Stratigraphy of the Valanginian? to Early Paleocene succession in central Saudi Arabia outcrops: Implications for regional Arabian sequence stratigraphy

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ABSTRACT

On the basis of regional lithostratigraphic field mapping, and biostratigraphic and sequence stratigraphic interpretations, the definitions and ranks of the Late Valanginian? to Early Aptian rock units that crop out in central Saudi Arabia were revised. The definition of the Late Valanginian? to Early Aptian Biyadh Sandstone is inconsistent with that of the same-named formation in subsurface Saudi Arabia. In outcrop, only the lower Dughum member of the Biyadh Sandstone corresponds to the subsurface Biyadh Sandstone. Accordingly, the Biyadh Sandstone at outcrop was redefined so as to correlate to the same-named subsurface formation; the term Dughum member is considered obsolete. Above the redefined Biyadh Sandstone, the Sallah Formation at outcrop (previously Sallah member of Biyadh Sandstone) yielded the Aptian and/or earliest Albian? ammonite Hypacanthoplites cf. milletianus d’Orbigny; it correlates (in part or completely) to the undifferentiated-Aptian Shu’aiba Formation in Abu Jifan field. The overlying Huraysan Formation (previously Huraysan member of Biyadh Sandstone) is assigned an Albian age based on its stratigraphic position above the Sallah Formation and below the Upper Albian and Cenomanian Majma Formation (previously Majma member of Wasia formation). The Huraysan Formation correlates by stratigraphic position and lithology to the Khafji and Safaniya members of the Wasia Formation in subsurface Saudi Arabia. The Majma Formation may correlate to the Mauddud, Wara and lower part of the Ahmadi members of the subsurface Wasia Formation in Saudi Arabia. The successively overlying Qibah and Malihah formations (previously Qibah and Malihah members of Wasia formation) complete the Cenomanian and Early Turonian succession below the pre-Aruma unconformity. These two formations may correlate to the upper part of the Ahmadi, Rumaila and Mishrif members of the subsurface Wasia Formation in Saudi Arabia. In central Saudi Arabia, the pre-Aruma unconformity is overlain by the Upper Campanian and Lower Maastrichtian Khanasir Member of the Aruma Formation. The Upper Maastrichtian Hajajah and Paleocene Lina members form the upper part of the Aruma Formation. In contrast, the subsurface Aruma Formation in Saudi Arabia may extend to the Coniacian Stage.

The Biyadh Sandstone consists of coastal-plain clastics deposited during several transgressive-regressive sequences. It overlies the pre-Biyadh unconformity, which is represented by west-cutting regional erosion that reaches down to the Jurassic Dhruma and underlying Marrat formations. The overlying Sallah Formation represents a transgressive-regressive sequence deposited in lagoonal and tidal settings, and includes limestone beds with marine fauna. The overlying Huraysan Formation consists of fluvial, fining-upward clastics and is, together with older units, regionally eroded by the pre-Majma unconformity. The associated pre-Majma hiatus probably occurred in the Late Albian and is characterized by the Az Zabirah Bauxite, a deposit that reflects a pedogenic episode that occurred in tropical humid conditions. The fluvial and marginal marine clastics of the Majma Formation, and marine clastics and carbonates of the Qibah Formation, can together be characterized in terms of three flooding events. The Malihah Formation was deposited in mixed proximal settings (tidal to fluvio-deltaic) and exposed (paleosols with bauxite). It represents a regression associated with the eastward tilting of the Arabian Plate during Turonian tectonism along the Neo-Tethyan margin. Central Saudi Arabia remained exposed during the Late Turonian through Middle Campanian, during which times the pre-Aruma Bauxite formed. The Aruma Formation is characterized by four third-order sequences; one in the Khanasir Member, two in the Hajajah Member – all of Late Cretaceous age, and the Paleogene Lina sequence.
INTRODUCTION

The Cretaceous System crops out in central Saudi Arabia in a N-S belt between 20°30’N and 28°30’N (Figure 1). Due to several regional unconformities, significant lithofacies changes, limited biostratigraphic data and the complex geometries of the clastic depositional units, the outcrop-to-subsurface correlations of this system are difficult to establish. In particular, the outcrop-subsurface correlations of the Cretaceous “Biyadh Sandstone” and “Wasia Formation” have been problematic since they were first defined (Steineke et al., 1958; Powers, 1968). Indeed, as noted by Powers (1968): “Correlation of the outcrop Biyadh top with the top as defined in well sections is believed to be incorrect. It seems quite likely that beds now assigned to the upper Biyadh on outcrop are in fact included within the Wasia Formation in the subsurface.”

The correlation of the Biyadh-Wasia between outcrop and subsurface became an issue during the 1980s and 1990s, when the DMMR (Deputy Ministry for Mineral Resources, Ministry of Petroleum and Minerals, Saudi Arabia; now Saudi Geological Survey, SGS) and France’s geological survey BRGM (Bureau de Recherches Géologiques et Minières) mapped several quadrangles in central Saudi Arabia (Figure 1). These two formations represent the upper lower and middle Cretaceous and their geological aspects were discussed in explanatory notes that accompanied the quadrangle maps; from south to north (Figure 1): (1) Sulayyimah (Vaslet et al., 1985), (2) Ar Riyadh (Vaslet et al., 1991), (3) Shaqra (Vaslet et al., 1988), (4) Qibah (Robelin et al., 1994), and (5) Turubah (Lebret et al., 1999). Additionally, detailed studies for bauxite exploration in the Az Zabirah area, Qibah quadrangle (Figure 1), provided additional stratigraphic data and interpretations (Le Nindre et al., 1989).

As a result of the outcrop mapping projects, Vaslet et al. (1991) divided the “Biyadh Sandstone” into three members (Table 1), from oldest to youngest: (1) Dughum, (2) Sallah, and (3) Huraysan; while Le Nindre et al. (1989) and Lebret et al. (1999) divided the “Wasia Formation” into three more members: (1) Majma, (2) Qibah, and (3) Malihah. In the subsurface of eastern Saudi Arabia, the corresponding stratigraphic interval consists of three formations; from base-up (Table 1): (1) Early Cretaceous Biyadh Sandstone (Powers, 1968), equivalent (in part) to the Dughum member; (2) Aptian Shu’aiba Formation (Owen and Nasr, 1958, first formal definition; Powers, 1968) equivalent (in part or completely) to the Sallah member; and (3) Wasia Formation (Powers, 1968), equivalent to the Huraysan member and “Wasia Formation” in outcrop.

This paper presents a synthesis of the many studies cited above. Initially we review the stratigraphy and definitions of the six members in the outcrops of the Ar Riyadh quadrangle that are attributed to the “Biyadh Sandstone” and “Wasia Formation”. In order to more clearly correlate the outcrop and subsurface rock units we propose raising the six members to formational status (Figures 1 to 6). In the next part of the paper we correlate the redefined formations in outcrop, to the Biyadh Sandstone, Shu’aiba and Wasia formations in a well in Abu Jifan field, located in the northern part of the Ar Riyadh quadrangle (Figures 2 and 7). This correlation confirms the Biyadh-Wasia miscorrelation from outcrop-to-subsurface as suspected by Powers (1968). Accordingly, we highlight the usage of these two terms in outcrop with quotation marks. In the next section we discuss the significance of the Az Zabirah Bauxite and its stratigraphic position from the Ar Riyadh to the Qibah quadrangles (Figures 1, 8 to 10). In the final discussion we place the six proposed formations, as well as the Late Cretaceous and Paleocene Aruma Formation, in a regional sequence stratigraphic framework that extends into the subsurface of the Arabian Gulf region.

BIYADH SANDSTONE

Authors: The “Biyadh Sandstone” was originally defined in the Ar Riyadh quadrangle by Steineke et al. (1958). They selected the type section in the Sila’at Biyadh area (South Section, Figure 2; 24°06’38”N, 47°23’53”E to 24°05’28”N, 47°38’07”E, and 24°00’03”N, 47°35’09”E to 23°58’38”N, 47°41’37”E). In the type section, the “Biyadh Sandstone” is 400 m (1,312 ft) thick. In this quadrangle, Vaslet et al. (1991) defined and mapped the Dughum, Sallah and Huraysan members of the “Biyadh Sandstone” (Table 1). The Dughum member was named after the Ad Dughum area located 30 km northeast of Riyadh city, where it crops out extensively. In the present study (Table 1 and Figure 7), the Dughum member is shown to correlate to the Biyadh Sandstone in subsurface Saudi Arabia, and as such the term “Dughum member” is rendered obsolete.
Synonyms: Unit B1 of the “Biyadh Sandstone” in Sulayyimah quadrangle (Figure 1) (Vaslet et al., 1985); Dughum member (obsolete) in Ar Riyadh quadrangle (Vaslet et al., 1991).

Type Section, Location and Thickness: The redefined Biyadh Sandstone (obsolete Dughum member) is 280 m (918.4 ft) thick in its type section (24°02’22"N, 47°23’39"E and 24°05’58"N, 47°35’20"E) (Figure 5).

