Devonian Jauf Formation, Saudi Arabia: Orbital Second-order Depositional Sequence 28

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ABSTRACT

The Devonian Jauf Formation (Huj Group) forms part of a regional transgressive-regressive depositional sequence that extends more than 1,500 km across the Arabian Platform from the Al Jawf outcrops in northwest Saudi Arabia, to the subsurface of eastern Saudi Arabia and Oman (Misfar Group). The formation ranges in thickness from 200–335 m in eastern Saudi Arabia to about 300–330 m in northwest Saudi Arabia. It disconformably (?) unconformably overlies the continental to shallow-marine Tawil Formation, and is unconformably overlain by the continental Jubah Formation. The Jauf Formation consists of five members that are apparently conformable; from base-up: Sha’iba Shale, Qasr Limestone, Subbat Shale, Hammamiyat Limestone and Murayr. In the Al-Qalibah reference section, it is divided into 21 informal units. The Early Devonian Emsian Hammamiyat Member represents the main marine flooding event; it consists of Hammamiyat units 1–6 each characterized by a clastic section that is capped by limestone.

The Jauf Formation is interpreted as an orbital second-order depositional sequence (denoted DS² 28), which is bounded by two second-order sequence boundaries: SB² 28 = Jauf/Tawil (c. 407.6 Ma) and SB² 27 = Jubah/Jauf (c. 393.0 Ma). The Jauf Formation appears to consist of six third-order depositional sequences (DS³ 28.1 to 28.6) that were deposited in the Early Devonian, ?Pragian and Emsian stages. The Hammamiyat Member (DS³ 28.4) is interpreted to consist of six fourth-order orbital cycles (DS⁴ 28.4.1 to 28.4.6) each deposited in 0.405 million years.

INTRODUCTION

The Devonian Jauf Formation crops out in northwestern Saudi Arabia (Powers et al., 1966; Powers, 1968), and was mapped in several quadrangles by the Saudi Arabian DMMR (now Saudi Geological Survey, SGS), the French Geological Survey (BRGM) and the United States Geological Survey (USGS). Some of the quadrangles where the formation is described in the Explantory Notes of maps (Figure 1) include: Baq’a (Vaslet et al., 1987), Ash Shuwahitiyah (Wallace et al., 1996), Al Jawf (Wallace et al., 1997), Al Qalibah (Janjou et al., 1997a), Tabuk (Janjou et al., 1997b) and Turubah (Lebret et al., 1999). The Jauf Formation in outcrop was also studied by Helal (1965), Bahafzallah et al. (1981), Al-Laboun (1982, 1986), Boucot et al. (1989) and Forey et al. (1992).

The Jauf Formation is also recognized in the subsurface in eastern Saudi Arabia (Wender et al., 1998; Al-Hajri et al., 1999, Rahmani et al., 2002; Rutty et al., 2002; Rahmani, 2004), and correlated to the Misfar Group in Oman (Hughes Clark, 1988). Over many structures and paleo-highlands the formation is absent due to Late Paleozoic uplift and erosion (Wender et al., 1998; Konert et al., 2001). In eastern Saudi Arabia, the Jauf Formation contains significant non-associated gas accumulations in stratigraphic traps along the eastern flanks of the Ghawar field (Al-Husseini, 1992; Wender et al., 1998; Carrigan et al., 1998; Al-Hajri et al., 1999). It is also reported to contain oil and gas/condensate in other fields in the Arabian Gulf region (Wender et al., 1997; Konert et al., 2001), and considered an exploration target in Oman (Al-Siyabi et al., 2001).

On the basis of a simplified orbital-forcing model of sea-level, Al-Husseini and Matthews (2005) calibrated a periodic second-order sequence stratigraphic framework for the Arabian Phanerozoic succession. In this framework (AROS: Arabian Orbital Stratigraphy), each second-order depositional sequence (denoted DS²) was deposited during a constant period of approximately 14.58 million years (my). The Jauf Formation corresponds to the 28th sequence (DS² 28) and was deposited between...
second-order sequence boundaries (denoted SB²) that coincide with the Jauf Formation/Tawil Sandstone Boundary (SB² 28 at 407.6 Ma) and Jubah Formation/Jauf Formation (SB² 27 at 393.0 Ma). To further support this interpretation, this paper attempts to determine if the stratigraphic architecture of the Jauf Formation reflects the predicted aspects of a DS². Specifically, the signature that we seek consists of the following general criteria (Figure 2).

1. The sequence is bounded by two regional stratigraphic discontinuities (disconformity, unconformity, major time hiatus) that are not associated with tectonism.
2. The two SB²s occurred approximately 14.58 million years apart.
3. Units within the DS² are conformable; i.e. separated by third-, fourth- and higher-order sequence boundaries.
4. The DS² may be interpreted in terms of no more than six third-order sequences that lasted either 2.025 my (short); 2.430 my (nominal) or 2.835 my (long), and abbreviated as 2.43 ± .405 my. In some cases two third-order sequences may form a double third-order sequence (4.86 = 2 x 2.43 my).
5. Some third-order sequences may be interpreted in terms of 5, 6 or 7 fourth-order sequences (0.405 my).

Before seeking this orbital signature, the paper reviews the stratigraphy of the Jauf Formation in a lexicon-style format. All the material presented in this review is taken from other publications, many of which are not generally well known.
DEFINITION OF THE JAUF FORMATION, HUJ GROUP

Nomenclature and Authors. The Jauf Formation was named by E.L. Berg et al. (1944, unpublished report, in Powers et al., 1966) after the town of Al Jawf (29°49'N, 39°52'E). It was originally defined by generalized section measurements in the vicinity of Al ‘Abd syncline, 15 km northwest of Al Jawf, but detailed plane-table mapping by A.F. Pocock et al. (1950, unpublished report, in Powers et al., 1966) resulted in improved measurement and description. To obtain a complete succession, Pocock et al. pieced together 10 isolated sections within a 30-km radius north and west of Al Jawf (Dawmat al Jandal in the northcentral part of the Al Jawf quadrangle. The resulting composite was adopted as the type section by Steineke et al. (1958). The type locality remains as published except for the addition of 27.1 m of calcareous shale and sandstone at the top. These beds were previously considered to pertain to the middle Cretaceous Wasia Formation, but the discovery of Devonian microflora resulted in their assignment to the Jauf Formation (Powers, 1968).

Members and Group. The Jawf Formation consists of five members, from base up: Sha’iba Shale, Qasr Limestone, Subbat Shale, Hammamiyat Limestone (Powers et al., 1966; Powers, 1968), and Murayr (DMMR, USGS and BRGM authors). The Jauf Formation and its lower four members have no synonyms; the Murayr Member was previously named the “transition zone member” (Pocock et al., 1950, unpublished report, in Powers, 1968) or the Fiy’adh member (Al-Hajri et al., 1999). The Tawil, Jauf, and Jubah formations constitute the Huj Group (Janjou et al., 1997a; DMMR-USGS-BRGM).

