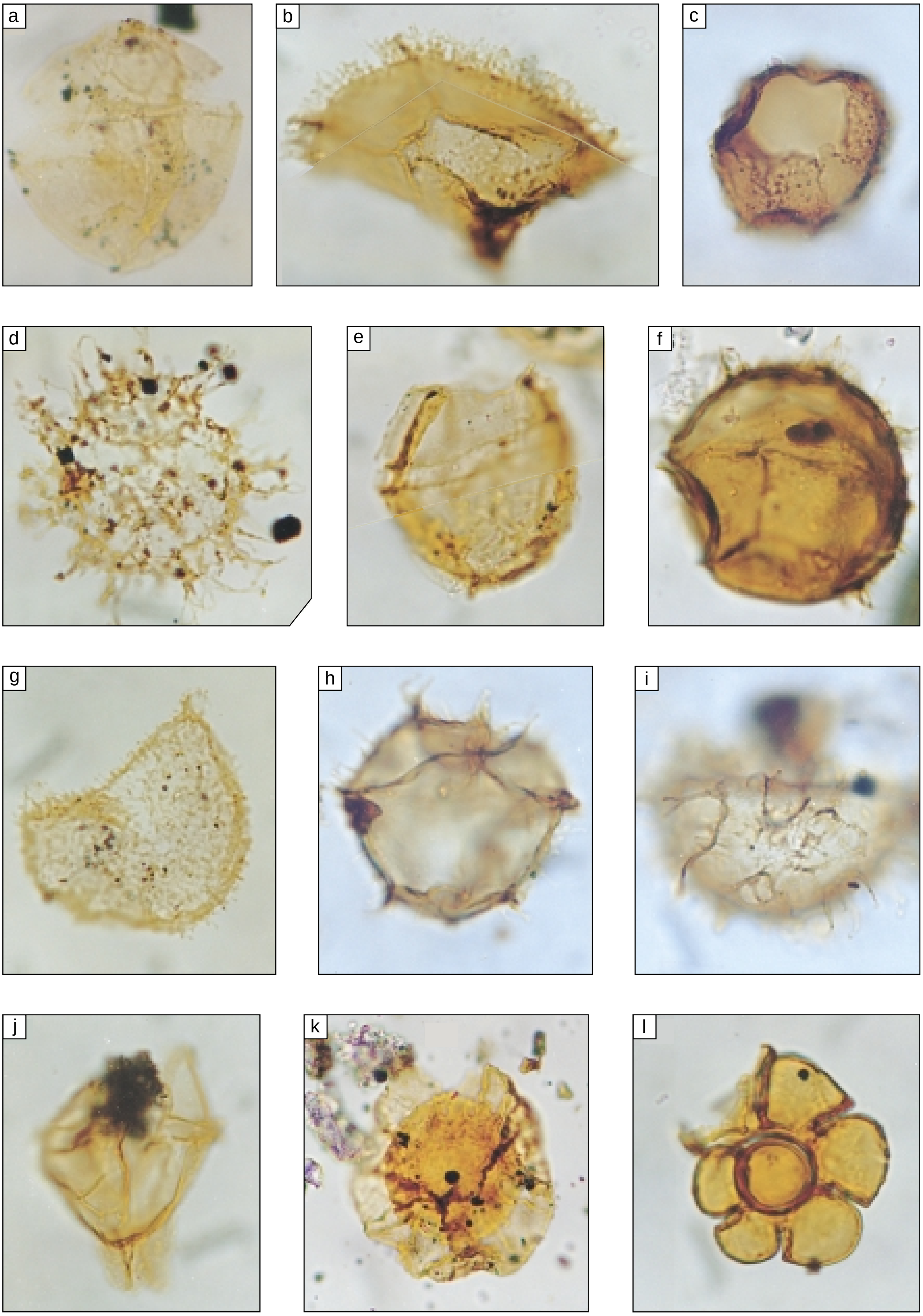


Plate 2



JURASSIC PALYNOFACIES, SOURCE ROCK POTENTIAL AND ORGANIC THERMAL MATURATION

Combaz (1964) was the first to apply the term "palynofacies" to describe the quantitative and qualitative palynological study of the total particulate organic matter assemblage. Palynofacies analysis involves the identification of individual palynomorphs, plant debris, and amorphous components, their absolute relative proportions, size spectra, and preservation states. Plate 3 illustrates palynomorphs from the Izhara, Araej, and Hanifa formations. Palynofacies analysis is an interdisciplinary technique that forms the natural interface between palynology, sedimentology, and organic geochemistry (Tyson, 1993, 1995). It represents the aspect of the organic facies that may be determined by transmitted light microscopy or, in other words, the petrographic recognition of kerogen parameters and types.

The Jurassic rocks in Qatar, as in the Gulf region in general, have high petroleum potential. The principal exploration objectives are formations of Middle and Late Jurassic age as these contain the near-ideal association of source rocks and high-porosity / permeability limestone reservoirs below excellent cap rocks. The rocks form broad open structures that hold very large accumulations of petroleum (Alsharhan and Nairn, 1997).

The methods used to assess the hydrocarbon potential of source rocks are of two main types: optical (palynofacies) and geochemical. Batten (1996) concluded that there was a reasonable correlation between optical and chemical data in terms of assessing the petroleum potential.

One of the most widely used methods of determining the amount of organic matter in rocks is to measure the TOC content expressed as a weight percent of the sediments. The TOC content is usually considered in the context of kerogen types and macerals, but some correlations with palynofacies have been reported. Most weight-percent values obtained link well with the abundance of amorphous organic matter (AOM) recorded from fine-grained sediments that accumulated in anoxic environments. It is generally accepted that for a rock to be a source of hydrocarbons it has to contain sufficient organic matter to allow significant generation and expulsion (Tissot and Welte, 1978). There is an agreement among organic geochemists that a rock can be considered as having source potential if it contains more than 0.5 percent TOC for shales, and at least 0.3 percent for carbonates (Tissot and Welte, 1978; Hunt, 1979; Tyson, 1995; Batten, 1996).

