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Sequence stratigraphy, biostratigraphy and paleontology of the Maastrichtian-Paleocene Aruma Formation in outcrop in Saudi Arabia

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ABSTRACT

The Aruma Formation is a predominantly carbonate lithostratigraphic unit of Late Cretaceous age that crops out in Saudi Arabia. It consists of three members: from base to top they are Khanasir Limestone Member, Hajajah Limestone Member, and Lina Shale Member. In order to establish a stratigraphic revision of the Formation, a reference section near Al Kharj, southeast of Riyadh in central Saudi Arabia, was logged and a hierarchical organization of the depositional sequences established. The Aruma corresponds to four third-order cycles bounded by erosional unconformities. Integrated biostratigraphical data mainly based on ammonites, nannoflora, rudists, and larger foraminifera point to a Maastrichtian age for the Khanasir and Hajajah members, and a Paleocene age for the Lina Member. Regional stratigraphic correlations were established within the outcropping Aruma Formation in Saudi Arabia. Biostratigraphy and sequence stratigraphy allowed a correlation framework to be proposed between the Aruma and the Qahlah and Simsima formations of the United Arab Emirates and the Oman Mountains, and with the Sharwayn Formation of the Hadramawt and Dhofar. The high-resolution stratigraphic scheme established for the Aruma Formation in Saudi Arabia is expected to be useful for subsurface correlations and in petroleum exploration.

INTRODUCTION

Location

The Aruma Formation (Figure 1) crops out in a wide band that extends southeast from the Iraqi border and the Al Jawf area in northern Saudi Arabia to east of Riyadh, and then south along the western edge of the Rub' Al-Khali. The outcrop in Saudi Arabia is about 1,500 km long. The Aruma overlies the Wasia Formation disconformably and is overlain by the Umm er Radhuma Formation.

In order to make a stratigraphic revision of the Aruma, we studied a well-exposed and complete fossiliferous reference section in central Saudi Arabia near Al Kharj (Figure 1) in the Ar Riyad 1:250,000-scale quadrangle (Vaslet et al., 1991). In order to make regional-scale comparisons and correlations, four other sections (Figure 1) were investigated in the northwestern part of the Aruma outcrop. They are Khashm al Buwaibiyat (Ruma quadrangle, unpublished); Khashm Tawqi (Shaqra quadrangle, Vaslet et al., 1988); and Al Matayih and Jibalah (Turubah quadrangle, Lebret et al., 1999).

Previous Stratigraphic Investigations

Steineke and Bramkamp (1952) gave the name Aruma Formation to a sequence of Late Cretaceous rocks that crops out on Al 'Aramah plateau, a broad upland surface east of Riyadh that is related to the easternmost Najd escarpments in Saudi Arabia. The type sequence was composited from several sections (Powers et al., 1966; Powers, 1968). The base was defined at the contact between Aruma carbonate rocks and underlying varicolored clastic rocks of the Wasia Formation. The upper limit was taken at the change from yellow-brown dolomitic shale below to gray crystalline *Lockhartia*-bearing dolomite of the Umm er Radhuma Formation above.

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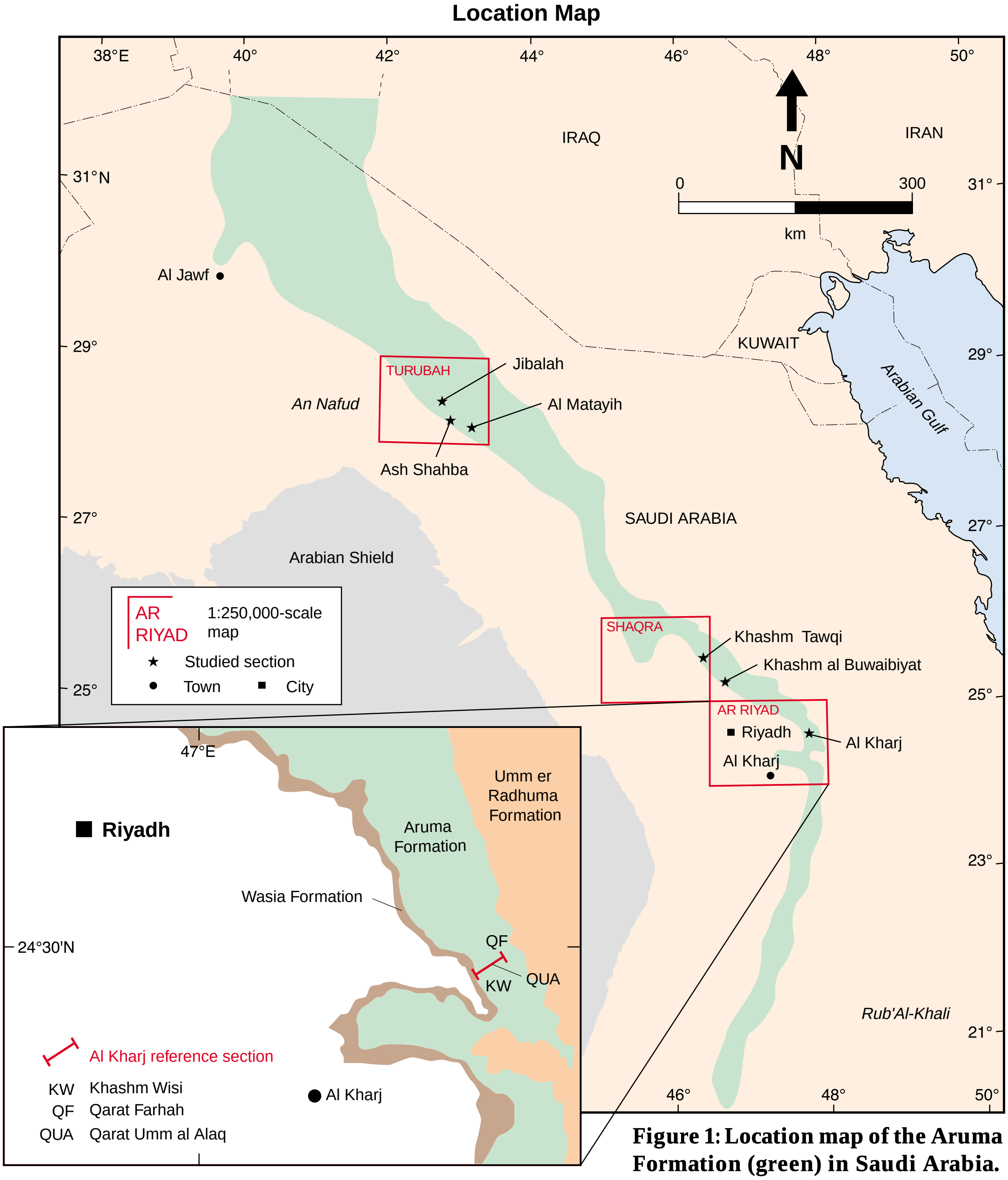

Figure 1: Location map of the Aruma Formation (green) in Saudi Arabia.

The Aruma Formation was subdivided by El-Asa'ad (1983a) into three informal members: from base to top they were the Khanasir Limestone, the Hajajah Limestone, and the Lina Shale members.

Based on the occurrence of ammonites and larger foraminifera, a Campanian-Maastrichtian age was assigned by Powers et al. (1966) to the Aruma Formation, although the Lina Member remained undated. Of particular interest was the mention by Powers et al. of "*Sphenodiscus acutodorsatus*", that is *Libycoceras acutodorsatum* (Noetling), in the lower part of the Aruma, and the suggestion of a disconformable relationship of the Lina Shale Member with other members of the Formation in the subsurface.

Nine fossiliferous intervals were recognized by El-Asa'ad (1983b) within the Aruma Formation and these ranged from Coniacian to late Maastrichtian. The main difference between this and the stratigraphic scheme of Powers et al. (1966) and Powers (1968) was the assignment by El-Asa'ad of the lower part of the Khanasir Limestone Member to the Coniacian, based on ammonites in this unit being attributed to *Tissotia tissoti* Peron. The upper part of the Khanasir Limestone Member was given a Santonian-Campanian age by El-Asa'ad who referred the Hajajah and Lina members to the Maastrichtian. The El-Asa'ad stratigraphic framework was agreed by El-Nakhal and El-Naggar (1994) and retained by Sharland et al. (2001).

Mapping of the Aruma Formation led Vaslet et al. (1988, 1991) and Le Nindre et al. (1990) to make a revision of the age of the Khanasir based on ammonites and nannofossils. Confirming the determinations of Powers et al. (1966) and Powers (1968), the ammonites found in the basal part of the Khanasir were identified by P. Juignet and J.W. Kennedy (written communication, 1989) as "*Sphenodiscus acutodorsatus* Noetling". A late Campanian to early Maastrichtian age was also indicated by the nannoflora in the Khanasir Member (see below). Vaslet et al. assigned a ?late Campanian age to the base of the Khanasir Member, its upper part to the early Maastrichtian, and Hajajah and Lina Shale members to the late Maastrichtian.