Type Section, Lithology: The redefined Biyadh Sandstone exhibits a very uniform lithology throughout the Ar Riyadh quadrangle as represented in the North, Central and South Sections (Figure 3). In its type South Section it is comprised of the following lithostratigraphic units, from base up (Figure 5):
Le Nindre et al.

Table 1: Cretaceous of Saudi Arabia

| Power (1968) | Outcrop | DMMR - BRGM (1980s-1990s) | This Study |
|--------------|---------|---------------------------|------------|
| Maastrichtian | Subsurface | Aruma Formation | Aruma Formation | Lina Member |
| Campanian | | | | PALEogene |
| Santonian | | | | Maastrichtian |
| Cenomanian | | | | Campanian |
| Turonian | | | | Santonian |
| Coniacian | | | | Cenomanian |
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Sulayyimah quadrangle (Figure 1, Vaslet et al., 1985), the redefined Biyadh Sandstone (B1 unit) and Sallah Formation (unit B2) are separated by a disconformity.

**Paleontology and Age: ?Late Valanginian to Early Aptian**

Powers et al. (1966) and Powers (1968) assigned a Barremian age to the lower part of the Biyadh Sandstone. Powers (1968) reported the age of the underlying Buwaib Formation as Hauterivian based on contained fossils and stratigraphic position (*Everticyclammina greigi* Henson, *Everticyclammina hensoni* Redmond and other lituolids). P. Andreieff (written communication, 1988; in Le Nindre et al., 1990) assigned the upper part of the Buwaib Formation to the Lower Valanginian based on foraminifera (*Anchispirocyclina*). The present authors consider the age of the Buwaib Formation as not younger than mid-Valanginian.

Further north, in the Qibah quadrangle (Figures 8 to 10), the Biyadh Sandstone could be as old as late Early Valanginian based on nannoflora (NC3 *Calcicalathina oblongata* Zone). In this quadrangle, the section below the Az Zabirah Bauxite was initially interpreted as the Middle Jurassic Dhruma Formation (Black et al., 1984). This interpretation was initially supported by detailed examination of spores, pollen and marine microplankton (dinoflagellate) from cores in well AZ 274 in North Qibah of Middle to Late Jurassic age (Danièle Fauconnier written communication, in Le Nindre and Brosse, 1988). However, further studies of nannoflora by Monique Bonnemaison (ibid.) identified several species including Lower Cretaceous assemblages such as *Rucinolithus wisei* of Berriasian to Valanginian age. It therefore appears that during the deposition of the Biyadh Sandstone, some microflora from the underlying Jurassic formations were reworked together with Lower Cretaceous marine nannoplankton.

In the North Qibah and Az Zabirah South Zone, a composite section illustrates the entire stratigraphic interval as follows (Figures 8 and 9): (1) Bajocian Lower Dhruma Member (51.75 m, 169.7 ft thick) (where a ferruginized surface is recorded in lithologic studies); (2) Biyadh Sandstone (30 m, 98.4 ft thick) in AZ 274. (3) Higher-up, but below the Az Zabirah Bauxite, *Eprolithus floralis* and *Nannoconus sp.* and nannoflora *Eprolithus floralis*, (generally observed from the Late Aptian) were recovered from a bioclastic sandy microsparry dolomitic horizon assigned to the Sallah Formation (Figure 9). (4) The overlying Az Zabirah Bauxite is 5.25 m thick. (5) Above the Az Zabirah Bauxite in well AZ 274, the Majma, Qibah and Malihah formations were encountered. The upper part of the composite section consists of the Aruma Formation in outcrop (27°37'N).

Another composite section in the Az Zabirah Central Zone (Figures 8 to 10) consists of drill-hole AZ 24 (27°56'16"N, 43°45'41"E) up to the “Nezzazata Limestone” (Qibah Formation), and outcrop from the top of the Majma Formation (underneath the *Rotalina Limestone* with a small overlap of the Qibah Formation) to the Aruma Formation upward (27°56'N). The Majma Formation overlies 8 m (26.2 ft) of the Az Zabirah Bauxite. Samples taken below the Az Zabirah Bauxite (AZ 24 well) and from the outcrop yielded a nannoflora of Middle Valanginian to Early Barremian age (zone NC3): *Calcicalathina oblongata, Watznaueria barnesae, Nannoconus sp.*

**SALLAH FORMATION**

**Authors:** Powers (1968, p. 49) noted: “in the north of Wadi As Sahba a prominent 10-meter interval of complexly interbedded clastic and carbonate rocks, about three-fourths of the way up from the base of the formation, which yielded poorly preserved marine mollusks. In addition, a non-diagnostic marine microfauna was found in an air-drilled hole, 25–30 m below the base of the mollusk-bearing interval.” Powers (1968) assigned this interval to the subsurface Wasia Formation by assuming it was either correlative to the carbonates of the Late Albian Mauddud Member or Early Cenomanian Ahmadi Member. This interval was explored by pits and drill holes and described by Villalard (1978) and Villalard et al. (1982) in the Wadi as Sallah. Vaslet et al. (1991) recognized the Aptian age of the Sallah Formation.

**Synonym:** “Biyadh Sandstone” (Powers, 1968); Unit B2 of the Biyadh “Sandstone” in Sulayyimah quadrangle (Figure 1) (Vaslet et al., 1985); Sallah member (obsolete) in Ar Riyadh quadrangle (Vaslet et al., 1991).
**Location and Thickness:** The Sallah Formation was named after Wadi Sallah, a small tributary of Wadi as Sahba, located southwest of Khushaym Radi and running alongside the small cuesta of Kubayshat (Figure 2). In the type section (24°05'58"N, 47°35'20"E and 24°06'02"N, 47°39'22"E) the Sallah Formation is 30 m (98.4 ft) thick (Figures 3 and 5). The Sallah Formation in the Ar Riyadh Central Section is shown in Figure 11.

**Lithology:** The Sallah Formation comprises the following lithostratigraphic units; from base up (Figure 5):

1. (10 m, 32.8 ft): Red, gray or white gypsiferous claystone interspersed with yellowish, medium- to coarse-grained slightly ferruginous sandstone.
Figure 3: Stratigraphic section showing the correlation of the Biyadh Sandstone, Sallah and Huraysan formations in the Ar Riyadh quadrangle (see Figure 2 for location).

Figure 4: Stratigraphic section showing the correlation of the Majma, Qibah and Malihah formations in the Ar Riyadh quadrangle (see Figure 2 for location).
(2) (11 m, 36.1 ft): Yellow to ocher calcareous claystone, pelletaloidal limestone, and red to gray claystone, capped by ocher bioclastic and fossiliferous sandy limestone, secondary dolomitized. This unit has yielded a marine fauna including an ammonite (Villalard, 1984).

(3) (9 m, 29.5 ft): Gray to green calcareous claystone, becoming gypsiferous in the upper part, and intersected by several black, decimeter-thick, iron crusts (Figures 12 and 13).

To the north of the Ar Riyadh quadrangle, between Jabhah and Al Khadam, the Sallah Formation is very similar in lithology; however, the calcareous middle part is replaced by lumachelle-bearing sparry dolomite and claystone. The same evolution is observed to the south (23°50′16″, 47°32′48″). Yellow to red pedogenetic limonitic sandstone occurs at the top of the Sallah Member and is easily identified in the Nisah Graben where it crops out in several localities as far west as 46°51′E. In the graben area, the middle carbonate of the formation gives-way to reddish-brown recrystallised fossiliferous dolomite; the thickness and lithology of the unit are similar to those of the type section.

Lower Boundary and Underlying Formation: The Biyadh Sandstone underlies the Sallah Formation. Upper Boundary and Overlying Member: The Sallah Formation is overlain by the Huraysan Formation. The top of the Sallah Formation is an erosive surface.

Paleontology and Age: Aptian-?Early Albian
The Sallah Formation yielded a rare but very significant marine fauna, which provided the first clue as to the age of the unit in outcrop (Vaslet et al., 1991). Among the fauna, an ammonite attributed by R. Busnardo (without further paleontologic description or illustration) to Hypacanthoplites cf. milletianus d’Orbigny, was found in the type section. This identification suggests an age ranging from Late Aptian (Clansayesian) to Early Albian (Tardefurcata Zone). A second ammonite specimen, found at the same stratigraphic level in the Nisah Graben, remains unidentified.

The Sallah Formation also yielded echinoids, including Cidaridae and Solenia sp., a lamellibranch identified as Cerastostreon tuberculiferum (Koch and Dunka), and a probable ammonite nucleus. Within the Sulayyimah quadrangle, the unit B2 (Vaslet et al., 1985) was correlated with the same Late Aptian-Early Albian event from stratigraphic position, bedforms, lithology, and thickness.

HURAYSAN FORMATION

Authors: Vaslet et al. (1991).

Synonym: “Biyadh Sandstone” (Powers, 1968); Unit B3 of the “Biyadh Sandstone” in Sulayyimah quadrangle (Figure 1, Vaslet et al., 1985); Huraysan member (obsolete) in Ar Riyadh quadrangle (Vaslet et al., 1991).