Relationships between palynofacies and source potential have been reported by palynologists and geochemists (see Staplin, 1969; Correia, 1971; Batten 1981, 1996; Thompson and Dembicki, 1986; Nøhr-Hansen, 1989; Firth, 1993; Wood et al., 1997; and Ibrahim et al., 1997). The major oil-prone classes of organic matter are the algal and amorphous material, prasinophyte, chlorococcales, and cyanobacteria. Conversely, structured woody material and other plant debris are commonly regarded as significant source of gas when abundant in sediments. Opaque fragments (charcoal) have no oil or gas potential.

Plate 2 (facing page): Dinoflagellate cysts (a–j) and other microplanktons (k, l) of the Araej and Hanifa formations; sample number, slide designation and England Finder reference (EF) are given sequentially for each illustrated specimen. All magnifications x 600.

(a) *Korystocysts pachyderma* (Deflandre) Woollam, 1983. Well Q-8, sample 64, slide 1; EF: F42 / 2.
(b) *Wanaea acollarris* Dodekova, 1975. Well Q-8, sample 84, slide 1; EF: L50 / 3.
(c) *Lithodinia* sp. Well Q-9, sample 6, slide 2; EF: E55 / 3.
(d) *Hystrichosphaerina* sp. Well Q-8, sample 50, slide 1; EF: Y63 / 4.
(e) *Lithodinia callomonii* (Sarjeant) Gocht, 1976. Well Q-8, sample 62, slide 1; EF: X45.
(f) *Ctenidodinium ornatum* (Eisenack) Deflandre, 1939. Well Q-8, sample 77, slide 1; EF: Z23 / 1.
(g) *Liesbergia liesbergensis* Berger, 1986. Well Q-8, sample 56, slide 1; EF: M19 / 3.
(h) *Ctenidodinium ornatum* (Eisenack) Deflandre, 1939. Well Q-9, sample 6, slide 2; EF: T19.
(i) *Systematophora areolata* Klement, 1960. Well Q-9, sample 7, slide 1; EF: L32 / 4.
(j) *Tubotuberella dangeardii* (Sarjeant) Stover and Evitt, 1978, emend. Sarjeant, 1982. Well Q-9, sample 7, slide 2; EF: Z64.
(k) *Pterosphaeridia* cf. *volkeimerii* Quattrocchio, 1980. Well Q-8, sample 87, slide 1; EF: T35.
(l) Microforaminiferal test linings. Well Q-9, sample 7, slide 2; EF: Z37 / 1.

Plate 3

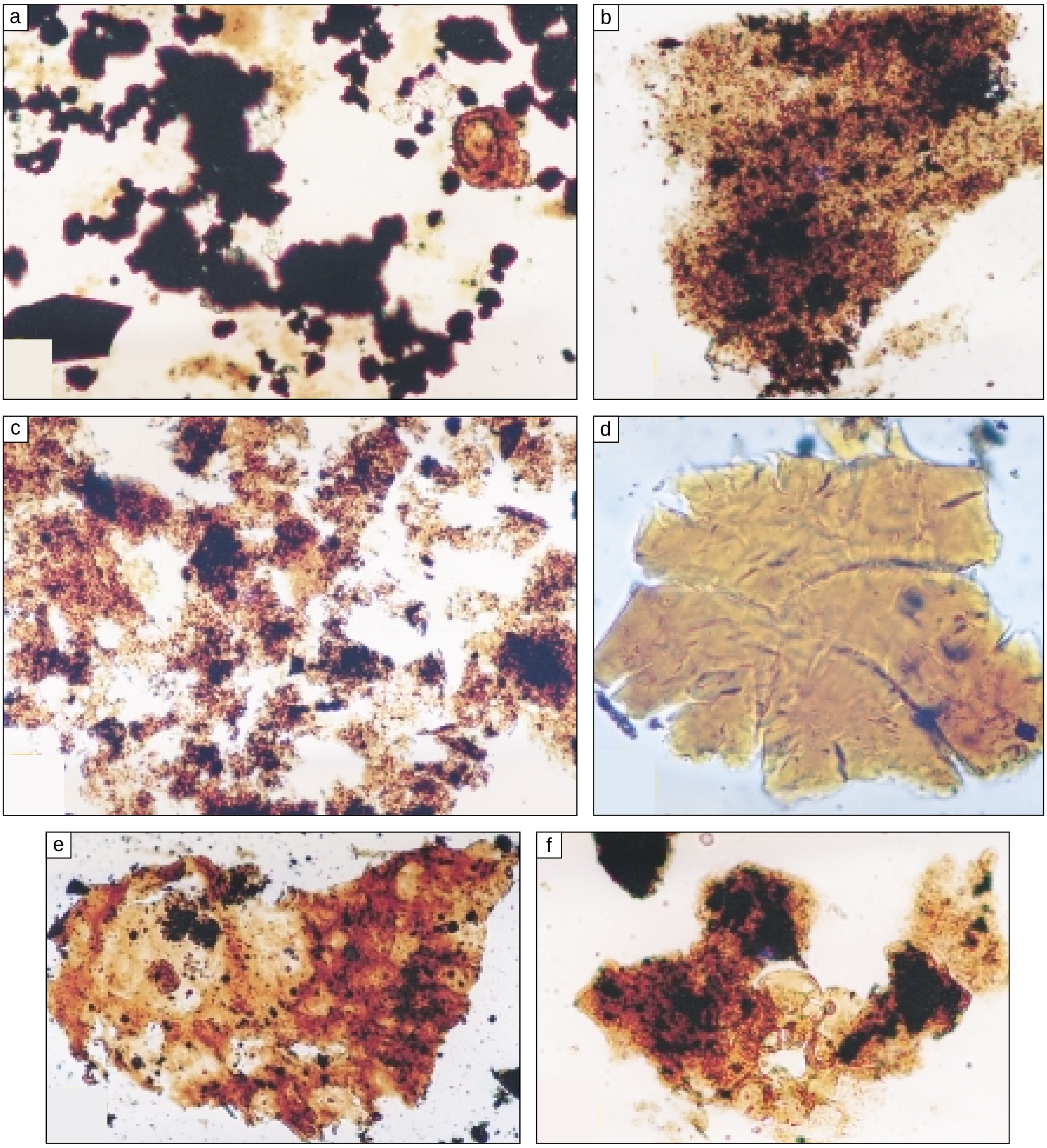


Plate 3: Palynomorhs of the Izhara, Araej and Hanifa formations in transmitted light; magnification, well, sample number, slide designation, and England Finder reference (EF) are given sequentially for each illustrated photograph.