A new rudist taxon (*Eodictyoptychus arumaensis*) from within the "*Sphaerulites/Biradiolites* Assemblage Zone" of El-Asa'ad (1983b) was described from the uppermost part of the Khanasir Limestone Member by Skelton and El-Asa'ad (1992). As a result, a Campanian age was assigned by Skelton and El-Asa'ad to the top of the Khanasir Member.

Age-diagnostic marine fossils are absent from the Lina Shale Member. However, the discovery of a new assemblage of marine vertebrates (ichthyofauna and turtles) allowed Thomas et al. (1999) to revise the stratigraphic status of this unit and to suggest a late Paleocene to early Eocene age.

Methods

Sections were logged in the field at 1:50 scale. Revision of the fossil content of the Aruma Formation (ammonites, calcareous nannofossils, rudists, and larger foraminifera) led us to propose a new chronostratigraphic framework for the Formation in Saudi Arabia. Paleoenvironmental and depositional systems were reconstructed from both paleoecological and sedimentological data provided by field and microfacies analyses. Depositional transgressive-regressive sequences were defined at various scales by well-marked erosional surfaces referred to sequence boundaries. These corresponded to major and minor regressive events that punctuated the development of the carbonate platform sequence of the Aruma Formation. Major sequence boundaries and maximum flooding surfaces were used as tools for correlation.

AL KHARJ SECTION

The Al Kharj section (Figure 2) is located about 50 km northeast of Al Kharj (Figure 1). The base of the section is at latitude 24°22.67'N, longitude 47°46.38'E and the top is at latitude 24°25.61'N, longitude 47°50.60'E. The Khanasir Limestone Member and the Wasia/Aruma boundary were investigated in the Kashm Wisi area, the Hajajah Member in the Qarat Umm al Alaq area, and the Lina Member on the Qarat Farhah plateau. The section is exposed in the area of the Ar Riyad 1:250,000-scale geological map (Vaslet et al., 1991).

Khanasir Limestone Member

The Khanasir Limestone Member (sequence 1) is unconformable on cross-bedded yellow-red sandstones of the topmost Wasia Formation (Figure 2). It is subdivided into three small-scale (possibly fourth-order) parasequences (1a, 1b, and 1c from the base up).

- **Parasequence 1a:** The lower part is claystone overlain by coarse-grained bioturbated (*Skolithos*) sandstones containing rare, reworked fish bones. Overlying the *Skolithos* sandstones are chalky bioturbated (*Thalassinoides*) wackestones rich in echinoderms, gastropods, sponges, inoceramids, and ammonites. This unit is in turn overlain by white bioturbated chalky wackestones rich in fragments of dasycladacean algae.

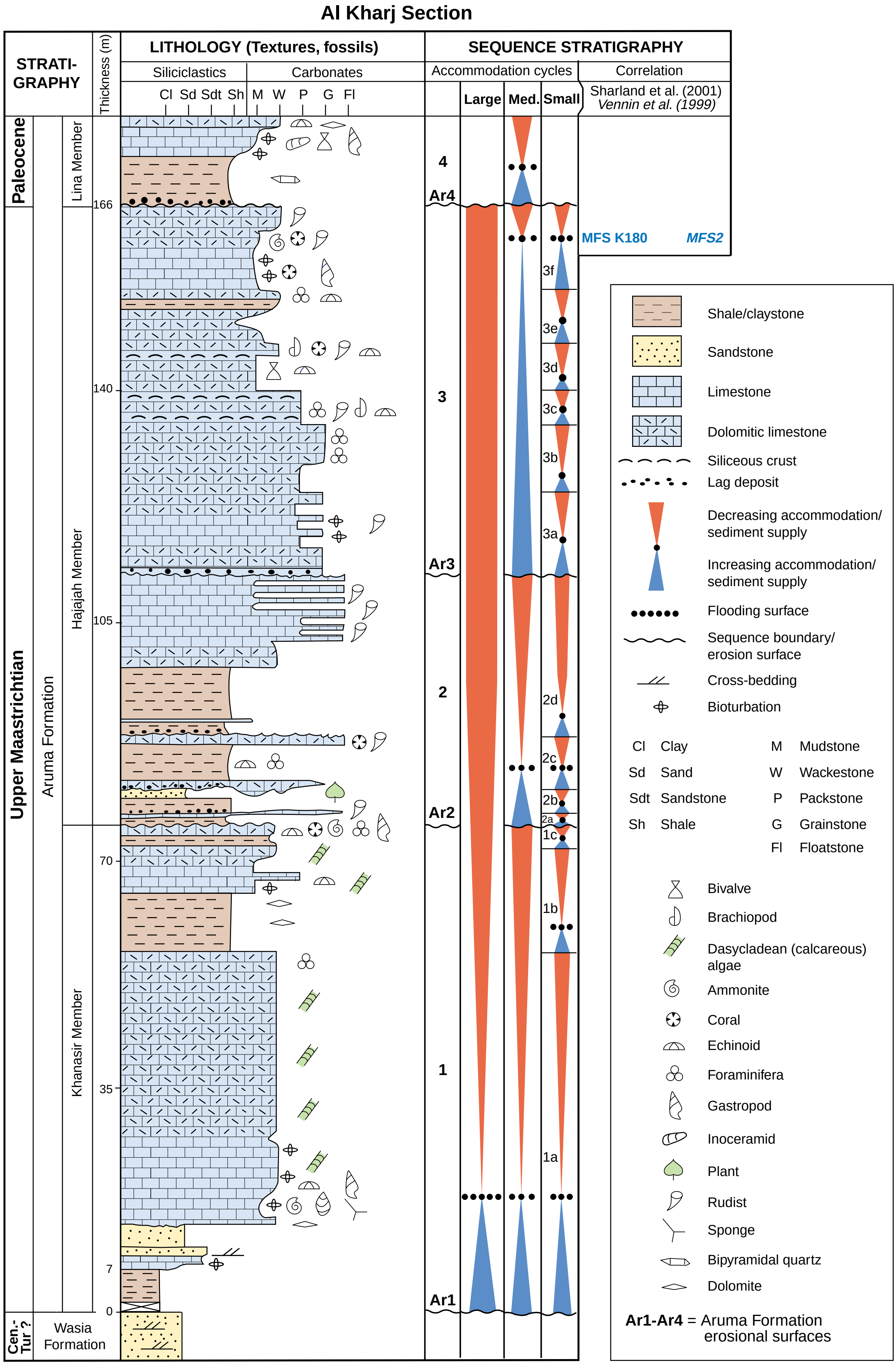

Figure 2: Lithological and sequential log of the Al Kharj section. See legend and text for explanations.

- **Parasequence 1b:** Dolomitic shales are overlain by cherty dasycladacean-rich wackestones.

- **Parasequence 1c:** Shales, passing upward into wackestones bearing a diversified benthic biota (echinoid, gasteropoda, solitary corals, and foraminifera). The conspicuous hardground Ar2 caps the parasequence.

Weathered, reddish facies (Vaslet et al., 1991) at top of the Wasia Formation provided evidence of emergence and continental weathering prior to the deposit of parasequence 1a. Hence, erosion surface Ar1 can be considered as a major sequence boundary separating the Aruma and Wasia formations. An ammonite fauna containing *Neolobites vibrayeanus* d'Orbigny in the middle part of the Wasia Formation enabled Vaslet et al. (1991) to assign a late Cenomanian to Turonian? age to the upper part of the Wasia Formation. The stratigraphic gap linked to surface Ar1 would therefore encompass the Coniacian-lower Maastrichtian interval.

The Khanasir Limestone Member is interpreted as a shallowing-upward unit deposited in a relatively protected (dysaerobic?), low-energy, carbonate platform environment that enhanced the development of green-algae-rich associations. The ammonite-bearing bed in the lower part of sequence 1 represents the maximum flooding surface of the Khanasir Limestone Member and of a large (possibly second-order) sedimentary cycle within the Aruma Formation.

Hajajah Limestone Member

The Hajajah Limestone Member consists of two medium-scale (possibly third-order) sequences (sequences 2 and 3) subdivided into parasequences 2a to 2d and 3a to 3f (Figure 2).

Sequence 2

The lower part of the Member (sequence 2) consists of alternating varicolored shales and limestones containing an abundant benthic fauna of rudists, corals, and larger foraminifera.

- **Parasequence 2a:** Its thickness varies laterally from 1 or 2 m to about 20 m. This probably indicates that an erosional contact affected the top of the Khanasir Limestone Member prior to the deposition of the Hajajah Limestone Member. The shales at the base of the parasequence contain plant fragments and fish bones. The shales grade upward into a biostromal rudist (*Biradiolites*), coral- and chaetetid-rich lenticular floatstone-framestone unit.

- **Parasequence 2b:** A hardground separates it from the underlying parasequence 2a. Basal shales that contain plant fragments grade upward into fine ocherous siliciclastic sands. The sands are laterally replaced (Figure 3b) by pedogenetic mudstones, indicating local emergence.