Thickness. Powers (1968) recognized a thickness of 299.2 m for the Jauf Formation in the type section. Other estimates for its thickness in the Al Jawf quadrangle are: 300–330 m (Helal, 1965), 330.2 m (Wallace et al., 1997), and on a regional scale about 270 m thick (Boucot et al., 1989). In the Baq’a quadrangle (Figure 1), the thickness of the Jauf Formation is 185 m at Ash Shu’aybah (Powers, 1968), and 163 m at Al Mayyah (Vaslet et al., 1987). In the Al Qalibah (Janjou et al., 1997a) and Ash Shuwahitiyah (Wallace et al., 1996) quadrangles, it is 307 m and 233.5 m thick, respectively. In the subsurface of eastern Saudi Arabia, near the Ghawar field, the formation increases from 200 to 335 m from west to east (Rahmani et al., 2002).

Lower Boundary and Underlying Formation. According to Powers (1968), the contact between the Jauf Formation and underlying Tawil Formation is conformable, and placed at the sharp change from lower Jauf shale and silty limestone, to crossbedded Tawil sandstones. Powers noted that evidence of discordance is lacking although the shift from continental (Tawil) to marine (Jauf) sedimentation would presumably involve a hiatus.

Wallace et al. (1997) state that in the Al Jawf quadrangle the base of the Sha’iba Member has no obvious angular discordance with the underlying beds of the Tawil Formation. They add that as the Juraniyat Member of the Tawil Formation varies in thickness below the Jauf, the contact is likely to be a disconformity. Wallace et al. (1996) note that southwest of the Ash Shuwayhtiyah quadrangle, the Sha’iba Member overlies the Tufayhah Member of the Tawil (next-older member of the Tawil), which suggests the contact is unconformable.

D. Janjou and Y.-M. le Nindre (2005, written communication) emphasize that the Jauf/Tawil Boundary is not an angular unconformity. In the Al Qalibah quadrangle (Janjou et al., 1997a), the Jauf Formation overlies the Tawil Formation in apparent disconformity. In the Baq’a quadrangle (Vaslet et al., 1987), the lower contact of the Jauf Formation is sharp and marked by a reworking of the paleosol capping the underlying Tawil Formation. Vaslet et al. (1997) noted that there is no evidence of a disconformity within this quadrangle. Similarly, Al-Hajri et al. (1999) described the contacts between the Tawil and Jauf formations as apparently conformable.

Upper Boundary and Overlying Formation. According to Al-Hajri et al. (1999), the contacts between the Jauf and Jubah formations appears to be conformable. In outcrop, where the Devonian Jubah Formation is recognized, the contact of the top of the Murayr Member (youngest member of the Jauf Formation) and the Jubah Formation is sharp (Wallace et al., 1997). In the Ash Shuwahitiyah quadrangle (Wallace et al., 1996), the Murayr shale beds are unconformably overlain by Jubah sandstone beds.
In the Al Qalibah quadrangle (Janjou et al., 1997a), the Jubah Formation forms a bench of rusty brown sandstone about 20 m thick that caps the pinkish-beige sandstone of the Murayr Member. The mapped contact is also a major sedimentologic boundary between the Murayr tidal sandstone and the Jubah fluviatile sandstone, and reflects an abrupt change in the sedimentary environment. The contact is erosional cutting into the Murayr clayey siltstone.

**Intra-Jauf Boundaries.** According to Wallace et al. (1996, 1997), the five members of the Jauf Formation constitute a conformable succession. The Murayr/Hammamiyat Boundary is described as sharp and probably conformable.

**Regional Extent.** The Jauf Formation of northwest and eastern Saudi Arabia is correlated to the Misfar Group (F.J. Winkler, 1975 as Misfar Formation; in Hughes Clark, 1988) in south-central Oman; a region of approximately 1,500 km in extent. The Misfar Group is separated by hiatuses from the early Silurian Sahmah Formation and Carboniferous Haushi Group (and possibly older Devonian-Carboniferous unnamed units). The Misfar Group/Formation consists of a sequence of shales, quartzose sandstones and sandy limestones (Hughes Clark, 1988), and is informally divided into five members (Al-Siyabi et al., 2001). The limestones contain ostracods of limited diversity and stromatolite-like structures, and suggest marine settings (Hughes Clark, 1988). The fine clastics contain palynomorphs that indicate terrestrial environments and an age close to the Middle/Early Devonian Boundary (late Emsian-early Eifelian, Hughes Clark, 1988; Al-Siyabi et al., 2001).

**LITHOSTRATIGRAPHY**

The type sections of the lower four members of the Jauf Formation are located in the Al Jawf quadrangle (Powers, 1968; Wallace et al., 1996). The Murayr Member is defined in Ash Shuwahitiyah quadrangle (Wallace et al., 1997). This section reviews the lithostratigraphy of the type sections of the members as well as the Al Qalibah reference section (Janjou et al., 1996) shown in Figure 2.

**Sha’iba Shale Member, Jauf Formation**

**Al Jawf quadrangle** (from Wallace et al., 1997). The type locality of the Sha’iba Member is in the vicinity of Barqa Shaybah (6 km northwest of Dawmat al Jandal) in the Al Jawf quadrangle (Figure 1). The thickness of the member in this quadrangle is variably reported: c. 50 m (Helal, 1965), 33.6 m (Powers, 1968), c. 17 m (Bahafzallah et al., 1981), c. 33 m (Boucot et al., 1989) and c. 50 (Wallace et al., 1997).

According to Wallace et al. (1996, 1997), the Sha’iba Member consists of grayish-green, gray, and grayish-red shale, grayish-pink and grayish-green calcareous and argillaceous siltstone, and lesser amounts of interbedded reddish-gray sandstone and gray and grayish-red argillaceous limestone. Secondary gypsum occurs in veins in the shale. A calcareous sandstone bed near the base of the member contains fragments of fish bones, phosphatic pebbles, and vertical animal burrows; the $P_2O_5$ concentration of this sandstone is 4.6%. Near the base there is also a 2–4 cm-thick bed of moderate-gray chert. Sandstone beds are thickest near the top of the member where several beds of crossbedded sandstone range from 0.5–1.0 m in thickness. At several places in the Al Jawf quadrangle, rare beds of gray laminated chert are interbedded with shale and sandstone.