(a) Opaque phytoclasts, Izhara Formation. x 300, well Q-8, sample 98, slide 1; EF: Z58 / 1.
(b) Well preserved amorphous organic matter palynofacies, Hanifa Formation. x 300, well Q-9, sample 3, slide 1; EF: P25 / 1.
(c) Amorphous organic matter palynofacies, Hanifa Formation. x 150, well Q-9, sample 5, slide 2; EF: N41.
(d) Large particle of cracked resin, Hanifa Formation, x 430. Well Q-9, sample 3, slide 1; EF: E44 / 1.
(e) Biodegraded biostructured phytoclast (root cortex tissues), Araej Formation. x 300, well Q-8, sample 82, slide 2; EF: N16 / 2.
(f) Biodegradation of microforaminiferal lining impeded by amorphous organic matter, Hanifa Formation. x 300, well Q-9, sample 4, slide 1; EF: K70.

Table 4

Summary of palynofacies, spore color, thermal alteration index, estimated vitrinite reflectance, kerogen type, total organic carbon content, maturity, and inferred paleoenvironment of the Izhara, Araej and Hanifa formations in the Jurassic of onshore Qatar. TAI = Thermal Alteration Index; TOC = Total Organic Carbon.

<table>
<tr><th colspan="2">Formation</th><th>Stage</th><th>Abundant Palynofacies</th><th>Spore Color</th><th>TAI</th><th>Estimated Vitrinite Reflectance R_o</th><th>Kerogen Type</th><th>TOC% (Mean)</th><th>Maturity</th><th>Depositional Environment</th></tr>
<tr><td colspan="2">Hanifa</td><td>Early Oxfordian</td><td>AOM + Phyto-plankton + Pyrite</td><td>Orange to orange brown</td><td>2+ 3+</td><td>0.7-0.8 Peak oil generation</td><td>I-II Highly oil-prone</td><td>0.06-0.93 (0.60)</td><td>Mature</td><td>Middle shelf (anoxic)</td></tr>
<tr><td rowspan="3">Araej</td><td>upper</td><td rowspan="3">Late Bajocian-early Callovian</td><td rowspan="3">Phyto-plankton + Structured organic matter + AOM</td><td rowspan="3">Light medium brown</td><td rowspan="3">3- 3</td><td rowspan="3">0.8-0.9 Peak oil generation</td><td rowspan="3">II-III Oil and gas-prone</td><td>0.34-0.60 (0.37)</td><td rowspan="3">Mature</td><td rowspan="3">Middle shelf (dysoxic)</td></tr>
<tr><td>Uwainat</td><td>0.03-0.42 (0.13)</td></tr>
<tr><td>lower</td><td>0.02-0.68 (0.31)</td></tr>
<tr><td colspan="2">Izhara</td><td>Hettangian-Bajocian</td><td>Opaques "charcoal" + structured organic matter</td><td>Medium brown</td><td>3 3+</td><td>1.0-1.3 Onset gas generation</td><td>III-IV Gas-prone to inert</td><td>0.02-0.68 (0.31)</td><td>Over mature</td><td>Inner shelf (oxic)</td></tr>
</table>

The type and amount of organic matter in the source rock and its organic maturation level, essentially control the generation of petroleum. Methods used to interpret and document the past thermal history of particulate organic matter include palynomorph color, spore translucency, vitrinite reflectance, and degree of fluorescence (Table 4). In the present study, the thermal alteration index (TAI) was determined using the changes in color of smooth pteridophytic spores (e.g., *Cyathidites*, *Dictyophyllidites*, and *Deltoidospora*) and gymnosperm pollen (*Classopollis* and *Araucariacites*) through the studied intervals. TAI was determined by comparing the spore/pollen color with the color chart of Pearson (1990). In general, the TAI values increase with depth from 2+, 3-, 3 to 3+, which indicates a mature to over-mature state for the organic matter.

Izhara Formation

The palynofacies of the Hettengian-Bajocian limestone and claystone of the Izhara Formation in wells Q-5 and Q-8 were well represented by opaque fragments (Figure 7 and Plate 3a) that resulted from oxidation of vitrinitic particles (phytoclasts). Phytoclasts and AOM of terrestrial origin were present in subordinate amounts. TOC values ranged from 0.02 to 0.68 percent (mean of 14 samples = 0.31%) (Figure 8 and Table 4). The spore/pollen color ranged from medium to dark-brown (Plate 1a–1c). The determined TAI was 3 and 3+, and its equivalent vitrinite reflectance (R_o) ranged from 1.0 to 1.3 and indicated the onset of gas generation (Table 4).