- **Parasequence 2c:** Its lower unit contains iron-oxide nodules, fish remains, and *Cyclolites* corals. Laterally (Figure 3a), this bed passes into channel-like sedimentary bodies about 6 m thick formed of cross-bedded packstones-grainstones containing *Biradiolites* rudists and *Loftusia* corals. Parasequence 2c passes upward into green or ocherous shales, the lower part of which contains numerous spatangoid echinoids. A biostromal body formed of massive and branched corals associated with small *Biradiolites* and *Cyclolites* is at the top of parasequence 2c, separated from the overlying sequence by an iron-stained hardground.

- **Parasequence 2d:** The lower part of parasequence 2d is formed of olive-green shales that grade upward into mudstones that contain small *Biradiolites*. The upper part of the parasequence consists of lenticular dolomitic rudist grainstones-packstones capped by rudist-rich (*Durania, Biradiolites, Bournonia*) floatstones.

The top of sequence 2 is a major erosional surface (Ar3) that has relief of at least 10 m. The geometry of the surface suggests that an irregular channel-like erosional pattern developed after cementation of the underlying rudist carbonate platform, probably during a sea-level lowstand.

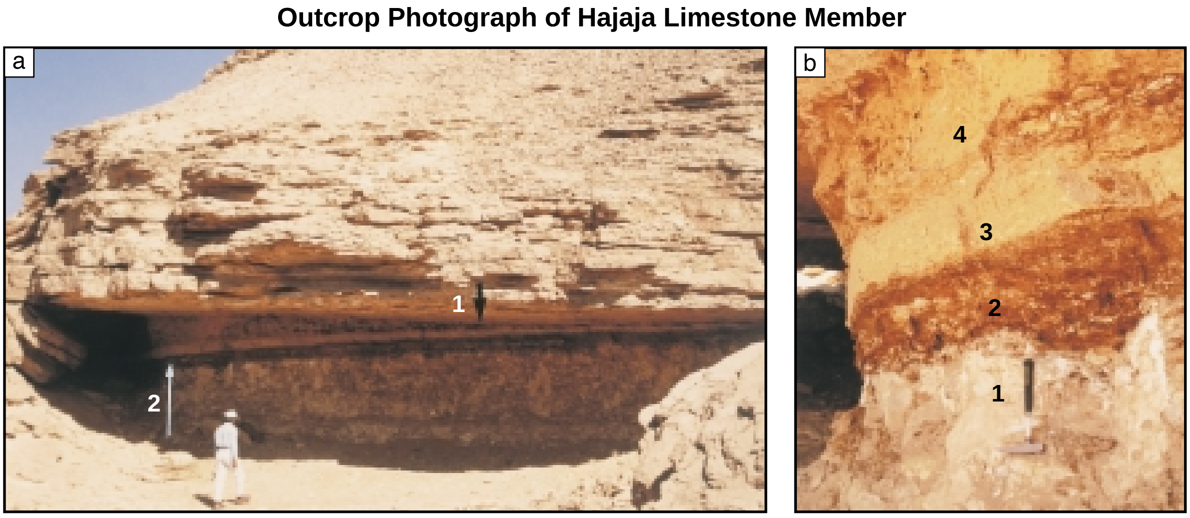

Figure 3: Lower part of the Hajajah Limestone Member in the Al Kharj section. (a) Erosional contact (arrow 1) between channel-like (tidal?) cross-bedded rudist packstones (above) and underlying mudstone-clay couplets (paleosols?) beds. (b) Close-up of the section indicated by arrow 2 in (a): from base to top: 1. Mudstones with pedogenetic structures; 2. Clays containing plant remains; 3. Microconglomerates and *Loftusia*-rich wackestones; 4. Argillaceous mudstones. The erosional contact is located just above unit 4, but is not visible here.

In summary, sequence 2 of the Hajajah represents a medium-scale transgressive-regressive cycle. The beginning of the transgression is represented by paleosols, tidal channels, and lenticular rudist-chaetetid biostromes of onshore and shoreface environments. Coral banks and rudist banks progressively developed, and the upper part of the parasequence corresponds to the development of a rudist carbonate platform. A major fall in sea level led to the formation of an incised surface at the top of the sequence.

Sequence 3

The sequence is divided into six small-scale parasequences.

- **Parasequence 3a:** The base is a lag deposit containing reworked rudists (*Durania*). Overlying the basal unit is an alternation of dolomitized-bedded grainstones and bioturbated rudist packstones that pass laterally into rudist (radiolitid) banks.
- **Parasequence 3b:** Bioturbated packstones-wackestones at the base grade upward into grainstones that contain larger foraminifera (*Omphalocyclus*, *Orbitoides*, and *Lepidorbitoides*). A silicified surface caps the parasequence.
- **Parasequences 3c**, **3d**: They are characterized by poorly fossiliferous (scarce spatangoid echinoids) dolomitized wackestones and mudstones, overlain by mudstones bearing brachiopods, solitary corals, echinoids and scarce radiolitid rudists. A siliceous crust caps both parasequences.
- **Parasequence 3e:** Fine wackstones at the base grade upward into shales in the middle part. These are overlain by wackestones-mudstones containing larger foraminifera (*Omphalocyclus* and *Orbitoides*) and fragments of regular echinoids.
- **Parasequence 3f:** The lower part consists of bioturbated mudstones-wackestones that contain solitary corals, and gastropods. The upper part is fossiliferous-rich mudstones-wackestones with numerous nautiloids and a benthic fauna of solitary rudists (*Bournonia*, *Biradiolites*), corals (*Cyclolites*), bivalves, and gastropods. Dolomitized rudist limestones occur at the top of the parasequence.

Sequence 3 evolved from high-energy carbonate platform environments (parasequences 3a and 3b) into low-energy offshore environments (parasequences 3c–3f). The maximum flooding surface in the sequence equates with the occurrence of the nektonic (nautiloid) fauna in parasequence 3f. The sequence is strongly asymmetric, probably due to major erosion having affected the regressive part of the sequence prior to the deposition of the Lina Shale Member.

Erosion surface Ar4 between the Hajajah Limestone Member and the Lina Shale Member is a disconformity interpreted as a major sequence boundary. It probably corresponds to a hiatus of several millions of years (Thomas et al., 1999).

Lina Shale Member

The Lina Shale Member shows strong facies changes and an impoverishment of the faunal content. It is composed of ocherous shales interbedded with subordinate dolomitic units. In the Al Kharj section, the Member is poorly exposed and incomplete. Reworked iron-oxide nodules at the base reflect its transgressive character. The shales contain bipyramidal quartz. Very rare bivalves, oysters, gastropods, and echinoids are present in the mudstones-wackestones in the uppermost part of the Member.

LATERAL VARIATIONS OF THE ARUMA FORMATION IN SAUDI ARABIA

In order to examine the variations of facies of the Aruma Formation in Saudi Arabia, sections located to the northwest of the proposed Al Kharj reference section were investigated (Figure 1). They are the Khashm al Buwaybihat and Khashm Tawqi sections north of Riyadh (previously studied by Skelton and El-Asa'ad, 1992), and the Al Matayih and Jibalah sections located on the eastern edge of the Nafud sand sea (Lebret et al., 1999). The sections are shown in Figure 4, correlated with the Al Kharj reference section

Khashm al Buwaybihat Section

In the Khashm al Buwaybihat section (Figure 4), the Khanasir Limestone Member is about 60 m thick and consists of bioturbated (*Thalassinoides*) dasycladacean-rich wackestones. Rare echinoids (cf. *Nucleopygus*), and benthic foraminifera (Rotaliidae and *Pseudedomia* cf. *globularis* Smout; determination E. Fourcade) have been found at 16 m above the Wasia/Aruma contact. These fossils could indicate more marine conditions during the deposition of the lower part of the Member, although ammonites are absent. A cherty unit at 28 m above the basal boundary of the Aruma Formation has been correlated with the cherty facies of parasequence 1b of the Al Kharj section. Skelton and El-Asa'ad (1992) described a rudist biostrome (the *Eodictyoptychus* bed) as capping the Khanasir Limestone Member in this area. The biostrome is a lenticular body (Figure 5a) hundreds of meters wide and about 1-m thick formed from rudists, some in life position, in a floatstone-wackestone matrix. The floatstone-wackestone contains angular and poorly sorted fragments of corals, rudists, ostracods, and benthic foraminifera (miliolids, *Cuneolina* sp., and *Pseudochoffatella* sp.). Northward, the biostrome grades laterally into a coarse rudistid packstone that has been correlated with the rich fossiliferous limestone that caps parasequence 1c in the Al Kharj section.

Only the lower part of the overlying Hajajah Limestone Member is well exposed at this locality. It consists of alternating brown and olive-green shales that are probably stratigraphic equivalents of parasequences 2a to 2d in the Al Kharj section.

Khashm Tawqi Section

In this section (Figure 4), the lower 25 m of the Khanasir Limestone Member is formed of bioturbated (*Thalassinoides*) dasycladacean-rich wackestones that correlate with parasequence 1a of the Al Kharj section. The upper part of the Member is a 15-m-thick alternation of well-stratified, finely laminated mudstone/shale couplets that correlate well with parasequence 1b of the Al Kharj section.