Location and Thickness: The Huraysan Formation was named after the Huraysan hills to the east of Sila at al Biyadh (southeast of the Ar Riyadh quadrangle, Figure 2). The greatest residual thickness of the formation is estimated at 90 m (295.2 ft) in the type South Section (24°06′02″N, 47°39′22″E to 24°09′28″N, 47°43′38″E) where it corresponds to a broad fluvial braided fan (Figures 3 and 5).

Lithology: From base up the Huraysan Formation consists of (Figure 5):

(1) (10 m, 32.8 ft): White conglomeratic to coarse-grained cross-stratified sandstone with quartz gravel and locally silicified trunks several meters long. Similar beds were previously described within the Sulayyimah quadrangle (unit B3, Vaslet et al., 1985).

(2) (73 m, 239.5 ft): White to pale-beige, medium- to fine-grained sandstone with cross-stratification and inclined bedding, including local conglomeratic horizons. The upper part of the assemblage contains small amounts of siltstone.

(3) (7 m, 23 ft): Beige to mauve pedogenic clayey siltstone, capped by ferruginized and bioturbated (roots) fine-grained sandstone.
In the central part of the quadrangle the lithology is coarser, including abundant conglomeratic layers at the base of graded, fining-upward channel deposits. The sandstone is locally more cemented by sparry calcite than in the south. In the upper part of the member, the claystone is replaced by coarse- to medium-grained sandstone with planar stratification and inclined bedding.

**Lower Boundary and Underlying Formation:** The Sallah Formation underlies the Huraysan Formation.

**Upper Boundary and Overlying Formation:** The upper boundary of the Huraysan Formation is not exposed in the type section. The Huraysan Formation is completely absent in the northern region of the Ar Riyadh quadrangle (Figure 3).

**Age: Albian**
The Huraysan Formation is undated in outcrop (Vaslet et al., 1991). In the Sulayyimah quadrangle (Figure 1), Vaslet et al. (1985) assigned the Huraysan Formation (unit B3) an ?Albian age.

**MAJMA FORMATION**

**Authors:** Le Nindre et al. (1989) and Lebret et al. (1999).

**Synonym:** Majma member (obsolete) (Le Nindre et al., 1989; Lebret et al., 1999).

**Location and Thickness and Lithology:** The type section of the Majma Formation is located in Khushaym Radi (Figure 2), in a central low of the platform close to the Nisah Graben in the southern part of the Ar Riyadh quadrangle (base at 24°08'09''N, 47°43'49''E; and top 24°09'27''N, 47°45'42''E for the entire section in Figure 6), where it is 32 m (105 ft thick) (Figures 4 and 6). It is comprised of two units:

1. **Majma Unit 1** (14.5 m, 47.6 ft thick): Red claystone, ocher-brown fine- to coarse-grained sandstone, red-brick to gray claystone and siltstone, red-ocher claystone with limonitic nodules, ferruginous crust with concretions around gastropods (Figure 14).

2. **Majma Unit 2** (17.5 m, 57.4 ft thick): Gray-green gypsiferous claystone and yellow sand, ocher to fine- or medium-grained ferruginized sandstone with ripples, white gray or red gypsiferous claystone and limonitic siltstone containing plants remains, limonitic crust with calcite nodules (replacing anhydrite?), gray claystone containing rare foraminifera, violet to yellow pedogenized siltstone and sand, beige fine-grained sandstone with calcite cement, hard ground with bioturbation.

In the Ath Thamama Section, located just north of the Ar Riyadh quadrangle in the Ar Rumah quadrangle (Figures 1, 2 and 4), the Majma Formation is 39 m (127.9 ft) thick and predominantly composed of fluvial sandstone indicating more proximal paleoenvironments towards the northern edge of the Ar Rumah quadrangle. In this section the formation again consists of two units.

1. **Majma Unit 1** (24 m, 78.7 ft thick): Conglomeratic channel including pebbles/cobbles (30 cm) of white kaolinite, white kaolinitic clayey sand, white or beige fine- to medium-grained sand with large scale-low angle cross stratification and rare layers of coarse-grained sandstone with clay pebbles of kaolinitic clay at the bottom of the troughs, white to beige fine-grained sandstone with planar and oblique bedding.

2. **Majma Unit 2** (15 m, 49.2 ft thick): White to beige medium-grained sand with planar to low-angle, cross-stratification and oblique bedding and containing rare clay pebbles, white massive kaolinite, yellow-cream medium-grained sand, white massive kaolinite (2nd horizon), white to beige and pink kaolinitic claystone with bauxitic pisoliths.

**Lower Boundary and Underlying Formation:** The lower contact is not exposed in the type section. On a regional scale the Majma Formation was deposited on a major angular unconformity that truncates Mesozoic formations (Figures 1, 9 and 10).
Figure 6: Lithostratigraphy and sedimentology of the Majma, Qibah and Malihah formations in the type section (Khushaim Radi in Figure 2) logged by Y.-M. Le Nindre, D. Vaslet, J.M. Brosse, M. Al-Muallem and S. Maddah (9 March, 1988). The second unit of the Majma Formation contains a remarkable plant horizon described by A.A. El-Khayal (1985). See Figure 5 for Legend of Symbols.
The type section of the “Wasia Formation” is located at Khashm Wisi’ (Wasi’a) (Figure 2; 24°23’04"N, 47°45’12"E to 24°22’38"N, 47°45’49"E; Steineke et al., 1958). Here the Majma Formation is described with its lower boundary coinciding with that of the “Wasia Formation” of Powers (1968) (Figure 15). The formation (14.5 m, 47.6 ft thick, Figure 4) consists of beige, fine-grained sandstone with clay pebbles, red to beige gypsiferous claystone, ocher medium-grained sandstone (bioturbated), gray to red silty claystone (ripples), ocher to beige medium-grained sandstone (megaripples), ferruginous crust.

In the At Tiraq section (Figures 8 and 9), located on the left bank of the Wadi ar Rumah-Al Batin (27°16’N), the Majma Formation lies on the Middle Callovian Tuwaiq Mountain Limestone. In the Qibah Section, located near the village of Qibah (27°25’N), the Majma Formation lies on the Middle Callovian Upper Dhruma Member. In wells AZ 274 (Az Zabirah south zone, North Qibah) (Figure 9), the Majma Formation overlies the Az Zabirah Bauxite, which in turn occurs above the Sallah Formation. In AZ 24 (Az Zabirah, central zone), the Majma Formation overlies the Az Zabirah Bauxite.

**Upper Boundary and Overlying Formation:** The Qibah Formation overlies the Majma Formation conformably (Figures 4 and 6). In the North Section of the Ar Riyadh quadrangle (Figures 2 and 3, in the Al Khadam area near 24°50’N) the Majma Formation is cut by the pre-Aruma unconformity and capped by the pre-Aruma Bauxite (3–6 m, 9.8–19.7 ft thick; Laville, 1980; Villalard, 1986; Villalard et al., 1987) (Figures 16 and 17).

**Paleontology and Age: Albian-Cenomanian**

This Majma Formation yielded rare nannoflora, which has no precise stratigraphic range. A sample collected very close to the Az Zabirah Bauxite (Az Zabirah area, Qibah quadrangle) yielded pteridophytes spores (Cyatheaeeae, Diksonoeaeae) typical of a warm and humid climate, rare Angiospermes pollens (Lilicadites, Retiticolporites) and marine dinoflagellates (Florentina radiculata), which are of Albian to Cenomanian age. A similar age was deduced from microflora by Black (1982).
QIBAH FORMATION

Authors: Le Nindre et al. (1989) and Lebret et al. (1999).

Synonym: Qibah member (obsolete) (Le Nindre et al., 1989; Lebret et al., 1999).

Location, Thickness and Lithology: The type section of the Qibah Formation is located in Khushaym Radi in the Ar Riyadh quadrangle (base at 24°08′09″N, 47°43′49″E; and top 24°09′27″N, 47°45′42″E for the entire section in Figure 6), where it is 7.5 m (24.6 ft) thick (Figures 2, 4 and 6). It consists of yellow sand and ochre-green claystone, gray claystone, brown clayey sandstone, brown vacuolar

Figure 8: Simplified geological map of the Qibah quadrangle showing outcrop belt of the Az Zabirah Bauxite of probable Late Albian age. The stratigraphy along the At Tiraq, Qibah, North Qibah (Well AZ 274), Az Zabirah South and Central Zones is shown in Figure 9.
Cretaceous stratigraphy, Saudi Arabia

In the Qibah quadrangle (Figures 8 and 9), the Qibah Formation includes two marker bed horizons: the Rotalina Limestone (dolomitic) and higher-up in the section the Nezzazata Limestone (calcareous) (see Figure 30). Further south in the type section at Khushaim Radi (Figure 6), a bioturbated calcareous sandstone occurs at the base of the Qibah Formation and a dolomite bed in its upper part. It is unclear whether these two units correlate to the Rotalina and Nezzazata Limestones.

Upper Boundary and Overlying Formation: The Malihah Formation overlies the Qibah Formation conformably.