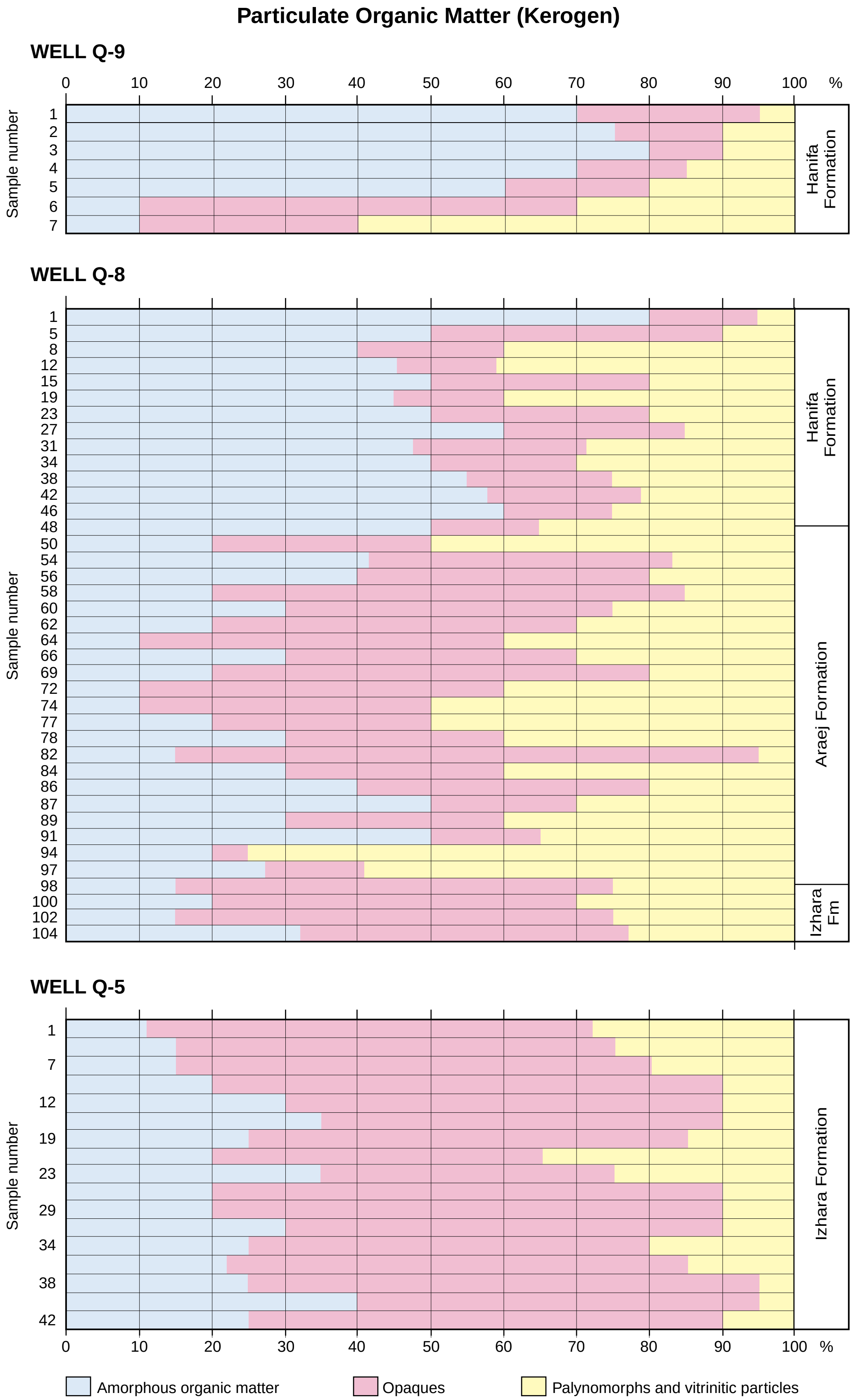


Figure 7: Percentage of particulate organic matter (kerogen) in samples from the Izhara, Araej and Hanifa formations in wells Q-5, Q-8, and Q-9.

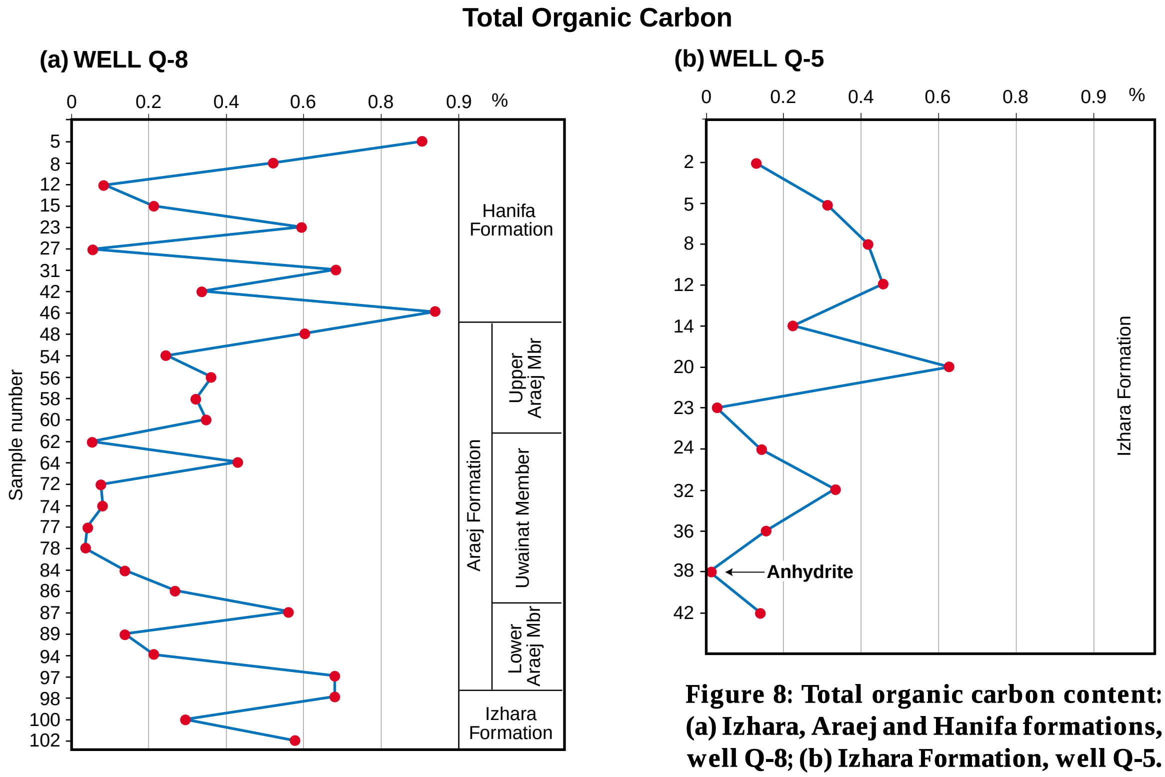


Figure 8: Total organic carbon content: (a) Izhara, Araej and Hanifa formations, well Q-8; (b) Izhara Formation, well Q-5.

Accordingly, the organic matter of the Izhara Formation was determined as mature to over-mature gas-prone to inert type-III to type-IV kerogen. However, based on the analysis of two core samples from well DK-5 in the Dukhan oil field, Khaled et al. (1999) concluded that the Izhara Formation reflected mature type-II kerogen, but had low genetic potential.

Araej Formation

The particulate organic matter in the lower and upper members of the Araej Formation showed no distinct abundance and consisted of AOM, opaques, and phytoclasts in similar proportions (Figure 7). The AOM in the Uwainat member was the lowest measured during the study and the TOC had a mean of only 0.13 percent (Figure 8a and Table 4). In contrast, the lower and upper Araej members had a mean value TOC content of 0.39 percent. The spore / pollen color was a light-medium brown that indicated a TAI of 3- to 3, and the estimated R_o ranged from 0.8 to 0.9 indicating peak oil generation.