As in the Al Kharj section, the Hajajah Limestone Member mainly consists of an alternation of brown or olive-green shales and rudist-rich biostromes. The biostromes contain numerous well-preserved rudists (*Eodictyoptychus* cf. *arumaensis* and *Biradiolites* aff. *aquitanicus*) associated with branched chaetetids. The Member is poorly exposed and only the lower part is present. A sharp erosive contact separates the Khanasir Limestone Member from the Hajajah above (Figure 5b). In the basal part of the Hajajah are 10-m-thick cross-bedded packstone-grainstone units (Figure 5b,c) rich in fragments of rudists, corals, and echinoids. It is a typical transgressive unit and can be compared (if not correlated) with parasequence 2b of the Al Kharj section.

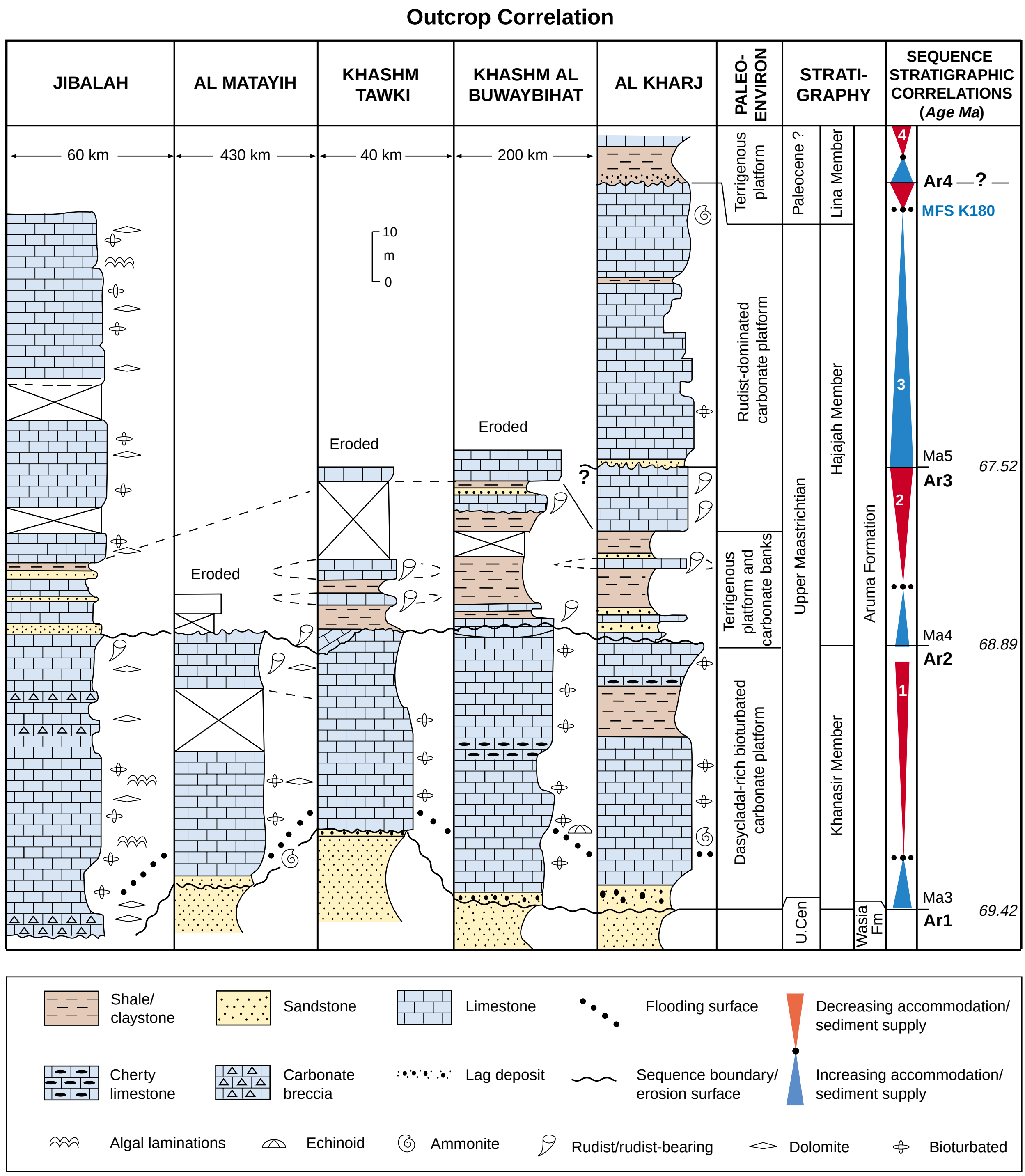

Figure 4: Outcrop correlation for the Aruma Formation. Ma3 to Ma5 = Maastrichian transgressive-regressive sequence boundaries of North America and Arctic regions (Hardenbol et al., 1998); MFS K180 = Maximum Flooding Surface of Sharland et al. (2001); Ar1–Ar4 = Aruma Formation erosional surfaces.

Outcrop Photographs of Khanasir and Hajajah Members

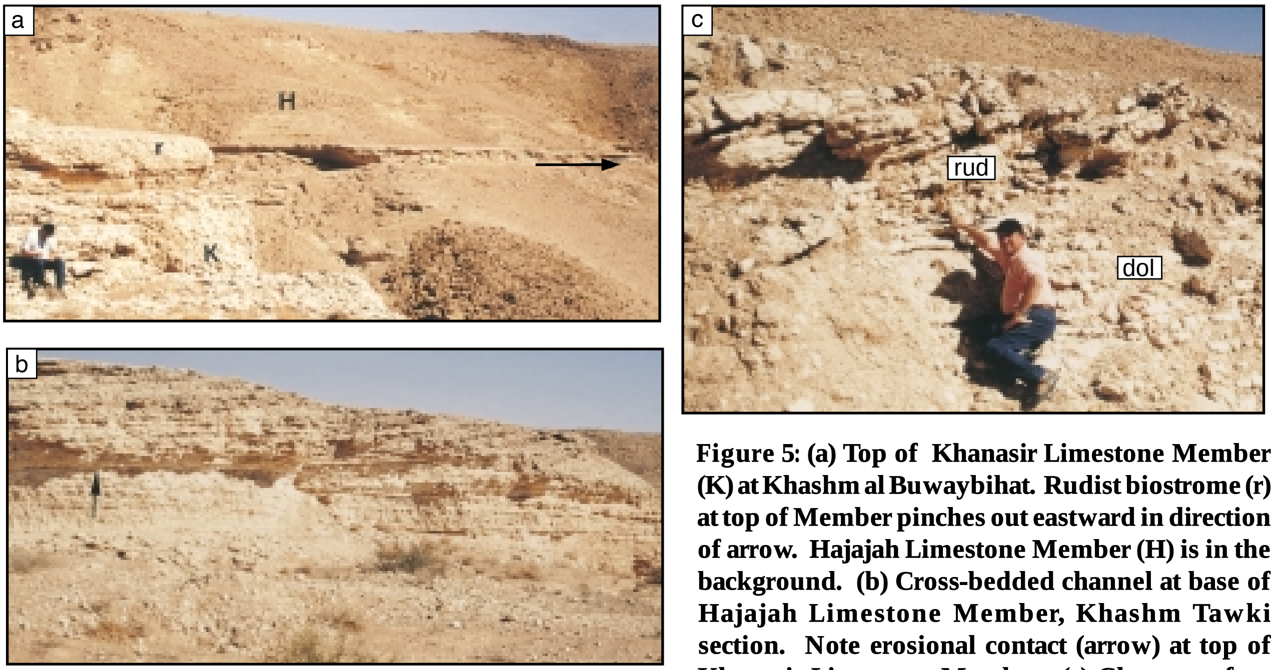

Figure 5: (a) Top of Khanasir Limestone Member (K) at Khashm al Buwaybihat. Rudist biostrome (r) at top of Member pinches out eastward in direction of arrow. Hajajah Limestone Member (H) is in the background. (b) Cross-bedded channel at base of Hajajah Limestone Member, Khashm Tawki section. Note erosional contact (arrow) at top of Khanasir Limestone Member. (c) Close-up of an erosional channel in lower part of Hajajah Limestone Member in same area as (b). Cross-bedded coarse rudist/ coral rudstones (rud) rest on pelletoidal dolostones (dol).

Al Matayih and Jibalah Sections

These sections (Figures 1 and 4) have recently been described by Lebret et al. (1999) from the Turubah 1:250,000-scale quadrangle. In the reference section on the Al Matayih escarpment (lat. 28º16.822′N, long. 43º17.181′E), the lower part of the Khanasir Limestone Member represents an open marine platform facies (highly bioturbated nodular wackestones, with dasycladacean remains, bivalves, gastropods, echinoids, and scarce ammonites). It is comparable with the open marine facies in the same stratigraphic interval (sequence 1a) in the Al Kharj section. However, the facies in the upper part of the Member are quite different from those in the Al Kharj section as they include biostromal rudist wackestones interbedded with bioturbated wackestones and mudstones containing algal laminations and mud-cracks. In the Jibalah area, the Khanasir shows a lateral change to tidal-flat dolomitic facies in response to increasingly restricted conditions. The highly bioturbated (*Thalassinoides*) wackestones are probably the equivalent of the ammonite-bearing beds at Al Kharj and in the Al Matayih escarpment sections.