**Al Qalibah quadrangle** (from Janjou et al., 1997a; Figure 2). In the Al Qalibah quadrangle the Sha’iba Shale Member is about 25 to 27 m thick in the reference section (base at 28°58’49”N, 38°18’07”N, top at 28°58’24”, 38°19’15”E), and it is represented by four units, from the base up:

**Sha’iba unit 1** (1.1 m thick). Above a paleosol in the Tawil Formation, a 30-cm-thick bed of oolitic ironstone, overlain by a heterolithic clayey-arenilitic and dolomitic layer that has wavy bedding and is 80 cm thick. Bioturbated carbonate lenses, several centimeters thick, contain a sandwich-like structure that has ghosts of gypsum crystals, and alternates with banded siltstone of violet, pink, or yellow-ocher color.
Jauf Formation, Huj Group, Al Qalibah Quadrangle

| STRATIGRAPHY | LITHOLOGY | ARABIAN ORBITAL STRATIGRAPHY (Ma) |
|--------------|-----------|----------------------------------|
| Tawil Fm     | Brown, orange-red, fine-grained sandstone with planar cross-stratification; overlies brown fine-grained sandstone with trough cross-stratification. | DS^2 27 |
|              | Beige, fine to medium-grained sandstone with trough cross-stratification and inclined sigmoid stratification; in situ Protatixes. | Relative Sea level |
|              | Alternations of beige fine-grained sandstone and pink dolomite sandstone; clayey dolomite marker layer. | SB^2 27 |
|              | Fining-up sequences of beige silty sandstone, clayey sandstone and green claystone; heterolithic stratification. Basal reworked layer. | SB^3 28.6 |
|              | Fining-up sequences of fine-grained sandstone; inclined and hummocky cross-stratification; stromatolitic dolomite at top. | DS^4 28.4.6 |
|              | Fine-grained sandstone with sigmoid stratification; stromatolitic dolosilite at top. | DS^4 28.4.5 |
|              | Interbedded green bioturbated claystone and bioturbated dolomite with heterolithic stratification. | DS^4 28.4.4 |
|              | Green claystone with sandstone base; stromatolitic limestone at top. | DS^4 28.4.3 |
|              | Yellow or blue-gray massive dolomite limestone; brecciated at base. | DS^4 28.4.2 |
|              | Fish debris Protatixes | DS^4 28.4.1 |
|              | Brown to green claystone interbedded with fine- to coarse-grained glauconitic sandstone. | SB^3 28.4 |
|              | Green, blue and red silty claystone interbedded with thin beds of dolomitic stromatolitic limestone and medium-grained sandstone. | SB^3 28.3 |
|              | Green to blue claystone interbedded with fine to medium grained cross-beded sandstone and thin beds of dolomitic limestone; coarsening and thickening-up sequences. Dolitic ironstone and paleosol at base. | SB^3 28.2 |
|              | Jurassic Member, Tawil Formation, Huj Group | MFI^1 28 |
|              | Jurassic Member, Tawil Formation, Huj Group | DS^2 28.1 |
|              | Jurassic Member, Tawil Formation, Huj Group | DS^2 28 |
|              | Jurassic Member, Tawil Formation, Huj Group | DS^2 29 |

Figure 2: Reference section of the Jauf Formation, Huj Group, Al Qalibah quadrangle (modified after Janjou et al., 1997a). The Jauf Formation consists of five formal members in Saudi Arabia, and 21 informal units in the Al Qalibah quadrangle. It disconformably (?)unconformably) overlies the Tawil Formation, and is unconformably overlain by the Jubah Formation. The Jauf Formation is interpreted as second-order depositional sequence DS^2 28 that is bounded by SB^2 28 (407.6 Ma) = Jauf/Tawil and SB^2 27 (393.0 Ma) = Jubah/Jauf (Al-Husseini and Matthews, 2005). Biostratigraphic dating approximately places the Jauf/Jauf transition at late Emsian-early Eifelian and the lower Jubah at late Eifelian (Al-Hajri et al., 1999; see Figure 3). The biostratigraphic age of the Jauf/Tawil transition varies considerably in the literature and ranges from Lower Lockovian-Pragian to Emsian (see Figures 3 and 4). The Jauf Formation manifests several aspects of a model DS^2 including six possible third-order cycles (DS^3 28.1 to 28.6) that are separated by five third-order sequence boundaries (SB^3 28.2 to 28.6). The Hammamiyat Member contains the maximum flooding interval (MFI 28 in Hammamiyat unit 2). It forms a `nominal` third-order sequence (Matthews and Frohlich, 2002), denoted DS^2 28.4, that consists of six fourth-order sequences (DS^2 28.4.1 to 28.4.6 = Hammamiyat units 1-6), each deposited in 0.405 million years.
Sha’iba unit 2 (13 m thick). A coarsening- and thickening-upward sequence, of green or blue claystone at the base, overlain by variably dolomitic, fine-grained sandstone that has ripple bedding or trough cross-stratification. The sandstone contains reworked debris of fish, crustaceans, and lingulid shells. Some beds are overlain by thin, gray-blue, dolomitic limestone layers c. 1 cm thick.

Sha’iba unit 3 (4.5 m thick). A pale-brown sandstone body, having a slightly channeled erosional base, sigmoid cross-stratification, clayey bottom sets, and clay drapes over the sets of laminae. Current directions are toward the east and north-northwest. The top of the sandstone is bioturbated and truncated by a channeling surface that marks the base of a 20-cm-thick layer of planar-laminated medium-grained sandstone.

Sha’iba unit 4 (8 m thick). A coarsening- and thickening-upward sequence that begins with 2 m of claystone in which are intercalated several dolomitic limestone beds that have wave ripples, shrinkage cracks, and lingulid debris. The claystone is overlain by a composite sandstone unit, 6-m-thick, composed of homogeneous sandstone (1 m), and a heterolithic facies of alternating 1–10-cm-thick beds of green slightly bioturbated silty claystone, and fine-grained sandstone with wave ripples, sigmoidal megaripple bedding, and planar to wavy lamination. Ball-and-pillow structures are present, together with cross-stratified sandstone beds that contain abundant reworked fish debris.

Qasr Limestone Member, Jauf Formation

Al Jawf quadrangles (from Wallace et al., 1997). The type locality of the Qasr Limestone Member is at the fort in Dawmat al Jandal, Al Jawf quadrangle, where Powers (1968) attributed an 18.8 m thickness to the member. Wallace et al. (1997) measured a thickness of 16.2 m, Bahafzallah et al. (1981) of 13.4 m, and Boucot et al. (1989) of 18.8 m. In the type section, the Qasr Limestone consists mostly of gray and grayish-green shale, light-grayish-brown, gray, and yellowish-gray, argillaceous and silty, thinly bedded limestone, and thin interbeds of reddish-gray, medium-grained sandstone. In some places, the base of the Qasr is marked by a prominent dolomite-cemented reddish-gray, crossbedded sandstone that contains abundant fish bone fragments; but in other places this distinctive sandstone bed is absent and the base is marked by a stromatolitic limestone that is 0.5–1.0 m thick. Sandstone and shale interbeds in the member contain abundant burrows. The abundance of limestone beds increases upward and dolomitic limestone beds, prominent stromatolites, and bioclastic beds that consist of brachiopod coquina and oncolites are common in the uppermost part. A stromatolitic limestone marks the top of the Qasr; in most places this bed is about 1 m thick, but in the area of Dawmat al Jandal this prominent stromatolite zone is 3–4 m thick, and stromatolite mounds are as much as 1–2 m in height and as much as 5–6 m in diameter.

Al Qalibah quadrangle (from Janjou et al., 1997a; Figure 2). In the reference section (base of section at 28°58’24”N, 38°19’15”E, top at 28°59’52”N, 38°18’48”E), the Qasr Limestone (24 m thick) is composed of green, blue, or red silty claystone within which a few beds of stromatolitic dolomitic limestone and sandstone are intercalated. The lithologic succession, from the base up is:

Qasr unit 1 (4 m thick). Green to blue, silty claystone incorporating several beds of dolomicrite that have cryptalgal lamination, in places with an interbrecciate structure, and decimeter-thick beds of medium-grained, planar-laminated sandstone. The sandstone contains debris of lingulids, fish, and crustaceans, together with some serpulids and solitary corals. The claystone forms small meter-high cuestas capped by beds of dolomite or sandstone that are 0.5–1 m thick.