In conclusion, organic matter in the lower and upper Araej members is mature type-II and type-III kerogen (oil and gas-prone material). The stylolitic limestone of the Uwainat member has poor potential as a source rock for oil and gas, but is considered to be the main reservoir rock in the Middle Jurassic of Qatar (Alsharhan and Nairn, 1994, 1997). In contrast, Khaled et al. (1999) emphasized that the Uwainat member of the middle Araej Formation contained relatively highly mature organic matter of type-I kerogen, but this assumption was based on the analysis of only one sample from well DK-24.

Hanifa Formation

The Oxfordian carbonate facies of the Hanifa Formation has a high AOM (Figure 7) and resin content (Plate 3d), and a high TOC content (Figure 8a; Table 4). The AOM is almost exclusively of marine algal origin, raised up to 80 percent in the upper part of the Formation by the abundance of pyrite. The TOC content has a maximum value of 0.93 percent and a mean of 0.60 percent (nine samples). In general, the spore / pollen color was orange to orange-brown, indicating a TAI of from 2+ to 3-, and the estimated R_o ranged from 0.7 to 0.8 (peak oil generation).

The organic matter in the black limestone of the Hanifa Formation was probably mature (highly oil prone) type-I and type-II kerogen. It is considered to be the source rock for the underlying and overlying limestone reservoirs of the Uwainat member (Bathonian) and the Arab-D member (Kimmeridgian), respectively. This conclusion was in accordance with the findings of Alsharhan and Nairn (1994, 1997). They concluded that the Hanifa Formation in Qatar was a source rock for the Late Jurassic formations and that it contains sapropelic, liptodetrinitic and algal organic matter with a TOC content of from 1 to 6 percent.

Ayers et al. (1982) identified the organic-rich source rock in the Jurassic of Saudi Arabia as being thermally mature and containing amorphous alginite mostly derived from blue-green algae. The organic-rich sediments accumulated in an intrashelf basin during Callovian to Oxfordian times to form the Tuwaiq Mountain Limestone and the Hanifa Formation.

CONCLUSIONS

Dating of the Jurassic sediments of Qatar was by means of strontium isotope rations ($^{87}Sr/^{86}Sr$) linked to the Howarth and McArthur (1997) global strontium seawater curve and related to the Gradstein et al. (1994, 1995) timescale. The results of the study show that the lower Izhara Formation (equivalent to the Marrat Formation of Saudi Arabia) has an age range of Hettangian to Sinemurian (202.4 to 195.6 Ma), whereas its upper part is Bajocian (175 Ma). The Araej Formation is dated as Middle Jurassic (late Bajocian / Bathonian to early Callovian; 164.7 to 170 Ma). The lower-middle Hanifa Formation is Upper Jurassic (Oxfordian; 157.8 Ma). The studied sequences correspond to the maximum flooding surfaces MFS J10 to MFS J50 of Sharland et al. (2001).

A major hiatus in the middle part of the Izhara Formation is shown by the absence of rocks of Pliensbachian, ?Toarcian and / or ?Aalenian age. Missing late Callovian-age sediments between the top of the Araej Formation and the base of the Hanifa Formation indicate another sedimentary break.

Palynological analysis of the Izhara, Araej, and Hanifa formations have led to the identification of 70 dinoflagellate species, 4 acritarch taxa and 18 miospore species. One barren zone (Hettangian-Toarcian), and five dinoflagellate assemblage biozones are proposed for the Hettangian-Oxfordian succession of the Izhara, Araej, and Hanifa formations. The biozones are zone I (early Bajocian), zone II (late Bajocian), zone III (Bathonian), zone IV (late Bathonian-early Callovian), and zone V (early Oxfordian).

The Izhara Formation may have been deposited in a shallow-marine inner oxic shelf environment. Organic matter of the Izhara Formation is mature to over-mature type-III to type-IV kerogen (gas-prone to inert material) with a mean TOC of 0.31 percent.

The carbonate sediments of the Araej Formation were deposited under shallow, normal marine conditions, most probably on the middle shelf in dysoxic conditions. The organic matter of both the lower and upper Araej members is mature type-II and type-III kerogen (oil and gas-prone material) with a TOC content of between 0.13 percent and 0.69 percent. The stylolitic limestone of the Uwainat member has poor source potential for petroleum (TOC between 0.03% and 0.13%) but is considered to be the main reservoir rock of the Middle Jurassic in Qatar.

The black limestone of the Hanifa Formation probably accumulated in shallow water of the middle shelf in anoxic bottom-water conditions. The organic matter is mature, highly oil-prone type-I and type-II kerogen (mean TOC 0.60%, maximum 0.93%). It is considered to be the main source rock for the underlying (Bathonian Uwainat) and overlying (Kimmeridgian Arab-D) limestone reservoirs.

ACKNOWLEDGMENTS

We thank Qatar Petroleum for the provision of core samples necessary for this study. The authors are indebted to Dr. Homaid Al-Madfa, Director of the Scientific and Applied Research Centre (SARC) of the University of Qatar, for his kind support and assistance. This research was supported in part by funds from SARC Project No. 10/2000 and Chevron Overseas Petroleum (Qatar) Ltd. for which the help of Robert J. Rossetter and Gary W. Jacobs is gratefully acknowledged. We acknowledge the use of Howarth and McArthur (1997) Sr-isotope database by A.C. Higgins (StrataData). We thank the three anonymous reviewers for their constructive comments and *GeoArabia* editors David Grainger and Moujahed Al-Husseini for helpful suggestions. The design and drafting of the final graphics was by Gulf PetroLink.

REFERENCES

Al-Husseini, M.I. 1997. Jurassic sequence stratigraphy of the western and southern Arabian Gulf. GeoArabia, v. 2, no. 4, p. 361–382.

Al-Saad, H.A. 1996. Stratigraphy of the Lower and Middle Jurassic formations in central and eastern Arabia. Unpublished PhD thesis, Faculty of Science, Ain Shams University, Cairo, 261 p.

Al-Saad, H.A., A.G. Hewaidy and C.G. Kendall 1992. Lithofacies and depositional setting of the Middle Jurassic Araej Formation in Dukhan oil field, western Qatar, Arabian Gulf. Neues Jahrbuch Geologie Paläontologie, Monatshefte, v. 10, p. 614–630.