The Hajajah Limestone Member was described by Lebret et al. (1999) from a section (lat. 28º36.061′N, long. 42º41.770′E, to lat. 28º38.160′N, long. 42º38.240′E) in the Jibalah area where it is well exposed. The lower part of the Member shows a predominance of claystones, marls, and plant-bearing sandstones that grade upward into dolomitic bioturbated wackestones with a restricted fauna of small mollusks. Algal-laminated mudstones are interbedded in these facies. Eastward, a dolomitized biostrome of *Durania* rudists and other radiolitids in the middle part of the Hajajah indicates the lateral development of localized more-marine conditions.

In summary, the Aruma Formation consists of extensive, moderately thick, shallow-marine, lithostratigraphic units. Slow subsidence of the Arabian shelf and a relative low sedimentation rate (about 40 m/My) during the Late Cretaceous is inferred. Littoral and restricted facies spread northwestward across the shelf, mainly during the deposition of the upper part of the Khanasir Limestone Member and the lower part of the Hajajah Member. Transgressive marine pulses in the lower part of the Khanasir and in the middle part of the Hajajah resulted in the development of maximum flooding surfaces. Despite the depositional environmental changes that led to facies variations, the sequence stratigraphy analysis of the Aruma Formation has enabled accurate correlation of its lithostratigraphical units in the 650-km-long transect from Al Kharj to Jibalah.

BIOSTRATIGRAPHY

Khanasir Limestone Member

Ammonites

Libycoceras acutodorsatum (Noetling) cited by Powers et al. (1966), Powers (1968) and Vaslet et al. (1988, 1991) was found in the ammonite-rich level in the lower part of sequence 1a of the Khanasir Member in the Al Kharj section (Figure 2) where it is relatively abundant (Plate 1a,d,e). Another specimen (Plate 1b,c) was from the uppermost part of the Member.

Noetling (1897) first reported *L. acutodorsatum* from the Maastrichtian of western Pakistan. However, according to Howarth (1965), the genus *Libycoceras* is more accurately dated as being in the *Polyplocum* Zone of late Campanian age. Zaborski (1982) shared this conclusion, except for the species *L. dandense* (Howarth) that was placed at the Campanian-Maastrichtian boundary in Nigeria. Later, Zaborski and Norris (1999) considered a younger age range of mid to late (?) Maastrichtian for *L. crossense* Zaborski, and also indicated the latest Maastrichtian arrival of *L. ismaele* (Zittel) in Nigeria. A recent revision of Maastrichtian ammonites from Pakistan (Fatmi and Kennedy, 1999) showed *L. acutodorsatum* associated with *Menuites fresvillensis* (Seunes), which has been proposed as a marker species for the early late Maastrichtian (Odin, 1996).

Nanofossils

The nannoflora identified in the lower part of the Khanasir Limestone Member in the Shaqra 1:250,000-scale quadrangle by Vaslet et al. (1988) (parasequence 1a), consisted of a "rich assemblage of coccoliths" 7 m from the base of the Member. The presence of *Arkhangelskiella cymbiformis* Vekshina, led H. Manivit (written communication, 1987) to attribute a late Campanian to early Maastrichtian age to the lower part of the Member. However, *A. cymbiformis* is not a marker species for the late Campanian to early Maastrichtian age (see also the recent biostratigraphic scheme proposed in Bown, 1998). A revision of the nannoflora assemblage allowed H. Manivit (in Vaslet et al., 1991) to reassign a late Mastrichtian age (*Micula murus* Zone) to the lower part of the Khanasir Limestone Member. Le Nindre et al. (1990) attributed the Khanasir Limestone Member to the nannofossil zones NC 20 (*Tetralithus trifidus*) and NC 21 (*A. cymbiformis*) that are considered as latest Campanian and late early Maastrichtian, respectively (Bralower et al., 1995).

In this study, three samples from the Khanasir Limestone Member were examined for their calcareous nannofossil content. One sample was taken from the upper part of the Member (parasequence 1c) and two samples from the lower part (parasequence 1a). One of the latter was taken from the internal mold of the ammonite *Libycoceras acutodorsatum*. Due to the unfavorable lithology of recrystallized wackestones, the samples are poorly preserved and strongly overgrown nannofossil assemblages. Only a few diagenetic-resistant taxa have been recognized; they are *Watznaueria barnesae*, *Micula decusssata*, *Octolithus multiplus*, *Lithraphidites quadratus*, and *M. murus* (Plate 2), and *Hexalithus hexalithus* and *Praediscophaera cretacea*. The identification of the strongly overgrown specimens of *M. murus* and *L. quadratus* is doubtful, especially in the lower part of the member. However, these taxa are clearly represented in the upper part of the Member that can be accurately attributed to the late Maastrichtian (NC 22-NC 23 Zones). These poorly preserved nannofossils cannot be compared to the "rich assemblage of coccoliths" of Vaslet et al. (1988) that was probably found in a different and more favorable lithology within the Khanasir Limestone Member.

Echinoids

Five echinoid species have been reported from the Khanasir Limestone Member by Néraudeau et al. (1995) and attributed to the Campanian with reference to the the study of El-Asa'ad (1983b). However, Néraudeau et al. pointed out the anomalous distribution of the genus *Noetlingaster* recorded in the lower part of the Khanasir Limestone Member but only known until now from the Maastrichtian.

Foraminifera

Benthic foraminifera are scarce throughout most of the Khanasir Limestone Member. However, *Pseudedomia* cf. *globularis* Smout, has been found at Khashm al Buwaybihat in the lower part of the Member. This species is known from the Campanian Bekhme Limestone of Iraq and from early