Lower Boundary and Underlying Formation: The Majma Formation underlies the Qibah Formation conformably.

Paleontology and Age: Cenomanian-Early Turonian
In the Qibah area, Upper Cenomanian to Lower Turonian ammonite species Neolobites vibrayeanus d’Orbigny was recovered at the base of the Rotalina Limestone and in the Nezzazata Limestone (Le Nindre et al., 1989). The formation also contains abundant marine fossils including lamellibranchs, gastropods, algae and echinoids: Orthopsis cf. globosa Cotteau and Gauthier, Coptodiscus nomiae

Northwest

South Zone
Az Zabirah

QIBAH QUADRANGLE

North Qibah Az 274 well
Qibah

Pre-Aruma Unconformity
Malihah Formation

Aruna Formation

Rotalina
Qibah Formation

Nezzazata
Majma Formation

Pre-Majma Unconformity
Jurassic

At Tiraq Outcrop
27°16’N

0 m

10 m

20 m

30 m

40 m

50 m

60 m

70 m

80 m

90 m

Malihah Formation

Early Turonian Late Cenomanian

Albian - Cenomanian

Majma Formation

Tuwaig Mountain Limestone

Upper Dhruma Member

Middle Dhruma Member

Lower Dhruma Member

Tuwaig Mountain Limestone

Pre-Biyadh Unconformity

Gypsiferous claystone

Sandstone

Dolomite

Siltstone

Limestone

Shale

Ammonite

Nanoflora

Foraminifera

Pollen (\*)

reworked

Lower boundary and underlying Formation:
The Majma Formation underlies the Qibah Formation conformably.

Paleontology and Age: Cenomanian-Early Turonian
In the Qibah area, Upper Cenomanian to Lower Turonian ammonite species Neolobites vibrayeanus d’Orbigny was recovered at the base of the Rotalina Limestone and in the Nezzazata Limestone (Le Nindre et al., 1989). The formation also contains abundant marine fossils including lamellibranchs, gastropods, algae and echinoids: Orthopsis cf. globosa Cotteau and Gauthier, Coptodiscus nomiae

Northwest

South Zone
Az Zabirah

QIBAH QUADRANGLE

North Qibah Az 274 well
Qibah

Pre-Aruma Unconformity
Malihah Formation

Aruna Formation

Rotalina
Qibah Formation

Nezzazata
Majma Formation

Pre-Majma Unconformity
Jurassic

At Tiraq Outcrop
27°16’N

0 m

10 m

20 m

30 m

40 m

50 m

60 m

70 m

80 m

90 m

Malihah Formation

Early Turonian Late Cenomanian

Albian - Cenomanian

Majma Formation

Tuwaig Mountain Limestone

Upper Dhruma Member

Middle Dhruma Member

Lower Dhruma Member

Tuwaig Mountain Limestone

Pre-Biyadh Unconformity

Gypsiferous claystone

Sandstone

Dolomite

Siltstone

Limestone

Shale

Ammonite

Nanoflora

Foraminifera

Pollen (\*)

reworked

Figure 9: Stratigraphic correlation of the Jurassic (pre-Biyadh unconformity) to middle Cretaceous (pre-Aruma unconformity) in the Qibah quadrangle (see Figure 8 for location).
Cotteau and Gauthier, *Heterodiadema* sp., *Hemiaster* sp., and *Cidaridae*. Abundant microfauna was also recovered from the limestone marker beds: (1) the Rotalina Limestone is characterized by *Rotalina* sp. and other *Rotaliidae*; (2) The Nezzazata Limestone contains *Trocholina [Nezzazata]* cf. *simplex*, *pre-Nezzazata* sp., *Montcharmontia appenninica*, *Cuneolina* sp., *Glomospira* sp., *Glomospirella* sp. and *Ammobaculites* sp., together with many other specimens of foraminifera. The assemblage from the Nezzazata Limestone could be Late Albian-Turonian, but is typically Cenomanian (M. Simmons, 2006, written communication).

The recovered nannoplankton species are *Predicosphaera gr. cretacea*, *Reinhardtites anthophorus*, *Quadrum gartneri*, *Eiffelithus eximius*, and *Eprolithus floralis* in the Rotalina Limestone; and *Luciana rhadus cayeuxi*, *Calculithes obscurus*, *Watznaueria barnesae*, *W. biporta*, and *R. anthophorus* in the Nezzazata Limestone. These associations confirm the Late Cenomanian to Early Turonian age given by ammonites (zone NC13).

**MALIHAH FORMATION**

**Authors:** Le Nindre et al. (1989) and Lebret et al. (1999).

**Synonym:** Malihah member (obsolete) (Le Nindre et al., 1989; Lebret et al., 1999).

**Location and Thickness and Lithology:** The type section of the Malihah Formation is located in Khushaym Radi in the southern part of the Ar Riyadh quadrangle (base at 24°08′09″N, 47°43′49″E; and top 24°09′27″N, 47°45′42″E for the entire section in Figure 6), where it is 12.5 m (41 ft) thick (Figures 2, 4 and 6). It consists of pale-gray claystone and fine-grained bioclastic sand with clay pebbles, gray silty claystone with marcasite, brown coarse- to medium-grained sandstone and cream to purple silty claystone, gray to ochre claystone.

In the Khashm Wisi‘ Section (Figure 4), the Malihah Formation is 19.5 m (64 ft) thick and consists of varicolored claystone, coarse-grained to conglomeratic (quartz gravel and clay pebbles) sandstone containing wood remains, channeled with oblique/cross bedding, ochre beige coarse- to medium-
grained sandstone, gray-green claystone, ocher bioturbated sandstone, green to ocher sandy claystone, bioturbated ocher coarse-grained sandstone (wood remains), yellow-greenish clayey sand, ocher-yellow sand (iron-coated grains) (Figure 19).

**Lower Boundary and Underlying Formations:** The Qibah Formation underlies the Malihah Formation.

**Upper Boundary and Overlying Formation:** The Aruma Formation unconformably overlies the Malihah Formation. In the Qibah quadrangle (Figure 9), the thickness of the Malihah decreases toward the northwest from 37.25 to 14.25 m (122.2 to 46.7 ft) due to erosion by the pre-Aruma unconformity (Figure 4).

![Figure 11: Sallah Formation, at Jabhah in the central part of the Ar Riyadh quadrangle; from bottom to top: marine siltstone and claystone, ferrugineous surfaces and cuesta capped by a coquina dolomite (see Figure 2 for location; photo by D. Vaslet).](image)

![Figure 12: Pedogenic features at the top of the Sallah Formation, Central Section, Ar Riyadh quadrangle; tubular structures in white and pink silt and claystone overlain by tidal sandstone with ripples (see Figure 2 for location; photo by D. Vaslet).](image)

![Figure 13: Iron crust marking the top of the Sallah Formation, Central Section, Ar Riyadh quadrangle (see Figure 2 for location; photo by Y.-M. Le Nindre).](image)
Paleontology and Age: Rare nannoplankton was found (*Watznaueria biporta*) and the presence of rocks younger than Turonian is not demonstrated.

**AR RIYADH OUTCROP TO SUBSURFACE CORRELATION**

A subsurface reference section (provided by Saudi Aramco; Figure 7) was published in the Ar Riyadh geologic map for the upper portion of an Abu Jifan well (Vaslet et al., 1991). The Abu Jifan oil field is located in the northeastern corner of the Ar Riyadh quadrangle (Figure 2), in the Nafud ad Dahna area, about 75 km to the northeast of the “Biyadh-Wasia” type section, and 40 km from the closest
Figure 16:
(a) White sandstone near the top of the Malihah Formation, underneath the Aruma Formation, Jabal Maqtu, Ar Riyadh quadrangle.
(b) Pedogenesis developed in the Malihah Formation. Sharp contact with the overlying Aruma limestone.
(c) Pisolithic pre-Aruma Bauxite developed during the Turonian-Early Campanian hiatus. Photos by D. Vaslet.

Figure 17: Aruma Formation (beige carbonate) resting on the Majma Formation (pink clastics), Ath Thamama Section, Ar Rumah quadrangle (see Figures 1 and 2 for location; photo by D. Vaslet).
“Wasia” outcrop. The Abu Jifan section begins in the Umm Er Radhuma Formation, and encountered the pre-Aruma unconformity at 249 m and the base of the Biyadh Sandstone at 867 m; the top Wasia to base Biyadh interval is 618 m (2,027 ft) thick. From the lithologic succession in the borehole, as described and interpreted by Saudi Aramco (but without biostratigraphic control), the following correlations are proposed, from base-up:

Biyadh Sandstone (obsolete Dughum member in outcrop) to Biyadh Sandstone in Abu Jifan (between 867–526 m; 341 m or 1,118.5 ft thick). In Abu Jifan, this interval consists of (1) sand and sandstone, clear to light-gray medium- to coarse-grained quartz sand locally cemented by calcite; and (2) sand, clear to milky fine- to coarse-grained, predominantly coarse, subrounded to subangular, loose quartz sand and ?lignite.