Qasr unit 2 (13.5 m thick). Green, yellow, or red, silty claystone that contains a few decimeter-thick beds of pale-yellow sandstone and white dolomicrite having cryptalgal lamination or an interbrecciate structure. The unit forms a cuesta 13.0 m high capped by stromatolitic limestone 50 cm thick.

Qasr unit 3 (6.5 m thick). Green or blue, silty claystone that contains several beds of dolomicrite and stromatolitic limestone, together with some reworked layers of algal debris.
Subbat Shale Member, Jauf Formation

Al Jawf quadrangle (from Wallace et al., 1997). The type locality for the Subbat Shale Member is located near the gardens of Subbat al Wadi near Dawmat al Jandal. Estimates of the thickness are 113.4 m (Powers, 1968), 100 m (Helal, 1965) and c, 113 m (Boucot et al., 1989). According to Wallace et al. (1997), the Subbat Shale Member is grayish-red, grayish-pink, maroon, greenish-gray, and grayish-green shale that contains detrital mica on bedding surfaces. Shale is silty and secondary gypsum veins are common. Interbedded grayish-red, gray, and reddish-gray sandstone beds range from several centimeters to 2 m in thickness. Near the top of the Subbat Member, a prominent reddish-tan-weathering ripple-marked sandstone is about 2 m thick.

Al Qalibah quadrangle (from Janjou et al., 1997a; Figure 2). In the reference section (base at 28°59'52" N., 38°18'48" E., top at 28°59'40" N., 38°19'04" E.), the Subbat Shale Member is about 92–94 m thick. The Subbat Shale Member is principally composed of claystone and micaceous siltstone, within which are intercalated several layers of fine- to medium-grained sandstone between a decimeter and several meters thick. The member crops out in the main cuesta of the Al Huj massif and is capped by the first carbonate bench of the Hammamiyat Limestone Member. The lithologic succession from the base up is:

Subbat unit 1 (16 m thick). Meter-thick, coarsening-upward sequences of green-blue, brown, or white claystone and of pale-beige or rusty-brown, fine- to coarse-grained, slightly clayey sandstone having indistinct planar bedding and rare trough cross-stratification. The clay content decreases upward.

Subbat unit 2 (19 m thick). Green or brown claystone that contains some decimeter-thick beds of green, fine-grained, glauconitic sandstone.

Subbat unit 3 (27 m thick). Beige or pale-green, fine-grained, silty sandstone having slightly wavy horizontal or flaser bedding, passing upward into pale-green, glauconitic siltstone with planar laminae. These facies are arranged in fining-upward sequences 3–5 m thick. In the most-massive sandstone beds (several meters thick), inclined sets define decimeter-scale channels that are locally incised by vertical burrows (tigliilites).

Subbat unit 4 (32 m thick). A fining-upward sequence of pale-yellow, fine-grained sandstone and glauconitic clayey siltstone. The base of the unit is marked by a reworked layer containing fish debris and clayey chips. In the lower 10 m, the sandstone has large-scale tangential cross-beds. Above this unit, mottled (flaser) bedding or sigmoid megaripples with clay drapes indicate a north-northwestward current direction. The m-thick sandstone layers form fining-upward sequences (increasing clay content) that in places are combined to form benches several meters thick. In the top few meters, siltstone contains several centimeter-thick beds of burrowed, fine-grained sandstone and a layer of brecciated gypsum 10 cm thick.

Hammamiyat Limestone Member, Jauf Formation

Al Jawf quadrangle (from Wallace et al., 1997). The type locality of this member is near Wadi al Murayr along the northern rim of the Al Jawf region (Powers, 1968). The member was named for Jibal al Hammamiyat northeast of Dawmat al Jandal and the spelling was changed to Hammamiyat by Powers (1968). The estimated thickness at the type locality is 106.3 m (Powers, 1968) or 105 m (Boucot et al. (1989). The Hammamiyat is about 118 m thick near Dawmat al Jandal (Helal, 1965). Wallace et al. (1997) measured the average thickness of the member in the Al Jawf and Ash Shuwayhitiyah quadrangles as 118 and 75 m respectively.

At the base of the Hammamiyat is a zone of moderate gray-, tan-, or light-grayish-yellow-weathering,stromatolitic, finely crystalline limestone interbedded with shale. Helal (1965) and Boucot et al. (1989) described six limestone zones that range from 4–11 m in thickness, which are separated by light-gray, grayish-brown, and yellowish-brown shale and rare beds of gray, fine-grained sandstone. Stromatolites are as much as one meter in diameter and occur as laterally linked hemispheroids and...
as isolated heads that are 10–20 cm in diameter. The limestone beds form cliffs and laterally extensive
dip slopes. Shale beds contain primary gypsum in thin layers and secondary gypsum fills fractures
and joints.

**Al Qalibah quadrangle** (from Janjou et al., 1997a; Figure 2). In the reference section (base and top of
section at 28°58’06”N, 38°20’35”E), the member is about 88 m thick. The Hammamiyat Limestone
Member is a mixed sandstone, claystone, and carbonate sequence that has great facies diversity; the
lithologic succession from base up is:

**Hammamiyat unit 1** (8 m thick). Yellow or gray-blue, dolomitic limestone in beds 0.5–2 m thick,
forming a topographic bench-like unit 8-m-thick. At the base, a brecciated dolomitic limestone is
overlain by dolosiltite or fine-grained dolarenite having planar or wavy laminations, swaley cross-
stratification, slumped laminations, and ball-and-pillow structures. The top 3 m consist of dolomite
with fine cryptalgal laminations and stromatolitic domes having shrinkage cracks. The top of the
bench is more clayey and reflects a transition to the overlying unit.

**Hammamiyat unit 2** (24 m thick). Claystone (15 m) overlain by a 9-m-thick carbonate succession of
individual layers as much as 1 m thick. The lower part of this bench-forming carbonate unit consists
of homogeneous clayey dolostone passing upward into dolostone with planar, wavy, or inclined
laminations, swaley cross-stratification, wave ripples, and ball-and-pillow structures. The internal
erosion surfaces are marked by fine bioclastic residue; shrinkage cracks are present but rare.

**Hammamiyat unit 3** (10 m thick). Green claystone, the base of which shows a channeled body
composed of pale-yellow, bioturbated, medium-grained sandstone containing fish debris. The top of
this unit is marked by a 50-cm-thick limestone bed that contains stromatolitic domes.

**Hammamiyat unit 4** (18 m thick). A unit composed of meter-thick intervals of green claystone, locally
bioturbated, containing several carbonate or sandstone layers as much as 10 cm thick that are rich in
brachiopod, orthocone, and fish debris. The upper third of the unit consists of bioturbated sandstone
layers 10–50 cm thick, that have heterolithic wavy or mottled stratification, including wavy bedding,
flaser bedding with current ripples directed northwestern, and sigmoid inclined stratification with
clay drapes. The top of the unit in outcrop is marked by a heterolithic bench in which beds of fine-
graded sandstone having wavy lamination or wave ripples alternate with centimeter-thick layers of
bioturbated dolomite.