Plate 1

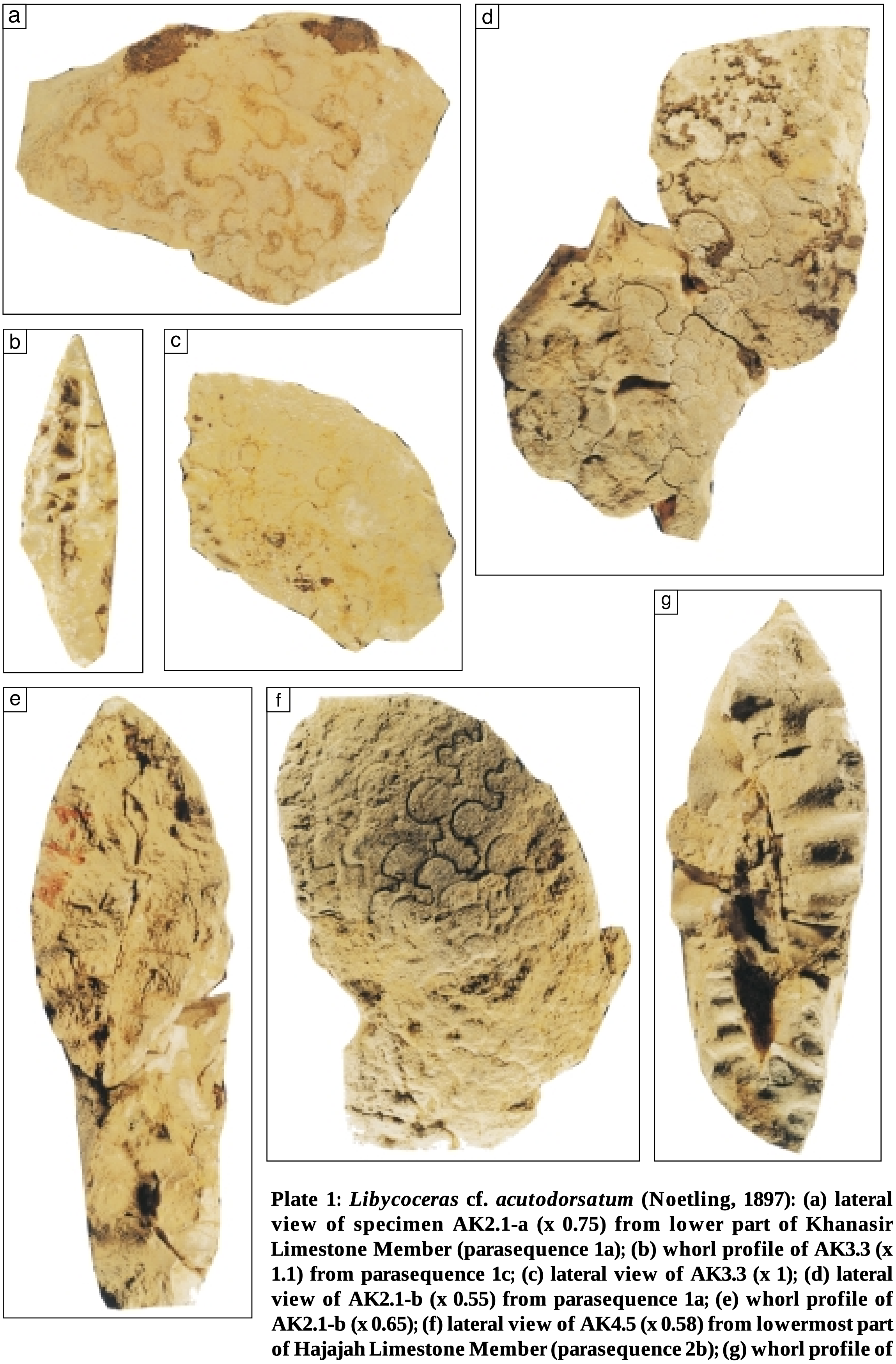

Plate 1: ***Libycoceras* cf. *acutodorsatum* (Noetling, 1897): (a) lateral view of specimen AK2.1-a (x 0.75) from lower part of Khanasir Limestone Member (parasequence 1a); (b) whorl profile of AK3.3 (x 1.1) from parasequence 1c; (c) lateral view of AK3.3 (x 1); (d) lateral view of AK2.1-b (x 0.55) from parasequence 1a; (e) whorl profile of AK2.1-b (x 0.65); (f) lateral view of AK4.5 (x 0.58) from lowermost part of Hajajah Limestone Member (parasequence 2b); (g) whorl profile of AK4.5 (x 0.57). All specimens are from the Al Kharj section.**

Plate 2

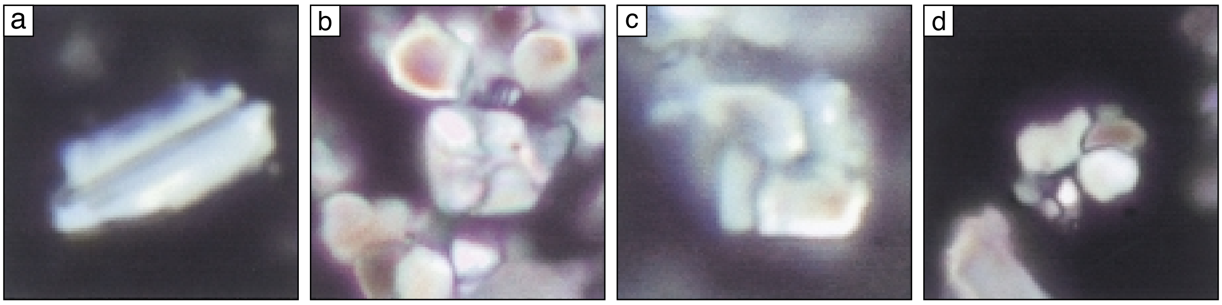

Plate 2: Nannofossils from the Khanasir Limestone Member, Al Kharj section. All photomicrographs were taken under polarized light and uniformly enlarged at x 2,500. (a) *Lithraphidites quadratus* Bramlette and Martini, 1964, parasequence 1c; (b) *Micula decusssata*, Vekshina, 1959, parasequence 1a; (c) *Micula murus* (Martini, 1961), parasequence 1c; (d) *Octolithus multiplus* (Perch-Nielsen, 1983), parasequence 1a; (e) *Watznaueria barnesae* (Black *in* Black and Barnes, 1959), parasequence 1c.

Santonian to late Maastrichtian rocks elsewhere in the Middle East. In the upper part of the Khanasir (parasequence 1d), a rich assemblage of benthic foraminifera is dominated by *Pseudedomia complanata* Eames and Smout (determination E. Fourcade), a species known from the Campanian-?early Maastrichtian of Kuwait, Saudi Arabia, and Iraq.

Inoceramids

An inoceramid identified by G. Lopez as *Endocostea* aff. *brooksi* Johnson, 1903, has been found in association with ammonites of parasequence 1a. The species is uncommon and cannot be considered as a precise biostratigraphic index due to its poor stratigraphic documentation. Commonly, a middle to upper Campanian age has been inferred for this taxon in agreement with the evolution of the *Endocostaea balticus* lineage to which *E. brooksi* is related. However, a Maastrichtian age is not impossible and in this context numerous species of *Endocostea* have been cited from the Maastrichtian of the United Arab Emirates-Oman border region (Morris 1995). The specimen from the Khanasir Limestone Member has characteristics in common with those identified by Morris (1995) as *Endocostea (Endocostea)* sp. indet. (G. Lopez written communication, April 2002) from the mid-Maastrichtian Simsima Formation of Jebel Rawdah, close to the border between the United Arab Emirates and Oman.

Rudists

Rudists are absent or very scarce in the Khanasir Limestone Member. However, some poorly preserved radiolitid specimens (*Biradiolites*, *Distefanella*, *Durania*) have been recorded from the top of the Member in the Turubah quadrangle (Lebret et al., 1999). Rudists were not found in the Member in the Al Kharj section and surrounding areas. Skelton and El-Asa'ad (1992) recorded specimens of a new genus, *Eodictyoptychus* (type species *E. arumaensis* Skelton and El-Asa'ad 1992) (Plate 3a) and *Biradiolites* cf. *aquitanicus* Toucas at the top of the Khanasir in the Khashm al Buwaibiyat section. The species *E. arumaensis* was noted by Morris and Skelton (1995) at the boundary of the Qahlah and Simsima formations of the United Arab Emirates that, according to Kennedy (1995), could be as old as late Campanian or as young as the early late Maastrichtian *fresvillensis* Zone. *Biradiolites aquitanicus* is known from the late Campanian to early Maastrichtian of southwest France and Spain.

Hajajah Limestone Member

The lower part of the Member (sequence 2b) has provided one specimen (Plate 1f,g) of the **ammonite** *Libycoceras acutodorsatum*. The olive-green claystone at the base of the Hajajah Limestone Member (sequence 2a) of the Shaqra quadrangle contains a **coccolith** assemblage with the typical *Micula murus* (Martini) of late Maastrichtian age (H. Manivit, written communication, 1987; in Vaslet et al., 1988 and Le Nindre et al., 1990).