Sallah Formation to Shu’aiba Formation (between 526–497 m; 29 m or 95.1 ft thick). In Abu Jifan, this interval consists of (1) hard and compact dolomite, tan, microcrystalline, grading to dolomitic limestone; and (2) limestone, off-white to light-gray, fine crystalline, soft chalky and local calcarenite with fossil fragments (Orbitolina sp.). By structural construction, this correlation results in a dip of 0.7° as consistent with the average regional dip.

Huraysan Formation to the Lower Sandy Interval of the Wasia Formation in Abu Jifan (between 497–249 m; 248 m or 813.4 ft thick). In Abu Jifan, this interval consists of sand and sandstone, very fine- to coarse-grained, clear to milky, sub-angular to sub-rounded and quartz sand, locally slightly calcareous cemented, dominantly medium- to coarse-grained.

Majma, Qibah and Mulayhah formations to the Upper Silty Interval of the Wasia Formation in Abu Jifan (between 291–249 m; 42 m or 137.8 ft thick). In Abu Jifan, this interval consists of shale, gray to green or red-brown, locally silty more or less fissile; sand, clear, fine- to medium-grained and commonly coarse, sub-angular, sub-rounded; lignite; sand, sandstone, clear, fine- to medium-grained, calcareous, cemented; quartz sand; shale gray, fissile. The Majma, Qibah and Mulayhah formations in outcrop appear very similar in thickness and facies to the Upper Silty Interval including the lignite beds.

AZ ZABIRAH BAUXITE

Authors: Bramkamp et al. (1963, in the 1:500,000 map of the Ar Rimah quadrangle north of Qibah, Figure 1) assigned the “beds of red, white and purple lateritic clay and bauxite” to the basal part of the “Wasia Formation”. Between 1979 and 1985, the mining company, Riofinex, prospected the whole area for the DMMR (Black et al., 1984). Additional exploration and mining studies for bauxite as well as for the lower kaolinic clay, were carried out by BRGM for the DMMR between 1989 and 1993, and last updated in 1999. Le Nindre and Brosse (1988) and Le Nindre et al. (1989) mapped the outcrops of the Az Zabirah-Qibah area, at a 1:50,000 scale, from 27°30’N, 44°15’E to 28°15’N, 43°15’E. These latter authors interpreted the subsurface stratigraphy using 68 wells drilled for bauxite exploration.

Location and Thickness: The Az Zabirah Bauxite crops out discontinuously as a low scarp, several meters high, along a strike length of 105 km, and has a gentle regional 1–2° dip to the NE, beneath progressively thicker overburden (Figures 8 and 9). The Az Zabirah Bauxite has an average thickness of about 6 m (19.7 ft).

Lithology and Depositional Environment: The Az Zabirah Bauxite is an in-situ deposit, constituting a late stage of a paleolateritic profile developed on a regional paleosurface (Figure 20). This pedogenic episode occurred in tropical humid climatic conditions, and transformed various kaolinic terrigenous clastic sedimentary rocks of the Triassic to Lower Cretaceous substratum.

In the Qibah quadrangle (Figure 8), the Az Zabirah Bauxite formed more deeply in the Central Zone and with a better chemical quality than the kaolinic facies in the South Zone (Az Zabirah area). The bauxite is present on the Middle Marrat Member, which also provided a clayey parent rock. Pedogenesis followed by retro-diagenesis due to weathering, led to tubular then to pisolithic bauxite, and the formation of an associated lower and upper clay. Towards the north, the bauxite was eroded and reworked as bauxitic granules in a matrix of coarse-grained sandstone or in fluvial levees. Relicts
of the Biyadh Sandstone and Sallah Formation are preserved in the Az Zabirah–Qibah area where bauxite, of probable Albian age, was formed in place of the Huraysan Formation.

**Upper Boundary and Overlying Formation:** The Az Zabirah Bauxite is overlain by the Majma Formation.

**Lower Boundary and Underlying Formations:** The Az Zabirah Bauxite is developed deeply within the silty facies of the Biyadh Sandstone, Sallah Formation (in well AZ 274) and Huraysan Formation, and also affects older sediments (Jurassic Marrat Formation and Triassic Minjur Sandstone (Figure 8)).

**Age:** The Az Zabirah Bauxite, based on stratigraphic position formed between the Late Aptian (latest nannoplankton below) and Cenomanian (earliest microflora above), and probably in the Albian after the Huraysan Formation was deposited.

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**Figure 18:** Carbonate beds of the Qibah Formation at Khashm Wisi', Ar Riyadh quadrangle (see Figure 2 for location; photo by D. Vaslet).

**Figure 19:** Horizon with rootlets at the top of Malihah Formation, Ar Riyadh quadrangle (Observation Point 66; photo by Y.-M. Le Nindre).
Figure 20: Representative section of the Az Zabirah Bauxite ore, Az Zabirah area (see Figure 8 for location; photo by Y.-M. Le Nindre); hardened upper part and tabular structure below. The Zabirah Bauxite is the result of in-situ transformation of kaolinitic clay of various ages. During the diagenesis, the aluminium-bearing crust evolved into a pisolithic and tubular bauxite, and subsequently to secondary kaolinitic clay by weathering (“upper clay” and “lower clay”).

DEPOSITIONAL ENVIRONMENTS, REGIONAL CORRELATIONS AND SEQUENCE STRATIGRAPHY

Figure 21 illustrates the proposed regional sequence stratigraphic correlations from central Saudi Arabia to the subsurface in the Arabian Gulf region. Also shown in Table 2 are the present author’s proposed positions of the Arabian Plate maximum flooding surfaces and sequence boundaries (MFS and SB; Sharland et al., 2001; Davies et al., 2002).

Pre-Biyadh Unconformity

The regional pre-Biyadh unconformity extends across the Arabian Platform and continues into Yemen, Eritrea and Ethiopia. In central Saudi Arabia the unconformity is younger than the Early Valanginian Buwaib Formation (Figure 21), which contains Early Valanginian MFS K30 (Sharland et al., 2001). Sharland et al. (2001) and Davies et al. (2002) interpret the presence of a regional Late Valanginian unconformity, which may correlate to the pre-Biyadh unconformity of central Saudi Arabia (Table 2).

In the subsurface of Kuwait, a major stratigraphic break occurs between the Lower Valanginian Ratawi Formation and Upper Hauterivian Zubair Sandstone (Varol Research, 1996, in Al-Fares et al., 1998). If this break correlates to the pre-Biyadh unconformity then the age of the lower part of the Biyadh Sandstone would not likely extend to the Late Valanginian and Early Hauterivian, as indicated in the discussion of its age.

Biyadh Sandstone

The coastal-plain clastics of the Biyadh Sandstone represent several transgressive-regressive sequences, which were mapped in the Ar Riyadh quadrangle as expressed by the landforms created by the rhythmic fining-upward lithology (Figure 2, Vaslet et al., 1991). The evidence of tidal influence
Figure 21: Correlation chart of the Valanginian to Paleocene interval based on biostratigraphy and depositional sequences. Geological Time Scale GTS 2004 after Gradstein et al. (2004); Subsurface Saudi Arabia (Powers, 1968); Kuwait (Al-Fares et al., 1998); Oman (van Buchem et al., 1996, 2002; van Buchem, written communication, 2007; Droste and van Steenwinkel, 2004); maximum flooding surfaces (MFS) (modified or after Sharland et al., 2001; Davies et al., 2002; R. Davies, written communication, 2007).

is demonstrated by typical bedforms such as sigmoidal megaripples (Figures 22 and 23), mud drapes (where present) and reversals of current directions.

In the Az Zabirah Central Zone (Qibah quadrangle), the Biyadh Sandstone overlies (from north to south) the Jurassic Lower and Middle Marrat (middle Toarcian) members (Figures 8, 9 and 24). Inspite of their unconformable contact, careful analysis was required to distinguish the two formations because they consist of similar clastic tidal facies. The Marrat Formation, often ferruginized, includes tidal-flat and strand-plain facies with well-preserved, small-scale ripple marks. In contrast, the Biyadh Sandstone is well-washed, and consists mainly of yellow and white sandstone and white-purple siltstone. It includes tidal channels with sigmoidal megaripples, channel fills and laminated or rippled tidal flats (Figure 25). Exposed bedforms provided numerous readings of flow directions,
which indicated north-to-south (flood) or south-to-north (ebb or residual fluvial) alternating currents. The marine origin of the Biyadh Sandstone, initially interpreted from the bedforms, was confirmed by the nannoflora. In morphology, the tidal facies of the Biyadh Sandstone is likely to represent the filling of a paleogulf limited at the paleoshoreline by the Marrat Formation.