Alsharhan, A.S. and A.E.M. Nairn 1994. The Late Permian carbonates (Khuff Formation) in the western Arabian Gulf: its hydrocarbon parameters and paleogeographical aspects. Carbonates and Evaporites, v. 9, p. 132–142.

Alsharhan, A.S. and A.E.M. Nairn 1997. Sedimentary Basins and Petroleum Geology of the Middle East. Elsevier, 843 p.

Al-Suwaidi, A.S. and S.K. Aziz 2002. Sequence stratigraphy of Oxfordian and Kimmeridgian shelf reservoirs, offshore Abu Dhabi. GeoArabia, v. 7, no. 1, p. 31–44.

Ayers, M.G., M. Bilal, R.W. Jones, L.W. Slentz, M. Tartir and A.O. Wilson 1982. Hydrocarbon habitat in main producing areas, Saudi Arabia. American Association of Petroleum Geologists Bulletin, v. 66, p. 1–9.

Batten, D.J. 1981. Palynofacies, organic maturation and source potential for petroleum. In, J. Brooks (Ed.), Organic Maturation Studies and Fossil Fuel Exploration. Academic Press, p. 201–223.

Batten, D.J. 1996. Palynofacies and petroleum potential. In, I. Jansonius and D.C. McGreger (Eds.), Palynology: Principles and Applications. American Association of Stratigraphic Palynologists Foundation, v. 3, p. 1065–1084.

Beydoun, Z.R. 1988. The Middle East: Regional Geology and Petroleum Resources. Scientific Press Ltd., London, 293 p.

Combaz, A., 1964. Les palynofaciès. Revue de Micropaléontologie, v. 7, p. 205–218.

Correia, M., 1971. Diagensis of sporopollenin and other comparable organic substances: application to hydrocarbon research. In, J. Brooks, P. Grant, M.D. Muir, G. Shaw and P. Van Gijzel (Eds.), Sporopollenin. Academic Press, London, p. 569–620.

de Matos, J.E. and R.F. Hulstrand 1995. Regional characteristics and depositional sequences of the Oxfordian and Kimmeridgian, Abu Dhabi. In, M. I. Al-Husseini (Ed.), GEO'94. Gulf PetroLink, Bahrain, v. 1, p. 346–356.

de Matos, J.E., R.F. Hulstrand and G.M. Walkden 1994. The biostratigraphy of the Lower Jurassic of the UAE. Proceeding of the 6th Abu Dhabi International Petroleum Exhibition and Conference, ADSPE 51, p. 449–459.

Dominguez, J.R. 1965. Offshore fields of Qatar. Institute Petroleum Review, v. 19, p. 198–210.

Droste, H.H.J. 1990. Depositional cycles and source rock development in an epeiric intra-platform basin: the Hanifa Formation of the Arabian Peninsula. Sedimentary Geology, v. 69, p. 281–296.

Enay, R. and C. Mangold 1994. First zonation by ammonites of Saudi Arabia Jurassic, a reference for the Arabian Province. Geobios, Memoire Special, v. 17, no. 1, p. 161–174.

Firth, J.V., 1993. Palynofacies and thermal maturation analysis of sediments from the Nankai. In, I.A. Hill, A. Taira, J.V. Firth et al. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, v. 131, p. 57–69.

Gaudette, H.E, W.R. Flight, L. Toner and D.W. Folger 1974. An inexpensive titration method for the determination of organic carbon in recent sediments. Journal of Sedimentary Petrology, v. 44, no. 1, p. 249–253.

Grabowski Jr., G.J. and I.O. Norton 1995. Tectonic controls on the stratigraphic architecture and hydrocarbon systems of the Arabian Plate. In, M.I. Al-Husseini (Ed.), GEO'94. Gulf PetroLink, Bahrain, v. 1, p. 413–430.

Gradstein, F.M., F.P. Agterberg, J.G. Ogg, J. Hardenbol, P. Van Veen, J. Thierry and Z. Huang 1994. Mesozoic Timescale. Journal of Geophysical Research, v. 99, p. 24051–24074.

Gradstein, F.M., F.P. Agterberg, J.G. Ogg, J. Hardenbol, P. Van Veen, J. Thierry and Z. Huang 1995. A Triassic, Jurassic and Cretaceous time scale. In, Bergren et al. (Eds.), Geochronology, Time Scales and Global Stratigraphic Correlation. Society of Economic Paleontologists and Mineralogists, Special Publication no. 54, p. 95–126.

Gradstein, F.M. and J.G. Ogg 1996. A Phanerozoic Time Scale. Episodes, v. 19, p. 3–5.

Haq, B.U., J. Hardenbol and P.R. Vail 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In, C.K. Wilgus, B.S. Hastings, C.A. Ross, H.W. Posamentier, J. van Wagoner and G.St.C. Kendall (Eds.), Sea-level Changes: An Integrated Approach. Society of Economic Paleontologists and Mineralogists, Special Publication no. 42, p. 71–108.

Hewaidy, A.G.A. and H.A. Al-Saad 1993. Foraminifera and age of the Araej Formation in the Dukhan oil field, western Qatar, Arabian Gulf. Qatar University Science Journal, v. 12, p. 200–201.

Hewaidy, A.G.A. and H.A. Al-Saad 2000. Foraminiferal biostratigraphy of the Lower-Middle Jurassic sequences in eastern Arabia. GeoResearch Forum, v. 6, p. 95–104.

Howarth, R.J. and J.M. McArthur 1997. Statistics for strontium isotope stratigraphy: a robust LOWESS fit to the marine Sr-Isotope Curve for 0–206Ma, with look-up table for derivation of numerical age. Journal of Geology, v. 105, p. 441–456.

Hunt, J.M. 1979. Petroleum Geochemistry and Geology. Freeman and Company, San Francisco, 617 p.

Ibrahim, M.I.A. in press. Middle-Late Triassic chronostratigraphy, palynostratigraphy and TOC in Dukhan oil field, Qatar. Micropaleontology.