Plate 3

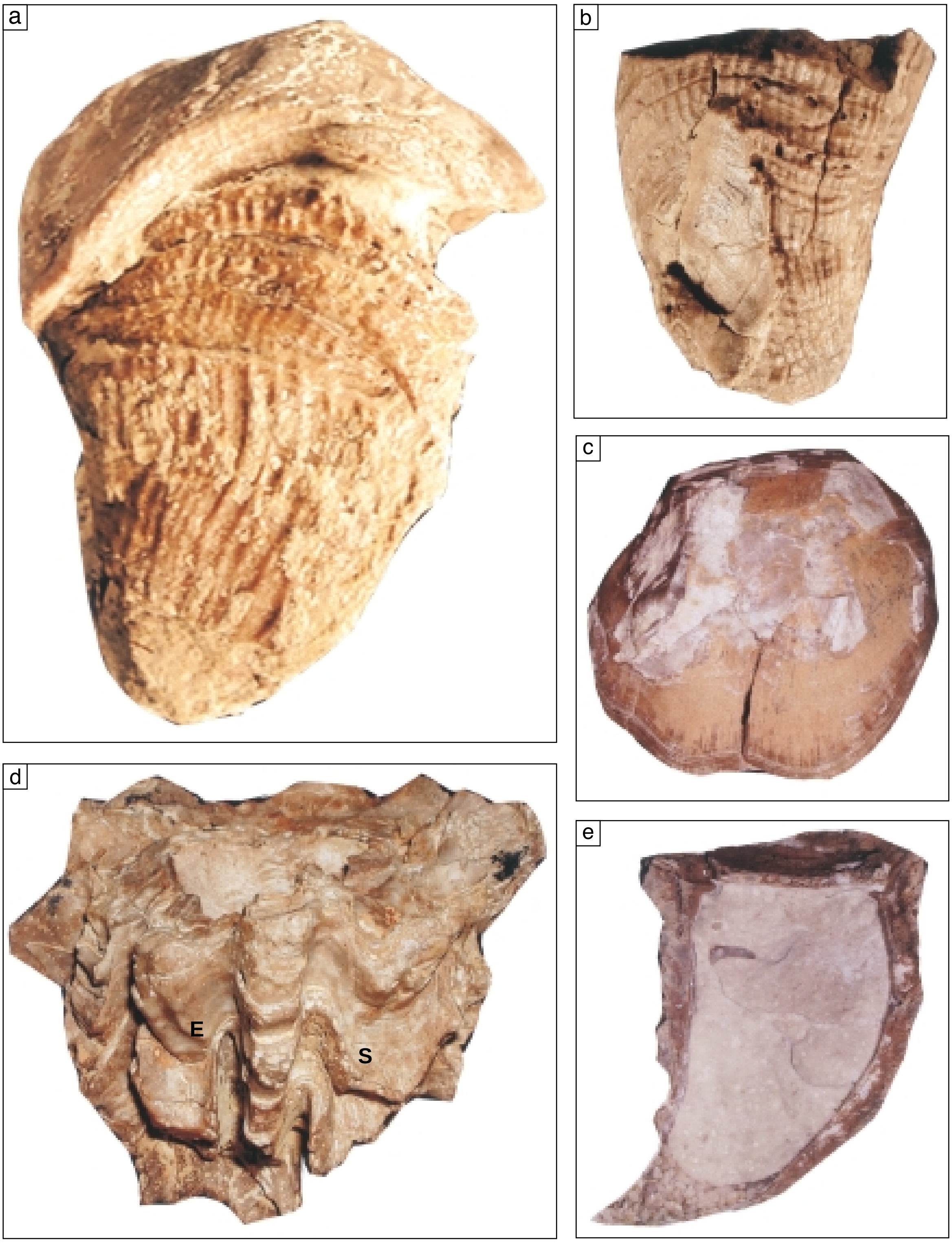

Plate 3: (a) *Eodictyoptychus arumaensis* Skelton and El-Asa'ad, bivalve specimen Bu W5 (x 1), top of Khanasir Limestone Member, Khashm al Buwaybihat section; (b) *Eodictyoptychus arumaensis* Ta W1, lateral view of right valve (x 0.75), lower part of the Hajajah Limestone Member, Khashm Tawqi section; (c) *Eodictyoptychus arumaensis* Ta W1, dorsal view of left valve (x 1), lower part of Hajajah Limestone Member, Khashm Tawqi section; (d) *Biradiolites* aff. *aquitanicus* Toucas 98 AK 3-4, ventral view showing siphonal bands S and E (x 1), lower part of Hajajah Limestone Member (sequence 2a), Al Kharj section; (e) *Radiolites* sp. bivalve specimen 98 AK 6-1 (x 1), upper part of Hajajah Limestone Member (parasequence 3d), Al Kharj section.

Larger foraminifera, rudists, and **echinoids** are common and provide accurate data for correlations. *Loftusia*-dominated assemblages form distinctive beds in the lower part of the Hajajah Limestone Member, especially in the shaly units of sequence 2. In the basal olive-green shale unit, El-Asa'ad (1989) noted *Loftusia arabica* sp. nov. In the United Arab Emirates-Oman border region, the *Loftusia*-beds were assigned a late Campanian to early late Maastrichtian age by Smith et al. (1995). The foraminiferal assemblage in the upper part of the Member (parasequences 3a to 3e) is quite different and has a dominance of *Omphalocyclus macroporus* and *Lepidorbitoides minor.* These species are present in the Simsima Formation on the northwestern flank of the Oman Mountains (Skelton et al., 1990) and were assigned by Smith et al. (1995) to the early late Maastrichtian *fresvillensis* Zone, or later.

Two assemblages of rudists are characteristic of the Hajajah Limestone Member. The first occurs at the base of the Member in parasequences 2a and 2b and includes *Eodictyoptychus arumaensis* Skelton and El-Asa'ad (Plate 3b,c), *Dictyoptychus* sp., and *Biradiolites* aff. *aquitanicus* Toucas (Plate 3d). *Eodictyoptychus* and *Dictyoptychus* are present only in some localities to the north of Riyadh. South of Riyadh in the vicinity of Al Kharj, only *Biradiolites* aff. *aquitanicus* is present.

The second assemblage characterizes the middle part of the member (parasequences 2a–3b). It is formed from colonies of small *Biradiolites* sp., *Distefanella* sp., and *Durania* sp., that are particularly abundant in the limestone beds. In the United Arab Emirates-Oman border region, *Eodictyoptychus* aff. *arumaensis* was found by Morris and Skelton (1995) in the *Loftusia* beds of late Campanian to early upper Maastrichtian age, and *Dictyoptychus* is present at the base of the Simsima Formation of late Maastrichtian age.

The uppermost deposits (parasequence 3d) are carbonate dominated and contain radiolitids (large *Bournonia* sp. and *Biradiolites* aff. *baylei* Toucas; and *Radiolites* sp., Plate 3e) associated with numerous nautiloids (*Cimomia* aff. *heberti* Blinckhorst, *Angulithes* aff. *neubergicus* Redtenbacher, *A.* aff. *gosavicus* Redtenbacher, and *Deltoidonautilus tamulicus* (Kossmat); determination by H. Tintant in Vaslet et al., 1991). According to Vaslet et al., these nautiloids indicate a Maastrichtian age. Internal molds of rudists and nautiloids have yielded benthic foraminifera *Loftusia* sp., *Rotalia trochidiformis* Lamarck, and *Laffitteina mengaudi* (Astre) (determinations by C. Bourdillon). This assemblage indicated a latest Maastrichtian age. The age was confirmed by the nannofossil assemblage of the nautiloid bed of the parasequence 3f that, although poorly preserved, was represented by *Watzauneria barnesae*, *Prediscophaera cretacea*, *Micula decussata*, *Cribocorona gallica*, *Lithraphidites quadratus*, and *Micula murus*.

Lina Shale Member

The shaly dolomitic facies of Lina Shale Member (sequence 4) is poorly fossiliferous with only infaunal bivalves, oysters, and gastropods; rudists or other definitive Cretaceous-age biomarkers are absent. Previous authors had attributed this unit to Maastrichtian but without indisputable biostratigraphic criteria. Indeed, sequence 4 could be correlated with the shaly dolomitic series of Lina Shale Member in northern Saudi Arabia in which Thomas et al. (1999) found Late Paleocene to Early Eocene marine vertebrates. This evidence, together with the presence in the lower part of the Lina Shale Member of the neritid *Velates* aff. *tibeticus* (detemination C. Cavelier; Vaslet et al., 1991) that is known only from the basal Eocene, invalidates the Cretaceous age previously assigned to the Lina Shale Member.

DISCUSSION

With reference to the biostratigraphical range of *Libycoceras acutodorsatum* (Noetling) in its type area of Baluchistan, the Khanasir Limestone Member can be asigned to the lower late Maastrichtian *fresvillen*sis Zone. This interpretation is supported by echinoids and by the nannoflora, although this latter is relatively poorly preserved and questionable. However, evidence of an older (middle Maastrichtian-?middle-late Campanian) age is provided by inoceramids and benthic foraminifera. This suggests that *L. acutodorsatum* could have a longer age range and thus be older than late Maastrichtian (mid Maastrichtian?) in Saudi Arabia. A study of other biostratigraphic elements, such as planktonic foraminifera, is required to support this interpretation.

As mentioned above, El-Asa'ad (1983a,b) assigned ammonites in the lower part of the Khanasir Limestone Member to the Coniacian genera *Tissotia* Douvillé, *Paratissotia* Hyatt, and *Hemitissotia* Peron. He consequently assigned this part of the Member to the Coniacian. Unfortunately, El Asa'd did not illustrate these ammonites and the localities from which they had been collected were not precisely indicated. We did not find a *Tissotia* assemblage in the ammonite-rich level in the lower part of the member and we strongly suspect that these ammonites were confused with the genus *Libycoceras* as the genus *Tissotia* includes forms whose sutures are similar to those of *L. acutodorsatus*. However, the species *Tissotia (Tissotia)* differs from *Libycoceras* in having a subquadrate whorl section and flat venter, whereas those of *Tissotia (Subtissotia)* are characterized by globular whorls (in the early stages) to rounded forms. *L. acutodorsatum* has a lanceolate whorl section whereas that of the species *Paratissotia* is more compressed and with weak ribs. Species of the genus *Hemitissotia* differ because of sutural characteristics (only the internal saddles may be entire) and some bear ornamentation with strong ribs in the lower half of the flank. As these *Tissotia* genera are limited to the Coniacian, they are older than our specimens as demonstrated by the complementary biostratigraphic data.

Biostratigraphic data from rudists, larger foraminifera, nannoflora, and ammonites are in agreement with the assignment of a late Maastrichtian age to the Hajajah Limestone Member. Based on ammonites, the lower part of the Member (sequence 2) can be attributed to the late Maastrichtian *fresvillensis* Zone. The undoubted occurrence of *Micula murus* in the upper part of the sequence 3 (Plate 2) is a convincing argument for assigning sequence 3 to the uppermost Maastrichtian NC 23 calcareous nannofossil zone.

In the Al Kharj section, the Lina Shale Member has not yielded any new biostratigraphic data that could lead to its accurate dating. It is characterized by a noticeable impoverishment in its fossil content with respect to the underlying Hajajah Limestone Member. Accordingly, we follow the recent revision from Thomas et al. (1999) and refer the Lina Shale Member to the Paleocene.

The erosional surface Ar2 between the Khanasir Limestone and the Hajajah Limestone members is a stratigraphic gap of undetermined duration. The surface at the top of the Hajajah Limestone Member (Ar4) could represent a break in sedimentation during the Lower Paleocene. That between sequences 2 and 3 of the Hajajah Limestone Member (Ar3) cannot be evaluated in term of zonal intervals but is considered to be within the uppermost Maastrichtian.