On a regional scale (Table 2 and Figure 21), the Biyadh Sandstone sequences may be third-order and contain the three MFS K40 to K60 (Sharland et al., 2001; Davies et al., 2002) that approximately encompass the same age period (Hauterivian-Barremian); however the lack of biostratigraphic data precludes a specific correlation. The surface-subsurface Biyadh Sandstone probably correlates (in part or completely) to the Hauterivian-Early Aptian Zubair Formation in southwest Iraq (H.V. Dunnington, in van Bellen et al., 1959) and Kuwait's Late Hauterivian-Early Aptian Zubair Formation in Well F in offshore Kuwait (Varol Research, 1996, in Al-Fares et al., 1998). Towards Oman, the formation probably passes to the carbonates of the Lekhwair and Kharaib formations and Hawar Member of the Kharaib Formation (Droste and van Steenwinkel, 2004).

### Sallah Formation

The Sallah Formation consists of lagoonal and tidal sediments, including locally a marine fauna. In the southernmost-mapped Sulayyimah quadrangle, it unconformably onlaps older Jurassic units (Vaslet et al., 1985) and reflects an important regional transgression. Although the correlation of the Sallah

| Central Saudi Arabia | Stage | MFS in Subsurface Arabia |
|---------------------|-------|--------------------------|
| Lina Member, Aruma Formation | Late Paleogene | Pg10 |
| Hajjah Member, Aruma 3 Sequence | Late Maastrichtian | None |
| Hajjah Member, Aruma 2 Sequence | Late Maastrichtian | None |
| Khanasir Member, Aruma 1 Sequence | Late Campanian-early Late Maastrichtian | K180 |
| Malihah Regression and Qibah Flood | Late Cenomanian and Early Turonian? | Early Turonian K140 in Mishrif Member or Middle Cenomanian K130 in Rumaila Member |
| Majma Cycle 2 | Early Cenomanian | Early Cenomanian K120 in Ahmadi Member |
| Majma Cycle 1 | Late Albian K110 | Late Albian MFS K110 in Maaddud Member |
| Pre-Majma unconformity | Late Albian | Late Albian SB K110 |
| Huraysan Formation | Albian | Middle Albian K100 in Dair Limestone |
| Huraysan Formation | Albian | Early Albian K90 in Burgan Formation and Khafji Member |
| Base Huraysan Formation | Base Albian? | Base Albian SB K90 |
| Sallah Formation | Early Aptian? | Early Aptian K70 in Lower Shu’aiba |
| Sallah Formation | Late Aptian and/or earliest Albian? | Middle? Aptian K80 in Unnamed Clastics Formation and Bab Member |
| Biyadh Sequences | Valanginian? or Hauterivian to Early Aptian | Hauterivian to Early Aptian K40 to K60 |
| Pre-Biyadh unconformity | Late Valanginian and Early Hauterivian? | Late Valanginian unconformity? |
| Buwaib Formation | Early Valanginian | Early Valanginian K30 |
Formation to the Shu’aiba Formation in the Abu Jifan borehole seems well-established by lithology (Figure 7), the chrono- and sequence stratigraphic relationships of this marine unit, in such proximal localities in central Saudi Arabia, to subsurface regions in eastern Arabia remain uncertain.

In Well F in Kuwait, the Shu’aiba Formation is dated as Early Aptian, while the Late Aptian is represented by the “Unnamed Clastics Formation” (Al-Fares et al., 1998). The latter formation consists predominantly of shales (c. 25–90 m, 80–300 ft thick) that were deposited in an open-marine neritic environment (Robertson Research, 1996, in Al-Fares et al., 1998). Over the Burgan field the “Unnamed Clastics Formation” correlates to the Lower Fourth Sand of the Burgan Formation, which consists of shallow-marine interbedded sands, shales and mudstones, and thin carbonates (Kirby and Al-Humoud, 1996; Kirby et al., 1998). Al Fares et al. (1998) showed that a major sequence boundary separates the “Unnamed Clastics Formation” from the overlying Albian Burgan siliciclastics.
Figure 24: Tidal Biyadh Sandstone and fluvial Huraysan Formation? in the Az Zabirah Central Zone (see Figure 8 for location). The thickness of the Az Zabirah Bauxite is contoured in meters.

In the United Arab Emirates and Oman, the Shu’aiba Formation is divided into an Early Aptian Lower Shu’aiba Sequence (platform carbonates) and Late Aptian Bab Sequence (basin infill) (van Buchem et al., 2002a; F. van Buchem, written communication, 2007). The Bab Sequence consists of mixed carbonates and shales, and correlates by age and lithology to the “Unnamed Clastics Formation” of Kuwait. The Lower Shu’aiba and Bab sequences are believed to be separated by a major sequence boundary, with the latter sequence representing the start of a second-order depositional sequence that culminated with the Albian Nahr Umr Formation (van Buchem et al., 1996, 2002a, b; Boote and Mou, 2003).

Thus, the Early Aptian depositional setting in Kuwait, Oman and the UAE can be characterized in terms of a carbonate platform, followed by a major relative sea-level fall in mid-Aptian (second-order sequence boundary). In the Late Aptian, a regional transgression deposited mixed carbonate and clastics, which subsequently in the Albian became covered by the massive progradational siliciclastics of the Nahr Umr and Burgan formations.

If the ammonite Hypacanthoplites cf. millesianus; d’Orbigny recovered from the Sallah Formation is indeed of Late Aptian and/or earliest Albian age, then the Sallah Formation would correlate to the Late Aptian transgression recorded in Kuwait, Oman and the UAE. In such a case it may contain MFS K80 positioned in the Bab Member (Davies et al., 2002). If the Sallah Formation is in fact Early Aptian in age then it would contain MFS K70 (Sharland et al., 2001; Davies et al., 2002).

Huraysan/Sallah Boundary

The base of the Huraysan Formation is a sharp sequence boundary with coarse conglomeratic lags in the lower part. If the Sallah Formation is correlated to the “Unnamed Clastics Formation” of Kuwait (Al-Fares et al., 1998), then the base Huraysan Formation would correlate to the base of the Main Fourth Sand of the Burgan Formation. In subsurface Saudi Arabia, the base Huraysan probably correlates to the base Main Khafji Sand above the Lower Khafji sand and shale stringers. In the UAE and Oman, it would correlate to the base Nahr Umr Formation (van Buchem et al., 1996, 2002a,b).
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plate-wide scale it would correlate to base Albian SB K90 (Table 2; Davies et al., 2002; Simmons et al., 2007).

**Huraysan Formation**

The Huraysan Formation is undated by fossils but falls in the Albian by stratigraphic position and regional correlations. Above the basal sequence boundary and conglomeratic lag, the formation’s main body consists of braided sand bars with flood deposits at the top. In the Qibah area (Figure 24), a fluvial unit occurs where the bauxite is best-preserved. This unidentified unit may be the Huraysan Formation in which case its base would correlate to the base Wasia Formation in subsurface. It consists of coarser, more ferruginous sandstone with large-scale trough stratification, and is capped by planar bedding and laminated lacustrine facies underneath the Az Zabirah Bauxite. The foreset readings indicate a dominant SW-NE flow direction converging towards a region where the bauxite attains its maximum thickness (≥ 6 m) (Figures 26 to 28).

At a regional scale, the Huraysan Formation is apparently the lateral equivalent of the main Burgan Third and underlying Fourth Main Sand, above the "Unnamed Clastics Formation" in Kuwait (Al-Fares et al., 1998; Kirby and Al-Humoud, 1996; Kirby et al., 1998; Strohmenger et al., 2002; Davies et al., 2002). The middle Albian K100 MFS, picked between the Burgan Third and Fourth Sands (Dair Limestone marker), would pass within the Huraysan Formation (Table 2). It is also probable that Early Albian MFS K90 occurs in the lower part of the Huraysan Formation. The formation passes laterally to the interval from the base of the Albian Khafji Main Sand and overlying Safaniya Member of the subsurface Wasia Formation in Saudi Arabia (Powers, 1968). It would correlate to the Nahr Umr Formation in Oman. It seems unlikely that the Huraysan Formation would correlate to the Mauddud and Wara formation/member of Kuwait and Saudi Arabia, as suggested by Entsminger (1981).

**Majma/Huraysan boundary and Az Zabirah Bauxite**

The upper boundary of the Huraysan Formation is represented by the regional pre-Majma unconformity, above which the Majma Formation was deposited during a regional transgression. The Az Zabirah Bauxite marks an important stratigraphic hiatus that occurred before the deposition of the Majma Formation and most likely in the Late Albian, following the deposition of the Huraysan Formation. This unconformity probably correlates to the base of the Upper Albian Mauddud Formation (and correlative Upper Burgan Third Sand) as shown in Figure 21. The base Mauddud Formation represents a regional carbonate flooding event in the Gulf region, which includes the Natih Formation in Oman.

Figure 25: Core from borehole AZ 144 (depth 27.0–27.7 m) shows tidal laminated sandstone and siltstone, Biyadh Sandstone, Az Zabirah area. Bedforms showing lateral to sigmoidal megaripples in channels correspond to associated sand and mud flats (see Figures 8 and 24 for location; photo by Y.-M. Le Nindre).
Majma Formation

The Majma, Qibah and Maliyah formations represent a marine incursion from the north, possibly along depressions as mapped by Ziegler (2001, his figures 13 and 14). The cycle began with the incision of valleys and reworking of the Az Zabirah Bauxite. In the Ar Riyadh area (Figure 4), the basal transitional facies of the Majma Formation infilled existing topography over the pre-Majma unconformity. In the Khushaym Radi Section, the lower part of the Majma Formation filled a central depression. In the Ath Thamama Section, the lower part of the Majma Formation filled an incised fluvial valley. The upper part of the Majma Formation exhibits a coarsening-upward evolution.