Ibrahim, M.I.A., N.M. Aboul Ela and S.E. Kholeif 1997. Paleoecology, palynofacies, thermal maturation and hydrocarbon source-rock potential of the Jurassic-Lower Cretaceous sequence in the subsurface of the north Eastern Desert, Egypt. Qatar University Science Journal, v. 17, no. 1, p. 153–172.

Ibrahim, M.I.A., S.E. Kholeif and H.A. Al-Saad in press. Dinoflagellate biostratigraphy and paleoenvironment of the Lower-Middle Jurassic radiogenic-dated succession, Qatar. Sciences Géologiques Bulletin et Mémoires.

Khaled, K.A., H.M. Holail and M.A. Younes 1999. Sedimentological studies and geochemical evaluation of source-rock petroleum potential of Jurassic succession in Dukhan oil field, western Qatar. 4th International Conference on Geochemistry, Alexandria University, Egypt, 15–16 Sept. 1999, p. 471–489.

Le Nindre, Y.M., J. Manivit, H. Manavit and D. Vaslet 1990. Stratigraphie sequentielle du Jurassique et du Cretace en Arabie Saoudite. Bulletin de la Société Géologique de France, serie 8, v. 6, p. 1025–1034.

Murris, R.J. 1980. The Middle East: stratigraphic evolution and oil habitat. American Association of Petroleum Geologists Bulletin, v. 64, p. 597–618.

Nøhr-Hansen, H. 1989. Visual and chemical kerogen analysis of the Lower Kimmeridgian Clay, Westbury, England. In, D.J. Batten and M.C. Keen (Eds.), Northwest European Micropaleontology and Palynology. Ellis Horwood Limited, Chichester, British Micropalaeontological Society, p. 118–134.

Owen, E.W. 1975. Trek of the oil finders: a history of exploration for petroleum. American Association of Petroleum Geologists, Memoir 6, 1,500 p.

Pearson, D.L. 1990. Pollen/spore color "Standard". Phillips Petroleum Company, Geology Branch, Bartlesville, Oklahoma, version 2.

QGPC (Qatar General Petroleum Company) 1984. Generalized stratigraphic column of Qatar, onshore operations. Unpublished company report.

Schlumberger 1981. Well evaluation conference, United Arab Emirates. Unpublished Schlumberger Technical Services report, Paris, 271 p.

Sharland, P.R., R. Archer, D.M. Casey, R.B. Davies, S.H. Hall, A.P. Heward, A.D. Horbury and M.D. Simmons 2001. Arabian Plate Sequence Stratigraphy. GeoArabia Special Publication 2, Gulf PetroLink, Bahrain, 371 p.

Smalley, P.C., A.C. Higgins, R.J. Howarth, H. Nicholson, C.E. Jones, N.H.M. Swinburne and J. Bessa 1994. Marine strontium isotopes: a Phanerozoic seawater curve for practical sediment dating and correlation. Geology, v. 22, p. 431–434.

Smout, A.H. and W. Sugden 1961. New information on the foraminiferal genus *Pfenderina*. Paleontology, v. 4, no. 4, p. 581–591.

Staplin, F.L. 1969. Sedimentary organic matter, organic metamorphism and oil and gas occurrences. Bulletin of Canadian Petroleum Geology, v. 17, no. 1, p. 47–66.

Sugden, W. and A.J. Standring 1975. Qatar Peninsula. Lexique Stratigraphique International, v. III, Centre National de la Recherche Scientifique, Paris, p. 1–85.

Thompson, C. L. and H. Dembicki 1986. Optical characteristics of amorphous kerogens and the hydrocarbon-generation potential of source rocks. International Journal of Coal Geology, v. 6, p. 229–249.

Tissot, B.P. and D.H. Welte 1978. Petroleum Formation and Occurrence. Springer-Verlag, 538 p.

Tyson, R.V., 1993. Palynofacies analysis. In, D.J. Jenkins (Ed.), Applied Micro-Palaeontology. Kluwer Academic Publishers, Netherlands, p. 153–191.

Tyson, R.V. 1995. Sedimentary Organic Matter, Organic Facies and Palynofacies. Chapman and Hall, London, 615 p.

Williams, G.L., J.K. Lentin and R.A. Fensome 1998. The Lentin and Williams Index of fossil dinoflagellates. American Association of Stratigraphic Palynologists Contributions Series, v. 34, p. 1–817.

Wood, G.D., M.A. Miller, Z. Sofer, W.N. Kerbs and R.W. Hedlund 1997. Palynology, palynofacies, paleoenvironments and geochemistry of the Lower Cretaceous (pre-salt) Cocobeach Group, North Gabon Subbasin, Gabon. African Geoscience Review, v. 4, nos. 3 & 4, p. 481–497.

APPENDIX

Taxonomic Species

The palynomorphs found in the present study are listed below. The dinoflagellate-cyst taxonomy used follows that of Williams et al. (1998).