**Hammamiyat unit 5** (11 m thick). Claystone 2.5 m thick, overlain by fining-upward sandstone having
sigmoidally inclined stratification that indicates a N-NW current direction, and by heterolithic
material having wavy bedding. It is overlain by a tidal-bar succession represented by an alternation
of heterolithic facies with cross-ripple stratification (bottomset) and layers of sandstone 20–80-
cm-thick having tangential stratification inclined N-NW. The upper part of the unit is a 4-m-thick
dolosiltite containing planar lamination and current ripples and capped by stromatolitic domes about
1 m in diameter.

**Hammamiyat unit 6** (17 m thick). A fining-upward sequence of fine-grained sandstone that contains
claystone pebbles and large-scale inclined and hummocky cross-stratification that passes upward
into composite inclined stratification and megarripples. The sandstone is overlain by a heterolithic
facies that increases in clay content upward and has inclined stratification, and by green claystone
containing cm-thick beds of fine-grained sandstone. Two layers of wavy-bedded clayey-silty dolomite
and overlain by a stromatolitic structure, form the top of the unit.

**Murayr Member, Jauf Formation**

**Ash Shuwayhitiyah quadrangle** (from Wallace et al., 1996). Based on a review of previous work and
the study by Janjou et al. (1997a), Wallace et al. (1996, 1997) renamed and defined the “transition zone
member” of Powers (1968) (also Fiy’adh member of Al-Hajri et al., 1999) as the Murayr Member of
the Jauf Formation in the type section exposures in Wadi al Murayr (30°04’22”N, 39°56’16”E, about
30 km NNE of Dawmat al Jandal in the Ash Shuwayhitiyah quadrangle). In this quadrangle, the
Murayr Member is 33 m thick and described almost identically as in the Al Jawf quadrangle (see below Wallace et al., 1997). Wallace et al. (1996, 1997) included the sandstone and shale beds of the Murayr Member in the Jauf Formation (rather than to the overlying Jubah Formation) because of their lithologic similarity to those in the underlying Jauf members. Shale and limestone beds occur in the Murayr Member as well as in underlying members of the Jauf Formation, and sandstone and siltstone beds are calcareous throughout the Jauf Formation. These features are not characteristic of the overlying Jubah Formation.

**Al Jawf quadrangle** *(from Wallace et al., 1997)*. The Murayr Member is exposed north and northwest of Dawmat al Jandal and along the northern part of At Tawil. In the reference section in Al Jawf quadrangle, the Murayr is 33 m thick along the northern border but thins near Dawmat al Jandal. Sandstone is light gray and light grayish brown and weathers to reddish brown and grayish brown. Sandstone, siltstone, and shale beds are poorly indurated and weather to moderate-angle rubble-covered slopes. Sandstone is thinly bedded (2–8 cm), and contains ripple cross-lamination, planar lamination, rib-and-furrow structure, and small- and medium-scale crossbeds. Sandstone beds generally coarsen upward and are mostly medium-grained at the base and fine-grained in the upper part of the member; most grains are subangular and subrounded. The sandstone is micaceous and some beds contain fragments of fish bones. The shale and siltstone are light green to light tan, and these fine-grained rocks contain abundant secondary gypsum and one thin bed of chert. A gastropod coquina bed near the top of this unit was first described by Lozej (1983, in Janjou et al., 1997a, b), and although only 2–3 cm thick, it is an easily recognizable marker bed near the top of the Murayr Member. Along the southern border of the quadrangle this coquina marker bed is absent and a yellowish-gray, sandy limestone (20 cm thick) occurs at about the same stratigraphic level below 2-m-thick beds of grayish-green shale. Secondary gypsum occurs as veins in sandstone and shale.

**Al Qalibah quadrangle** *(from Janjou et al., 1997a; Figure 2)*. In the reference section (28°59'21"N, 38°20'52"E), the Murayr Member is about 71.5 to 76.0 m thick. The member is essentially arenilitic, representing a transition from the lagoonal facies that dominate the Jauf Formation to the typically fluviatile facies of the overlying Jubah Formation. The lithologic succession from base-up:

**Murayr unit 1** (10–30 cm thick). A reworked layer that contains fish debris and quartz gravel, marks an irregular channeling surface that slightly incises the stromatolitic limestone at the top of the Hammamiyat Limestone Member.

**Murayr unit 2** (21 m thick). Five fining-upward sequences, each several meters thick, have an erosional base. They consist of the following units: pale-beige, fine-grained, silty-clayey sandstone with inclined hummocky or sigmoid stratification, and clay bundles and drapes; clayey-sandstone having wavy heterolithic stratification or current ripples; and green claystone with silty laminae containing vegetal fragments.

**Murayr unit 3** (13.5 m thick). A clayey-dolomite layer 30 cm thick, overlain by an alternation of beige, fine-grained, and rarely microconglomeratic sandstone, in beds 10–30 cm thick, and of decimeter-thick beds of dolomitic pink sandstone. The base of the sandstone layers has sigmoid inclined stratification and is marked by reworking of fish debris (bone beds) in units as much as 30 cm thick. The sandstones also contain in situ plant fragments of *Prototaxites* sp.

**Murayr unit 4** (47 m thick). Beige or yellow-ocher, medium- or fine-grained sandstone in beds 1-3 m thick, bounded by discontinuous siltstone intervals. The base of the sandstone beds is irregular and marked by siltstone pebbles or reworked fish debris. A hummocky cross-stratification at the base of layers is overlain by sigmoid inclined stratification, clay bundles and drapes. The uppermost part of this homogeneous unit is a 2-m-thick pink, fine-grained sandstone containing siltstone chips, overlain by 2 m of light gray, clayey siltstone that contains fragments of *Prototaxites* sp.

**PALEONTOLOGY AND AGE**

Powers (1968) reported that brachiopods in the upper part of the Jauf Formation, including *Anathyris* and *Rensselaeria*, have been tentatively determined as Early Devonian by G.A. Cooper *(in Powers,
1968). Uppermost beds have yielded ostracode and fish remains. *Knoxiella* and fish dermal scutes considered by R.W. Morris (1960, in Powers, 1968) to be definitely Devonian and probably Early or Middle Devonian. Hemer (1965, 1968, in Powers, 1968) reported that associations of acritarchs and chitinozoans characteristic of the Middle and Late Devonian, were recovered in drill holes.

Bahafzallah et al. (1981) interpreted the age of the upper part of the Hammamiyat Limestone Member as Emsian, mainly on the basis of identification in the lower part of this member, of for example the brachiopod *Hysterolites hystericus* (Schlotheim) accompanying bryozoans, brachiopods, gastropods, bivalves, cephalopods, crinoids, and fish debris of minor stratigraphic interest. They therefore assigned the lower part of the Hammamiyat Member and the earlier Jauf members to the Siegenian (late Lockhovian and early Pragian). They considered the Murayr Member as Middle Devonian because it yielded plant remains such as *Prototaxites laganii* Dawson.