Figure 26: Trough cross-bedding (foresets dipping 16°) in coarse-grained sandstone, Huraysan Formation, Az Zabirah area. The cuesta is formed by the lower clay zone of the Az Zabirah Bauxite weathering profile with a solid bauxite cover (Observation Point 19; photo by Y.-M. Le Nindre).

Figure 27: Laminated sandstone with clay pebbles from eroded mudstone beds in a channel with flow direction of N25–30° beneath the Az Zabirah Bauxite (Observation Point 12, Az Zabirah area; photo by Y.-M. Le Nindre).

Figure 28: Upper part of the weathering profile of the Az Zabirah Bauxite showing gray clay below (“lower clay zone”), and hardened oolithic (pisolithic) clay above (Observation Point 12, Az Zabirah area; photo by Y.-M. Le Nindre).
In the Qibah area (Figures 8, 29 and 30), the Majma Formation is interpreted in terms of three detrital units and two flooding intervals. Majma Detrital Unit 1 is a coarse-grained, trough-stratified, ferruginous fluvial sandstone. It is the lowest body incised into the Az Zabirah Bauxite (basal sequence boundary of Majma Cycle 1). The fluvial system flowed toward the NNE, dominantly NE, and reworked bauxite granules accumulated as fluvial levees. This fluvial unit corresponds to the lowstand-transgressive systems tracts (LST-TST) of Majma Cycle 1.

Majma Tidal Siltstone 1 overlies Majma Detrital Unit 1 and consists of bioturbated and laminated tidal siltstone with tidal sand bars (Figure 31). It represents the flooding interval (MFI) of Majma Cycle 1. The regressive part of the Majma Cycle 1 is not apparently represented and may correspond...

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Figure 29: Map of Majma and Qibah formations in the Az Zabirah Central Zone (see Figure 8 for location). The thickness of the Az Zabirah Bauxite is contoured in meters. The arrows indicate the flow direction of the three Majma Detrital Units.

Figure 30 (left): Between the pre-Majma and pre-Aruma unconformities, the Majma and Qibah formations are interpreted in terms of three transgressive-regressive cycles. Two maximum flooding intervals (MFI 1 and 2) are picked in the Majma Formation and one in the Qibah carbonates. The Malihah Formation was deposited during a regression associated with Turonian tectonism and the pre-Aruma unconformity.

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to a hiatus (SB of Majma Cycle 2). The Majma Cycle 1 MFI may correlate to Late Albian MFS K110 that passes through the Mauddud member/formation and lower Natih Formation (Sharland et al., 2001) (Table 2 and Figure 21).

Majma Detrital Unit 2 consists of coarse-grained, yellow sandstone with directional foresets, planar bedding and gravel lags, which implies a depositional setting involving a powerful, low-sinuosity fluvial system (Figures 32 and 33). The geological map highlights the channel system from bedforms (Figure 29). The Majma Cycle 2 river-valley system was almost perpendicular to that of the Majma Cycle 1, with a new flow direction towards the NNW. It cut by regressive erosion the underlying

Figure 31: Laminated tidal siltstone with ripples and megaripples represents the maximum flooding interval (MFI 1, see Figure 30) above Detrital Unit 1 of the Majma Formation, Bauxite Trench 2, southern part of Az Zabirah Central Zone (see Figure 29 for location, photo by Y.-M. Le Nindre).

Figure 32: Low-sinuosity river deposits (brown, above) with large foresets (N350°) of Detrital Unit 2 (from right to left) of the Majma Formation, resting on the bauxite. This unit erodes the bauxite upstream. See Figure 33 for detail of bedforms. Location in the Az Zabirah Central Zone (see Figures 29 and 30) (Observation Point 243, photo by Y.-M. Le Nindre).
Majma sediments, then the Az Zabirah Bauxite, and finally the older units. In the Central Zone, the Az Zabirah Bauxite initially formed as a plateau that was dissected by this fluvial network. The bauxite and the kaolinite of the lower clay of the bauxite are best-preserved between the channels (Figure 20).

Above the Majma Detrital Unit 2, lagoonal deposits with a tidal influence represent a second transgressive systems tract (TST of Majma Cycle 2), which covered the previous paleogeographic patterns. This flooding interval corresponds to the clayey portion of the Majma Formation (MFI of Majma Cycle 2). Majma Detrital Unit 3 consists of sandstones deposited in a broad deltaic/marine wedge that prograded towards the northeast. Tree trunks, partially calcitized, were carried by tributary channels and are found

Figure 33: Low-sinuosity river deposits consisting of coarse-grained sandstone with steep foresets and flat beds with residual gravel lag, Detrital Unit 2 of the Majma Formation, Az Zabirah Central Zone (DU2, see Figures 29 and 30) (Observation Point 137b; photo by Y.-M. Le Nindre).

Figure 34: Sand wave at the top of the Detrital Unit 3 of the Majma Formation. The direction of the sandwaves is southwestwards. They are interpreted as bars of a flood tidal delta with waves and swell approaching from the northeast (Observation Points 82 and 83, Az Zabirah Central Zone; photo by Y.-M. Le Nindre).
in the low delta plain. Figure 34 shows large sand waves that resulted from the reworking of fluviatile clastics by waves in the marine domain. In the Az Zabirah area (Figure 29), this sandstone directly overlies the Az Zabirah Bauxite. Majma Detrital Unit 3 represents a major regression (or lowstand) and separates Majma Cycle 2 from the Qibah flooding event. The Majma Cycle 2 MFI may correlate to Early Cenomanian MFS K120 (Sharland et al., 2001) (Table 2 and Figure 21).

**Qibah Formation**

The carbonates of the Qibah Formation were affected by secondary dolomitization as highlighted by a uniform bench of bioturbated red-brown dolomite with calcite geodes in the Qibah area. Petrographical analysis indicated that the Qibah carbonates are a sparry dolomite with euhedral, zoned and ferroan crystals of 80–150 µm, and a silty quartz content of 6–10%. The dolomitic beds and associated fauna suggest a subtidal to shallow inter-tidal paleoenvironment. In outcrop, this horizon is more-or-less de-dolomitized. The dolomitic bench is over lain by a calcareous assemblage, richer in marine fauna (molluscs, echinoids, ostracods, foraminifera), indicating a more open-marine environment (Nezzazata Limestone). Ammonites were collected in both facies.

The Qibah transgression started with tidal pulses and culminated with a flooding interval represented by a confined limestone shelf environment (Rotolina Limestone). The associated flooding deposits infilled all the older differentiated paleogeographic patterns. The main Qibah flooding is correlated to the global flooding event near the Cenomanian-Turonian boundary (93.5 Ma ± 1.0 Ma, Gradstein et al., 2004); it corresponds to the MFS at 91.5 Ma (Haq et al., 1988) and either Middle Cenomanian MFS K130 or Early Turonian K140 (Sharland et al., 2001) (Table 2).

**Malihah Formation**

The Malihah Formation exhibits a facies shift towards various proximal environments, from tidal to fluvio-deltaic, and paleosols with bauxite. At the base, diagenesis, influenced by overlying pyritic shales, pass to iron and chalcedony crusts at the boundary with the carbonates of the Qibah Formation (Figure 35). The paleoenvironment is illustrated by remains from swampy areas (Figure 36) and microripples in tidal siltstone (Figure 37). The regression associated with the Malihah Formation is related to the Turonian tectonic movements involving the ophiolite obduction along the Neo-Tethyan margin. The Malihah Formation may be equivalent to the upper clayey part of the Rumaila Member (ostracod-bearing facies) with a regressive facies shift to clastic deposits.

**Pre-Aruma Unconformity and Pre-Aruma Bauxite**

Starting from the Middle Turonian, and continuing throughout the Coniacian, Santonian and Early Campanian times (i.e. a period of nearly 20 million years), a regional hiatus developed over Central Saudi Arabia (Figure 21). It was caused by the regional eastward-tilting of the Arabian Plate due to loading by obducted ophiolites along the Neo-Tethys margin (eastwards along the Zagros Suture and southeast by the Semail Ophiolite). The pre-Aruma Bauxite formed during this period of subaerial exposure, and it is capped-by or locally overlain by reworked pebbles in the first beds of the Aruma Formation. This relationship provides supporting evidence for the pre-Aruma erosional edge (Murris, 1980; Koop and Stonely, 1982; Ziegler, 2001, his Figure 16) that was unconformably onlapped by Coniacian-Maastrichtian open-marine carbonates.