Dinoflagellate Cysts

Aldorfia sp.
Barbatacysta pilosa (Ehrenberg) Courtinat, 1989
Barbatacysta sp.
Batiacasphaera spp.
Chlamydophorella ectotabulata Smelror, 1989
Chlamydophorella sp.
Chytroeisphaeridia chytroeides (Sarjeant) Downie and Sarjeant, 1965, emend. Davey, 1979
Chytroeisphaeridia spp.
Cribroperidinium crispum (W. Wetzel) Fenton, 1981
Cribroperidinium spp.
Ctenidodinium continuum Gocht, 1970
Ctenidodinium ornatum (Eisenack) Deflandre, 1939
Ctenidodinium spp.
Diacanthum sp.
Dichadogonyaulax sellwoodii Sarjeant, 1975
Dichadogonyaulax spp.
Dissiliodinium cf. *volkeimeri* Quattrocchio and Sarjeant, 1992
Dissiliodinium cf. *willei* Bailey and Partington, 1991
Dissiliodinium sp.
Ellipsoidictyum cinctum Klement, 1960
Ellipsoidictyum sp.
Escharisphaeridia pocockii (Sarjeant) Erkmen and Sarjeant, 1980
Escharisphaeridia psilata Kumar, 1986
Escharisphaeridia rudis Davies, 1983 emend Prauss, 1989
Escharisphaeridia spp.
Gonyaulacysta jurassica adecta longicornis (Deflandre) Downie and Sarjeant, 1965, emend. Sarjeant, 1982
Gonyaulacysta jurassica (Deflandre) Norris and Sarjeant, 1965, emend. Sarjeant, 1982
Gonyaulacysta pectinigera (Gocht) Fensome, 1979
Gonyaulacysta spp.
Hystrichosphaerina sp.
Impletosphaeridium varispinosum (Sarjeant) Islam, 1993
Kallosphaeridium sp.
Korystocysta gochtii (Sarjeant) Woollam, 1983
Korystocysta kettonensis (Sarjeant) Woollam, 1983
Korystocysta spp
Korystocysts pachyderma (Deflandre) Woollam, 1983
Liesbergia liesbergensis Berger, 1986
Lithodinia callomonii (Sarjeant) Gocht, 1976
Lithodinia caytonensis (Sarjeant) Gocht, 1976
Lithodinia jurassica Eisenack, 1935, emend. Gocht, 1975
Lithodinia reticulata (Dodekova) Gocht, 1976
Lithodinia spp.
Mancodinium cf. *semitabulatum* Morgenroth, 1970, emend. Below, 1987
Mancodinium semitabulatum Morgenroth, 1970, emend. Below, 1987
Mancodinium sp.
Mendicodinium groenlandicum (Pocock and Sarjeant) Davey, 1979
Mendicodinium microscabratum Bucefalo Palliani, Riding and Torricelli, 1997
Mendicodinium sp.A
Mendicodinium spinosum subsp. spinosum Bucefalo Palliani, Riding and Torricelli, 1997
Mendicodinium spp.
Nannoceratopsis gracilis Alberti, 1961, emend. Evitt, 1962, emend. Van Helden, 1977
Pareodinia ceratophora Deflandre, 1947, emend. Gocht, 1970
Pilosidinium echinatum (Gitmez and Sarjeant) Courtinat, 1989
Prolixosphaeridium sp.
Rhynchodiniopsis cladophora (Deflandre) Below, 1981
Rhynchodiniopsis? cf. *regalis* (Gocht) Jan du Chêne et al., 1985
Rhynchodiniopsis? regalis (Gocht) Jan du Chêne et al., 1985
Scriniodinium sp.
Sentusidinium rioultii (Sarjeant) Sarjeant and Stover, 1978, emend. Courtinat, 1989
Sentusidinium sparsibarbatum Erkmen and Sarjeant, 1980
Sentusidinium spp.
Systematophora areolata Klement, 1960
Systematophora spp.
Tubotuberella dangeardii (Sarjeant) Stover and Evitt, 1978, emend. Sarjeant, 1982
Valensiella ovulum (Deflandre) Eisenack, 1963, emend. Courtinat, 1989
Valensiella sp. A.
Valensiella sp. B
Valensiella spp.
Wallodinium sp.
Wanaea acollarris Dodekova, 1975

Other Microplankton

Cymatiosphaera sp.
Leiosphaeridia sp.
Micrhystridium sp.
Microforaminiferal linings
Pterosphaeridia cf. *volkeimerii* Quattrocchio, 1980

Spores and Pollen

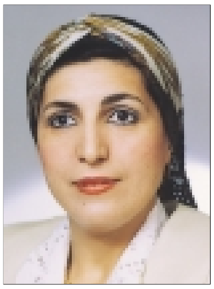
Apiculatasporites sp.
Araucariacites australis Cookson, 1947 ex Couper, 1953
Callialasporites dampieri (Balme) Sukh Dev, 1961
Callialasporites trilobatus (Balme) Sukh Dev, 1961
Callialasporites spp.
Cibotiumspora jurienensis (Balme) Filatoff, 1975
Circulina parva Brenner, 1963
Classopollis classoides Pflug, 1953
Cyathidites major Couper, 1953
Cyathidites minor Couper, 1953
Cycadopites spp.
Deltoidospora hallii Miner, 1935
Dictyophyllidites harrisii Couper, 1958
Dictyophyllidites spp.
Inaperturopollenites spp.
Matonisporites crassiangulatus (Balme) Dettmann, 1963
Staplinisporites caminus (Balme) Pocock, 1962
Staplinisporites perforatus Dettmann, 196

ABOUT THE AUTHORS

Mohamed I.A. Ibrahim *rejoined the staff of the University of Alexandria, Egypt, in mid-2002 after secondment to the Geology Department of Qatar University as an Assistant Professor since October 1996. Mohamed has a BSc (Honors, 1981) in Special Geology and an MSc (1986) in Palynology and Micropaleontology from the University of Alexandria. He obtained his PhD in Micropaleontology and Paleoecology in 1993 from the University of Alexandria and the Technical University of Berlin through a combined channel program. He taught Micropaleontology and Paleoecology from 1993 to 1995 at the University of Alexandria and was a Palyno-stratigraphic Consultant for GEOEX-Egypt (1994–96). He is the author of about 25 research articles on the palynology, micropaleontology, and paleoecolgy of Egypt, Libya, and Qatar. He is National Coordinator and Member of the IGCP 831, 'South Atlantic Mesozoic Correlation Program', and a member of AASP, BMS, GSE, and ESQUA.* *mohamedibrahim59@hotmail.com*

Hamad Al-Saad *is Chairman of the Geology Department at the University of Qatar. He has an MSc in Geology from the University of South Carolina, USA, and a PhD from Ain Shams University, Egypt, 1997. His publications have concentrated on the Middle Jurassic of Qatar. Hamad's current research interests include the sequence stratigraphy of the Jurassic of eastern Arabia. He is a member of SPE and BMS.*

hamadsaad@qu.edu.qa



Suzan Kholeif *is a Lecturer in Micropaleontology at the National Institute of Oceanography and Fisheries in Alexandria, Egypt. She received a BSc in Geology from the University of Alexandria in 1983 and worked for Alexandria Petroleum Company until 1985 when she returned to university. She was awarded an MSc (1989) and PhD (1999) from Mansoura and Cairo universities, respectively, for work on palynology, palynofacies, and paleoecology. She joined the National Institute in 1999. Suzan is the author of research articles on the palynology and paleoecology of Egypt and the Gulf region. She is a member of IGCP 831, 'South Atlantic Mesozoic Correlation Program', and a member of the Geological Society of Egypt and ESQUA.*

suzan_kholeif@hotmail.com

Manuscript Received February 13, 2002

Revised May 15, 2002

Accepted June 4, 2002