From subsurface samples, McClure (1976, in Al-Laboun, 1982) dated the Jauf Formation as Siegenian (late Lockhovian and early Pragian) to Emsian from the base until the top of the Hammamiyat Limestone Member, and assigned the Murayr Member to the Middle and Late Devonian. Boucot et al. (1989) studied fossils from 14 sites in the Al Jawf region. The samples were mainly from the Qasr and Hammamiyat Limestone members, and Boucot et al. (1989) assigned an Early Devonian (Pragian to early Emsian) age to the Jauf Formation.

Janjou et al. (1997a) in the explanatory notes for the Al Qalibah quadrangle, concluded that the faunas collected from the many fossiliferous layers in the Jauf Formation indicate an age ranging from Lochkovian-Pragian (in the Sha’iba Shale Member) to early to late Emsian (in the Hammamiyat Limestone Member); the Qasr Limestone Member being assigned to the Pragian. They added that none of the vertebrate taxa represented in the Jauf Formation is truly characteristic of the Eifelian, although some of the impressions found in the Murayr Member may indicate a Middle to Late Devonian age.

The following fauna were collected from outcrops in the Al Qalibah quadrangle (Janjou et al. 1997a reference Lelievre et al., 1994, for determinations on the vertebrates; and Gourvennec, 1994, for conodont information):

**Sha’iba Shale Member.** The member yielded brachiopods such as *Lingula* sp. and *Globithyris* cf. *callida* (Clarke), a form known from the Pragian and possibly also the Emsian. Abundant fish debris was also found, consisting of scales and spines of acanthodians (*Gyracanthides* sp., *Onchus* sp., and *Gomphonchus* sp.), remains of Arthrodires, Phlyctaeniiides, and one ichnacanthiform specimen. Preliminary comparison of two of these forms with better-known species from the Lower Devonian of Podolia and Spitsbergen appears to confirm the early Pragian age of these beds.

**Qasr Limestone Member.** The member contains abundant remains of a new species of the placoderm *Acanthoradea*, closely related to the Radotinida and Romundina, as described from the Lochkovian of the Canadian Arctic. Acanthothoracidi are only known in the late Lochkovian and early Pragian, which is consistent with the Pragian age assigned to the Qasr Limestone Member on the basis of conodonts (Boucot et al., 1989). The trilobite *Malladaia macclurei* Struve, noted by Boucot et al. (1989), is also present.

**Subbat Shale Member.** The member contains no invertebrate fossils but one coarse-grained layer yielded rare vertebrate remains, including large spines of acanthodians of the *Onchus* type, and poorly preserved placoderm plates (probably Actinolepides).

**Hammamiyat Limestone Member.** The member is rich in vertebrate and invertebrate fossils, and contains several highly fossiliferous layers that yielded indeteminate brachiopods of the genus *Centronellida* and of the species *Howittia howitti* Chapman (typical of the Emsian), *Fimbrispirifer?* sp., *Hexarhytis campomanes* (Verneuil and Archiac), and *Spinella?* sp. *subspeciosa* (Verneuil). At the base of the member, a layer of saccharoidal sandstone contains remains of chondrichthyans and acanthodians,
associated with large ostracode. The arthrodire plates can be assigned to Actinolepids. Of the many spines collected, a large number are of the Onchus and Gyracanthides type, but some are similar to the chondrichthyan Antarcstilamna, known from the Emsian to Givetian of Gondwana. Higher in the succession, a layer of sandstone with a calcareous cement yielded remains of placoderms, including one large specimen of Rhenanid, a small Petalichthyid similar to Wijdeaspis, Acanthothoracides scales, and two new species of Arthrodires and Eubrachythoracides. These fossil remains are associated with spines and scales of acanthodians and chondrichthyans. Two types of Nostolepis scales are recognized, together with a new species of Cheiracanthoides and spines of Gyracanthides sp., Onchus sp., and "Antarcstilamna".

Murayr Member. Several layers rich in vertebrate remains were discovered that contain spines of acanthodians (Gyracanthides, Onchus) and chondrichthyans, together with non-diplodont teeth of a new species of chondrichthyan. Two impressions of large, incomplete placoderm plates were found in the topmost layers of the Murayr Member: the ornamentation on one is similar to that of Actinolepides and the other is similar either to the arthrodire Holonema or to some species of Antiarche Asterolepides, two taxa known in the Middle to Late Devonian. Fragments of Prototaxites have been collected in place from the base through to the top of the Murayr Member. The remains of vascular plants (Psylophitales?) were found in the clayey layers at the base of the member.

Stump et al. (1995), based on palynological studies by Steemans (1995) and Loboziak and Stree (1995), summarized the ages of the Tawil, Jauf and Jubah formations. They attributed five spore biozones that were recognized by Steemans (1995) from the upper part of the Tawil Formation in central and eastern Saudi Arabia, to a suggested Lockhovian-Pragian age. Stump et al. (1995) added that based on Saudi Aramco data, the Tawil ranges from late Silurian Pridoli to early Emsian. Aoudeh and Al-Hajri (1995, their figure 7), and Al-Hajri and Owens (2000, their figure 2) extended the base of the Tawil Formation to the late Silurian, early Ludlow ( Gorstian Stage), and its top to early Pragian.

Stump et al. (1995) noted that several outcrop and subsurface sections that are considered equivalent to the Jauf Formation have produced primitive Middle to possibly late Early Devonian land plant material that was assigned by C. Hill (1993, unpublished report) to the Orestovia complex of the family Spongiophytaceae. They added that abundant land-plant debris from the Jauf and Jubah formations indicate an Emsian-Frasnian age for these two formations (Loboziak and Stree, 1995).

Al-Hajri et al. (1999; Figure 3) in northwest Saudi Arabia, identified Palynozone D4A assemblages in samples from the lower part of the Jauf Formation and upper part of the underlying Tawil Formation. According to these authors, D4A has an age range of early Pragian to late Emsian. They associated Subzone D3/D4 with the lower part of the Jauf Formation in northwest and eastern Arabia and favor an Emsian age. They associated the Arabia-wide Subzone D3B with the Hammamiyat and possibly the Subbat members, and suggested a likely late Emsian age. In northwest and eastern Arabia, they associated Subzone D3A with the upper Jauf and lower Jubah formations and suggested a late Emsian-early Eifelian age. In both northwest and eastern Saudi Arabia, Palynozone D2 consistently occurs in the lower and middle Jubah Formation, and includes palynoflora recovered from the base of Jubah that is considered late Eifelian.

Al-Ruwaili et al. (2004) reported the results of palynological analysis from samples taken from cores in shallow wells in northern Saudi Arabia. The palynological assemblages are dominated by miospores, with trilete spores dominant and cryptospores rare. Al-Ruwaili et al. characterize the D3B biozone as a sudden bloom of a monospecific leisphaerid that appears to be manifested as an isochronous event (marine transgression) across the Arabian Platform. Al-Ruwaili et al. (2004) report the presence of rare biocstratigraphically valuable miospore taxa that indicate that most of the studied section is Emsian in age. They add that the presence of Retusotriletes regulatus, in the upper part of the sequence suggests an Eifelian age.