**Khanasir Member, Aruma Formation**

The Aruma Formation, in central Saudi Arabia outcrops, consists of the Khanasir, Hajajah and Lina members. The Khanasir Member was interpreted as Aruma Sequence 1 by Philip et al. (2002). The age of the lower part of the Khanasir Member was incorrectly interpreted as Early Coniacian by El Asa’ad (1983a,b). Sharland et al. (2001, see their Table 4.106) adopted this age and wrongly positioned their Coniacian MFS K150 at the base of the Khanasir Member. However, this does not invalidate other identifications of Sharland et al.’s MFS K150 elsewhere on the Arabian Plate. The correct age of the Khanasir Member was determined in the Ar Riyadh quadrangle (Vaslet et al., 1991).
where ammonites found in its basal part have been identified as *Sphenodiscus [Libycoceras] acutodorsatus* Noetling of latest Campanian-Early Maastrichtian age (Le Nindre et al., 1990, 1991). In the Az Zabirah South Zone and North Qibah (Figure 8), ammonites identified as *Sphenodiscus* sp. have also been found at the base of the Aruma Formation.

In addition to the ammonite fauna, the nannoflora recovered from the Khanasir Member support a Late Campanian to Maastrichtian age. Hélène Manivit (written communication, 1989, in Le Nindre et al., 1990) identified the following association, which characterizes the NC20 (*Tetralithus trifidus*) and NC21 (*Arkangelskiella cymbiformis*) biozones (latest Campanian to early Middle Maastrichtian): *Micula staurophora* (Gardet) 1963; *Ceratolithoides aculeus* (Prins and Sissingh) 1977; *Micula cf. concava* (Stradner) Verbeek 1976; *Quadrum gothicum* (P. Prins and Perch-Nielsen) 1977; *Calculites obscurus* (De Flandre) Prins and Perch-Nielsen 1977; *Lucianorhabdus Cayeuxi* (Stradner) Prins and Perch-Nielsen 1977; *Lucianorhabdus Cayeuxi* (De Flandre) Vekshina 1959; and *Quadrum trifidum* (Stradner) Prins and Perch-Nielsen 1977. The nannoplankton contains the following species: *Reinhardtites anthophorus*, *Lucianorhabdus Cayeuxi*, *Calculithes obscurus*, *Watznaueria biporta* and *W. barnesae*, none of which indicates a precise age.

The age of the middle part of the Khanasir Member was also incorrectly interpreted by El Asa’ad (1983a,b) as Santonian. Sharland et al. (2001, see their Table 4.108) incorrectly adopted this age to position Santonian MFS 160 in the middle part of the Khanasir Member (this does not invalidate other identifications of Sharland et al.’s MFS K160 elsewhere on the Arabian Plate). The middle part of the Khanasir Member is of early Late Maastrichtian age (zone NC 21, *Arkhangelskiella cymbiformis*, Le Nindre et al., 1990; Philip et al., 2002).

**Hajajah Member, Aruma Formation**

Above the Khanasir Member, the Hajajah Member was interpreted as Aruma Sequences 2 and 3 by Philip et al. (2002). It has been correlated lithostratigraphically to the Simsima Formation in Oman and the United Arab Emirates (Philip et al., 2002), and the Tayarat Formation in Iraq. The middle part of the Hajajah Member was previously interpreted as Middle Campanian...
(El-Asa’ad, 1983a, b), and Sharland et al. (2001) therefore positioned their Middle Campanian MFS K170 in it. The Hajajah Member, however, was redated as latest Maastrichtian (zone NC23, Micula murus, H. Manivit, written communication, 1989, in Le Nindre et al., 1990) thus invalidating Sharland et al.’s MFS position for the Hajajah Member. The Middle Campanian MFS K170 could, however, be preserved in erosional troughs in units that are older than the Khanasir Member. The ammonite fauna found to the north of Riyadh do not belong to the Sphenodiscus genus (El Asa’ad, 1983a,b), and could represent older localized deposits of possible Middle Campanian age.

**Lina Member, Aruma Formation**

The base of the Lina Member of the Aruma Formation was previously dated as Middle Maastrichtian, but was re-assigned by Le Nindre et al. (1990) to the first Tertiary TA1 sequence (Haq et al., 1988) and is now dated as Paleocene (Thomas et al., 1999; Philip et al., 2002). The fauna of marine vertebrates found by Thomas et al. (1999), *- a dozen selachian and actinopterygian fishes, as well as a giant sea turtle representing a new dermochelyid taxon -* ranges from Late Paleocene to Early Eocene age. In addition, the neritid *Velates aff. tibeticus*, from the base of the Lina Member (C. Cavelier, in Vaslet et al., 1991) is only known from the basal Eocene. The Lina Member is overlain by the Upper Paleocene and Lower Eocene Umm Er Radhuma Formation (Powers, 1968). The boundary is placed at the sharp contact between aphanitic limestone and sparry dolomite above, and the fossiliferous shales and limestone, below, with only a “possible disconformity” (Powers, 1968).

Sharland et al. (2001, their Table 4.112) incorrectly positioned Middle Maastrichtian MFS K180 in the Lina Member. Philip et al. (2002, see their Figure 2) moved the position of MFS K180 to near the top of the latest Maastrichtian Hajajah Member (MFS of Aruma 3 Sequence). However, according to these authors the upper part of the underlying Khanasir Member is also Late Maastrichtian (NC22–NC23 nannoflora zones). Because MFS K180 is dated as Middle Maastrichtian (rather than Late Maastrichtian) it would correspond to the transgression of the Khanasir Member. The Lina Member represents the Pg10 flooding (Sharland et al., 2001, their table 4.114) and corresponds to the shale member at the base of the Umm er Radhuma Formation in their plate-wide correlation. Therefore the major unconformity lies between the late Maastrichtian Hajajah member and the late Paleocene-Lower Eocene Lina Member and the Lina Member would represent the most basal deposit of the Umm er Radhuma Formation.

**CONCLUSIONS**

The succession representing the late Early Cretaceous to Early Paleocene was mapped in outcrop in central Saudi Arabia in terms of seven formations (Table 1): (1) Late Valanginian? to Early Aptian Biyadh Sandstone, (2) Aptian (Late?) and/or earliest Albian? Sallah Formation; (3) Albian Huraysan Formation; (4) Late Albian and Cenomanian Majma Formation; (5) Cenomanian Qibah Formation; (6) Late Cenomanian to Early Turonian Malihah Formation; and (7) Late Cenomanian to Early Paleocene Aruma Formation. The first three formations were previously considered members of the “Biyadh Sandstone”, and the following three were members of the “Wasia Formation”. This historical nomenclature has resulted in a significant miscorrelation with the same-named Biyadh Sandstone and Wasia formations in subsurface Saudi Arabia. The miscorrelation not only masked the regional stratigraphic architecture of most of the lower and middle Cretaceous, but more crucially, it miscorrelated the Late Albian pre-Majma unconformity to the much older (Late Aptian or Early Albian?) pre-Wasia unconformity.

Following previous studies, three more regional unconformities were recognized: (1) pre-Biyadh unconformity of probable Late Valanginian? and/or Hauterivian? age; (2) pre-Aruma unconformity of Late Turonian through Middle Campanian age; and (3) “intra-Aruma” or “pre Umm er Radhuma” unconformity separating the Upper Maastrichtian Hajajah Member (Aruma Formation) from the Upper Paleocene and Lower Eocene Lina Member (Aruma Formation) and Umm Er Radhuma Formation. The seven formations were interpreted in terms of transgressive-regressive sequences (Figure 21 and Table 2), some of which contain maximum flooding intervals that can be approximately correlated (with repositioning) to the maximum flooding surfaces of the Arabian Plate (Sharland et al., 2001). A more conclusive correlation across the Arabian Plate is not considered possible without more definitive biostratigraphic data and additional subsurface geological and seismic data.
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### Lithostratigraphy and Sedimentology

#### Legend of Symbols
- **Legend of Symbols**

### Lithology

#### Formation
- **Biyadh Sandstone**
- **Sallah Formation**
- **Huraysan Formation**

#### Age
- **Hauterivian-Barremian**
- **Aptian**
- **Albian**

### Description

| Formation         | Age      | Lithology                                                                 |
|-------------------|----------|---------------------------------------------------------------------------|
| Biyadh Sandstone  | Hauterivian-Barremian | Very coarse or graded medium-fine-grained sandstone |
| Sallah Formation  | Aptian   | Fine-grained sorted sandstone, silt, medium-grained                         |
| Huraysan Formation| Albian   | Coarse-grained, poorly sorted, subrounded sandstone                        |

### Sedimentary Structures

#### Fig. 2
- **N120**
- **N310**
- **N45**
- **N40**
- **N115**

### Other Information

- **Trough megaripples**
- **Laminated/warved, beds**
- **Lags and foresets**
- **Graded bedding, troughs**
- **Flat stratification, troughs**
- **Metric megaripples, bars**
- **Mega-ripples**
- **Low angle foresets**
- **Amygdaloid**
- **Red clay, silt, rare polished cemented sandstone**
- **Clay, cover of ferrugineous sandstone**

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*Note: The table and diagram contain complex geological and sedimentological information. The page also includes references and additional data not fully transcribed here.*