The Aruma Formation of Saudi Arabia has been correlated with the Simsima Formation of Oman and the United Arab Emirates (Steineke et al., 1958; Powers et al., 1966; Nolan et al., 1990) and with the Sharwayn Formation (Nolan et al., 1990) of the Hadramawt and Dhofar. However, the authors provided no precise elements of correlation. Biostratigraphic correlations are based on the occurrence of standard fossil taxa such as ammonites, rudists, and larger benthic foraminifera that are represented in the formations. Sequence stratigraphic correlations imply transgressive or regressive events that were able to occur simultaneously on the Aruma platform and around the Oman Mountains. Of particular interest are the major sequence boundaries and maximum flooding surfaces that can be traced, at least approximately, within both domains.

From our investigations, the Khanasir Limestone Member is not exposed in the United Arab Emirates and the Oman Mountains. This could indicate one of two possibilities. Either an early transgression of the Maastrichtian sea onto the Arabian platform that is not recorded around the obducted Semail Ophiolite, or an extreme condensation of the sequence that corresponds to the lower part of the Qahlah Formation in the United Arab Emirates and the Oman Mountains. The maximum flooding surface (MFS) recorded in sequence 1a of the Khanasir Limestone Member (Figures 2 and 4) has no known equivalent elsewhere on the Arabian Plate. In the sequence stratigraphic scheme of Sharland et al. (2001), this flooding surface would be MFS K150. However, the early Coniacian age (88 Ma) of K150 does not equate with the late Maastrichtian age newly assigned to the Khanasir Member.

According to Smith et al. (1995) the *Loftusia*-beds that characterize the lower part of the Hajajah Limestone Member (sequence 2) are well represented in the upper part of the Qahlah Formation and the lower part of the Simsima Formation in the United Arab Emirates and the Oman Mountains. *Eodictyoptychus arumaensis* Skelton and El-Asa'ad has also been found in the topmost Qahlah or basal Simsima formations (Morris and Skelton, 1995), and *Libycoceras*? sp. occurs in the basal conglomeratic bed of the Simsima Formation at Jebel Buhays (Kennedy, 1995). This allowed a correlation of the lower part of the Hajajah Limestone Member with the upper Qahlah to lower Simsima of the United Arab Emirates and Oman. Larger foraminifera, such as *Omphalocyclus macroporus*, are abundant in the middle part of the Hajajah Limestone Member and in the middle part of the Simsima Formation. This suggests a synchronism in the settlement of the rudist carbonate platforms in both domains. However, the rudist association is more diversified in the Simsima Formation (Morris and Skelton, 1995) than in the Hajajah Limestone Member. Ammonite data (Kennedy, 1995) do not contradict these correlations. They suggest that the *Loftusia*-rich units of the Qahlah may be as old as late Campanian or as young as lower late Maastrichtian, whereas the Simsima Formation appears to be lower late Maastrichtian (*fresvillensis* Zone), or younger (Smith et al., 1995).

Two depositional sequences have been distinguished in the Simsima Formation of the United Arab Emirates and the Oman border region (Vennin et al., 1999) that could correlate with the two sequences of the Hajajah Limestone Member. The nautiloid-rich MFS of sequence 3 in the Hajajah Limestone member can be correlated with the MFS2 of Vennin et al. (1999) that also contains abundant nautiloids (see Figure 2). This is the same as MFS K180 of Sharland et al. (2001) that is considered to be a Plate-wide correlation surface.

On a more global scale, and despite difficulties of accurate dating, sequence stratigraphic correlations can be attempted with the late Maastrichtian of North America and the Arctic regions. There, three transgressive-regressive sequences and their subordinate bounding surfaces (Ma3 at 69.42 Ma, Ma4 at 68.89 Ma, and Ma5 at 67.52 Ma) have been dated as late Maastrichtian (Hardenbol et al., 1998). This sequence stratigraphic scheme is consistent with what we have established in Saudi Arabia. We have tentatively correlated these sequence boundaries with erosional surfaces Ar1 to Ar3 in the Aruma Formation (Figure 4).

CONCLUSIONS

The highly fossiliferous, complete and well-exposed Al Kharj section has allowed a chronostratigraphic revision of the Aruma Formation, and the establishment of a sequence stratigraphic framework. Stratigraphic correlations based on biostratigraphic data, facies, and sequences have been established for much of the Aruma outcrop in Saudi Arabia and has been extended to the Qahlah and Simsima formations of the United Arab Emirates and Oman. The Aruma Formation corresponds to a major transgressive-regressive cycle. The maximum flooding surface of this cycle is represented in the lower part of the Khanasir Limestone Member by an ammonite-rich unit.

Biostratigraphic data from ammonites, nannoflora, inoceramids, larger foraminifera, and rudists have led to a revision of the chronostratigraphy of the Aruma Formation. The Khanasir Limestone Member and the Hajajah Limestone Member have been assigned a late Maastrichtian age and the Lina Shale Member a Paleocene age. These new age relationships should be taken into account in the perspective of correlations with subsurface sections and neighboring areas on the Arabian Plate.

Rudists and larger foraminifera are abundant in the Hajajah Limestone Member and, in some places, at the top of the Khanasir Limestone Member. Close paleobiogeographic relationships have been established with the Maastrichtian rudist limestones (Simsima Formation) of the United Arab Emirates and the Oman Mountains where the same benthic assemblages, although more diversified, have been described.

The Aruma Formation is a minor target for petroleum exploration (Alsharhan and Nairn, 1990; Ziegler, 2001). The present study could contribute to improving chronological correlations between outcrop sections and subsurface data. Similarly, the application of paleoenvironmental reconstructions and high-resolution sequence stratigraphy (as established in our study) could provide better information on the organization of the Aruma sedimentary systems and of its potential for petroleum exploration.

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APPENDIX

Paleontology

Ammonites

Five ammonite specimens (Plate 1) were collected from the Al Kharj section: three (AK2.1) from parasequence 1a and one (AK3.3) from parasequence 1c of the Khanasir Limestone Member; and one (AK4.5) parasequence 2b from the lower part of the Hajajah Limestone Member. All specimens belong to the genus *Libycoceras*. They are internal molds that were eroded and incomplete as the body chamber was not preserved. They have an involute compressed shell with a sharp venter. The whorl section is lanceolate and the whorl breadth increases with growth. The largest specimen remains septated at a diameter of 19 cm. No trace of ornamentation is visible (probably due to erosion) except for some very weak ondulations in AK3.3 that start at mid-flank and fade below the venter. The typical pseudoceratitic suture line is characterized by a first lateral saddle (S_1) divided into two branches by an adventitious lobe. The first (ventrolateral) branch of S_1 is further subdivided in all specimens. These characteristics suggest that the specimens can be attributed to the species *Libycoceras acutodorsatum* (Noetling), although they are larger than both Noetling's type (1897, p. 76, pl. 21, fig. 3) and Fatmi and Kennedy's (1999, fig. 14.5) specimens. The late Campanian (Levy, 1977) *L. chargense* Blanckenhorn also has strong morphological similarities: its whorl section is lanceolate and it is larger than *L. acutodorsatum*, probably reaching the same size as our specimens. However, it differs because of its undivided first (ventrolateral) branch of S_1 and the more compressed whorls. Other species of the genus *Libycoceras* have a different whorl section and are clearly ornamented.

Rudists

Specimens of *Eodictyoptychus arumaensis* collected from the top of the Khanasir Limestone Member at Khushum al Buwaybihat, show strong similarities with those originally described by Skelton and El-Asa'ad (1992) from this locality. A bivalve specimen (Plate 3a) has the prominent radial ribs of the right valve that are typical of the genus (see also Plate 3b), and the cap-shaped, moderately convex left valve curved toward the ventral part of the right valve. The left valve is partially broken off on the dorsal part (right of the picture) but in other specimens the left valve is larger than the right one.

A specimen (Plate 3c) from the lower part of the Hajajah Limestone Member has a well-preserved brown calcitic outer shell layer with fine growth lines on the left valve. In most cases, this layer has been worn off to reveal the fine and regular pallial canals of the left valve.

Large specimens of the genus *Biradiolites* are common at the top of the Khanasir Limestone Member and in the lower part of the Hajajah Limestone Member. Most of them show affinities with *B. aquitanicus* Toucas, a species known from the late Campanian to early Maastrichtian of the Aquitaine Basin of southwestern France and the Pyrenees. The specimen (Plate 3d) has ventral bands S and E and the well-marked folds separated by deep sinuses of the right valve, whereas the left valve is nearly flat.

The specimens from the Aruma Formation show particular affinities with radiolitids from the Campanian of Somalia, attributed by Pons et al. (1992) to *Biradiolites bulgaricus* Pamouktchiev. Systematic studies are necessary for a better understanding of the specific status of these different forms and of their paleobiogeographic relationships.

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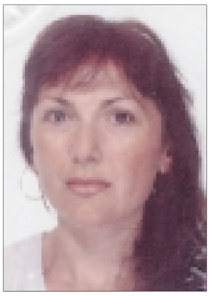

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