The biostratigraphic ages for the Jauf Formation and some of its members suggests the following numerical age ranges (Ma) based on GTS 2004 (Gradstein et al., 2004):
Figure 3: Palynological age dating of the Tawil, Jauf and Jubah formations (Al-Hajri et al., 1999). Palynzone D4A is recognized in the lower part of the Jauf Formation (northwest Saudi Arabia) and upper part of the Tawil Formation (eastern Saudi Arabia) and has a probable Pragian to Emsian age (possibly no younger than mid Emsian). Palynzone D3A spans the lowermost Jubah to upper Jauf formations (in both northwestern and eastern Saudi Arabia), and has a suggested age of late Emsian-earliest Eifelian. Palynzone D2 is recognized in the basal Jubah and is considered late Eifelian. The implied palynological age ranges of the Jauf Formation boundaries are Jauf/Tawil: Pragian-mid Emsian; and Jubah/Jauf: c. Eifelian/Emsian to late Eifelian. Geological time scale GTS 2004 (Gradstein et al., 2004) is shown in million years before present (Ma) with one standard deviation. Kaufman et al. (2005) estimate the age of the Eifelian/Emsian Boundary as 391.8 ± 0.4 Ma which equals the Givetian/Eifelian age of GTS 2004 (indicated with ?) of Gradstein et al. (2004).
**Jauf/Tawil Boundary**: Early Devonian; early Emsian [407.0–403.8 ± 2.8 Ma] (Stump et al., 1995); Lochkovian-Pragian [416.0–407.0 ± 2.8 Ma] or ?early Pragian [411.2–409.8 ± 2.8 Ma] (Janjou et al., 1997a); Pragian to late Emsian [411.2–397.5 ± 2.7 Ma] or possibly no younger than mid Emsian [older than 402.3 Ma] (D4A, Al-Hajri et al., 1999).

**Hammamiyat Member**: Early Devonian; Emsian [407.0 ± 2.8 to 397.5 ± 2.7 Ma] (Bahafzallah et al., 1981; Janjou et al., 1997; Al-Hajri et al., 1999; Al-Ruwaili et al., 2004).

**Murayr Member**: Middle Devonian (Bahafzallah et al., 1981); Middle to Late Devonian (McClure et al., 1976; Janjou et al., 1997); late Emsian-early Eifelian (Al-Hajri et al., 1999). The Murayr/Hammamiyat Boundary appears to approximately coincide with the Middle/Early Devonian Boundary [c. Eifelian/Emsian = 397.5 ± 2.7 Ma].

**Jubah/Jauf Boundary**: Middle/Early Devonian, late Emsian-early Eifelian [397.5 ± 2.7 Ma] (D3A of Al-Hajri et al., 1999); or Middle Devonian, late Eifelian [393.2–391.0 ± 2.7 Ma] (D2 of Al-Hajri et al., 1999).

In Figure 4, the age of the Jauf/Tawil Boundary is shown in terms of several Devonian time scales and biostratigraphic stage assignments. The figure illustrates the great uncertainty associated with estimates for the age of this stratigraphic discontinuity. For example the stage assignment for Jauf/Tawil of early Pragian-mid Emsian (Al-Hajri et al., 1999) implies an age range of 396–386 Ma according to the scale of Harland et al. (1990) compared to 411.2–402.3 Ma according to the geological scale of Gradstein et al. (2004).

**DEPOSITIONAL ENVIRONMENT AND SEQUENCE STRATIGRAPHY**

**Sha’iba Shale Member, Saudi Arabia Outcrop** (from Janjou et al., 1997a, b). The basal Sha’iba was deposited in a transgressive, shallow-marine and nearshore setting of low local relief (Boucot et al., 1989). Siliciclastic lagoonal systems (e.g. confined-marine environment such as a bay-type)
are characterized by claystones and thin sandstone bodies (sand flats) deposited at the mouth of distributary channels under a tidal influence. This environment succeeded fairly abruptly the sandy deltaic system of tidal influence represented by the top units of the Tawil Formation. The basal discontinuity is marked by clayey oolitic ironstone (Sha’iba unit 1, Figure 2) that is interpreted as a transgression surface. Boucot et al. (1989) indicated that near the middle of the Sha’iba Member, a calcareous sandstone bed contains concentrated fragments of fish bones and has a P₂O₅ content of 5.5% (probably Sha’iba unit 2 of Janjou et al.). At the top of the member (Sha’iba unit 4), the association of ball-and-pillow structures and cross-stratified sandstone beds containing fish debris, indicates a bay-type environment in which thin sandstone bodies accumulated either at the mouths of tidal distributary channels, or in sandy flats under mixed tidal and wave influences.

Qasr Limestone Member, Saudi Arabia Outcrop (from Janjou et al., 1997a). Boucot et al. (1989) determined that the clastic beds in the Qasr were deposited in deeper water than the clastic beds of the Sha’iba Member, and stromatolitic and oncotic limestone beds represent deposition in a shallow-marine, subtidal environment in the photic zone. Beds that contain fish remains may record brackish-water estuarine conditions. Janjou et al. interpreted the deposits of the Qasr to represent a carbonate lagoon environment in which clayey sedimentation was succeeded by stromatolitic carbonates characteristic of an environment relatively distant from terrigenous sediment sources. The progressive reduction in the influx of terrigenous material toward the top of the member may reflect a relative rise in sea level and led to the deposition of stromatolitic carbonates.

Subbat Shale Member, Saudi Arabia Outcrop (from Janjou et al., 1997a). According to Boucot et al. (1989), the depositional environment of Subbat Shale Member was shallow-marine and nearshore, in a region of low relief; in most respects it was deposited in an environment similar to the Sha’iba Member. Janjou et al. interpreted the deposits of the Subbat to have formed in a siliciclastic lagoonal system of principally clayey sedimentation overrun by meandering channels, and characterized by weak hydrodynamics and tidal influence. This type of environment is represented by various types of sandstone facies: channel-fill, meander bar, crevasse and onlap. Progradation of this terrigenous lagoon sequence over the marine carbonates of the Qasr Member represents a regressive phase that succeeded the first transgressive episode at the base of the Jauf Formation.

Sedimentological analysis of the deposits of the Subbat Shale Member shows that it is composed of three main facies.

1) A lower onlap facies (in crevasses) deposited in a period of sea-level fall (Subbat unit 1).
2) A middle channel-fill facies that may correspond to the period of maximum regression (Subbat unit 2).
3) An upper facies of meander-bar sandstone deposited under tidal influence (Subbat units 3 and 4); it may reflect the resumption of a transgressive trend that led to deposition of the Hammamiyat Limestone Member.

Hammamiyat Limestone Member, Saudi Arabia Outcrop (Janjou et al., 1997a). According to Boucot et al. (1989), the depositional environment of the Hammamiyat limestones was a shallow sea-bottom, distant from shore and distant from sources of clastic debris; mud and rare sand beds accumulated rapidly in quiet water below wave base. Janjou et al. characterized the great facies diversity of the Hammamiyat in terms of environments ranging from carbonate lagoon (dominant) to siliciclastic tidal complexes. The facies succession records six cycles of regression and transgression (Hammamiyat units 1–6, Figure 2), having a generally regressive trend upward. The six cycles may correlate to the six limestone beds noted by Helal (1965) and Boucot et al. (1989).

Janjou et al. added that Hammamiyat units 1 and 2 are principally carbonate and indicate maximum distance from the terrigenous source and represent maximum transgression in the Jauf Formation. Units 3, 4, and 5 have sandstone facies predominant over clayey facies. The final Hammamiyat unit 6 begins with a thick, channeled, sandstone body indicative of a strong hydrodynamic system and increasing terrigenous influx, followed by a predominance of clayey facies, and finally by a return to dolomitic sedimentation. The Hammamiyat Limestone Member represents the maximum flooding of the Devonian cycle as expressed by the two Hammamiyat carbonate units 1 and 2, typical of shoreface or lagoon facies.
Murayr Member, Saudi Arabia Outcrop (Janjou et al., 1997a). The Murayr Member was deposited in a brackish and estuarine environment and the beds of sandstone may represent beach deposits and estuarine channels (Boucot et al., 1989). Janjou et al. interpreted the facies of the lower part of the Murayr Member (Murayr units 1 and 2, Figure 2) to define depositional sequences of estuarine channel fill. The dolomitic layers (Murayr unit 3) represent transgressive fluctuations that replaced estuarine sedimentation by more-lagoonal deposition. The uppermost sandstone deposits (Murayr unit 4) indicate an environment having a strong hydrodynamic system and considerable terrigenous influx, but nonetheless under tidal influence. Taken as a whole, the deposits of the Murayr Member belong to a regressive siliciclastic estuarine complex.

Jauf Formation, Saudi Arabia Subsurface. In the subsurface of eastern Saudi Arabia, Rahmani et al. (2002) divided the Jauf Formation into a Lower Member or Sequence S1 (= SQ55 of Rahmani, 2004), and Middle and Upper members together forming Sequence S2 (= SQ60). The D3B Biozone (Al-Hajri et al., 1999) occurs in a mainly dark-colored marker shale at the top of the TST of Sequence S2 (Rahmani et al., 2002). Wender et al. (1999) suggested a similar interpretation in which the D3B marker was considered a possible condensed section and maximum flooding interval.

Rahmani et al. (2002) interpreted each of the two Jauf sequences as “third-order”. They identified 16 “fourth-order” sequences in Sequence S1 and 15 more in Sequence S2. Sequence S1 probably corresponds to the Sha’iba, Qasr and Lower Subbat members; and Sequence S2 to the Upper Subbat, Hammamiyat (D3B marker) and Murayr members. Rahmani (2004) described Sequence S1 (SQ55) as dominated by a falling stage systems tract (forced regressive shoreface) which prograded from west to east over a distance of 150–200 km. Sequence S2 comprises transgressive and highstand system tracts with the reservoir quality rocks developed in the TST.

ORBITAL SIGNATURE OF THE JAUFT FORMATION

This section examines whether the Jauf Formation manifests some of the criteria associated with an orbital second-order depositional sequence. The first criteria is that the Jauf Formation should be bounded by two sequence boundaries expressed as regional stratigraphic discontinuities (regional disconformity, ?unconformity, time hiatus). The Jauf Formation appears to meet this criteria as both of its contacts are associated with periods of non-deposition or/and minor erosion. The lower contact, the Jauf/Tawil Boundary, is interpreted as a disconformity (Janjou et al., 1997a); the top of the Tawil is characterized by a paleosol (Vaslet et al., 1987) as well as erosion (Wallace et al., 1996, 1997). The upper contact, the Jubah/Jauf Boundary, is interpreted as unconformable (Wallace et al., 1996, 1997). Both boundaries of the Jauf Formation are not associated with any known tectonism and therefore they appear to be regional sequence boundaries. The Jauf also meets a second criteria that requires that its internal contacts (between members, units, etc.) should be conformable (Wallace et al., 1996, 1997).

Showing that the depositional period of the Jauf Formation is c. 14.58 million years is not possible. This is because biostratigraphic-radiometric age dating techniques are highly inaccurate for the Early Devonian. To illustrate this point, consider the age of the Eifelian/Emsian Boundary. It was estimated at 397.5 ± 2.7 Ma by Gradstein et al. (2004) or 391.8 ± 0.4 Ma by Kaufman et al. (2005). The difference of 5.7 my (red interval in Figure 3) suggests an uncertainty that far exceeds the quoted standard deviations by these authors.

Similarly, SB² 27 (predicted here at 393.0 Ma) may be correlated to the Jubah/Jauf Boundary in Middle Devonian, late Eifelian [393.2–391.8 ± 2.7] as apparently consistent with Palynozone D2 (Al-Hajri et al., 1999) that is characteristic of the lower and middle Jubah Formation (Figures 2 and 3). Alternatively, SB² 27 = Jubah/Jauf could be correlated in late Emsian (Eifelian/Emsian = 391.8 ± 0.4 Ma, Kaufman et al., 2005) as apparently consistent with Palynozone D3A (Al-Hajri et al., 1999) recognized in the upper Jauf and lower Jubah formations.

These examples of the biostratigraphic-radiometric estimates for the ages of stages and stratigraphic units show the great level of uncertainty that renders model-data correlation inconclusive. Al-Husseini and Matthews (2005) arrived at a similar conclusion for the entire Arabian Phanerozoic succession.
The Jauf Formation manifests several stratigraphic elements that could be interpreted in terms of third- and fourth-order orbital cycles. A major sequence may be represented by the Sha’iba, Qasr and Subbat units 1 and 2. This sequence shows two MFI’s: (1) Sha’iba unit 2 that contains thin limestone layers, dolomitic sandstone with fish debris; and (2)stromatolitic limestones of Qasr units 2 and 3. This major sequence may be a double third-order sequence (28.1 and 28.2 in Figure 2), and it probably correspond to subsurface Sequence 1 of Rahmani et al. (2002) that consists of their 16 ‘fourth-order’ sequences.

The upper Subbat units 3 and 4, and Hammamiyat Member may each represent a third-order sequence (28.3 and 28.4 in Figure 2). In the general section (Figure 2), Subbat unit 3 is shown as three fining-upwards sandstone-claystone cycles, and unit 4 as two more (Janjou et al., 1997a). D. Janjou (2005, written communication indicated that the more detailed section contains one more cycle in unit 3, and two thin cycles in unit 4. Thus Subbat units 3 and 4 may consist of some 8 cycles most of which are likely to be fourth-order. The Hammamiyat Member is represented by units 1–6 that appear to be fourth-order cycles (here numbered 28.4.1 to 28.4.6). This member could therefore constitute a ‘nominal’ third-order deposition sequence (2.43 my) (Matthews and Frohlich, 2002).

The Murayr Member may represent another double third-order sequence (28.5 and 28.6) that was deposited in about 4.86 my (Figure 2). In this interpretation, Murayr unit 1 (10–30 cm, reworking) could represent the third-order sequence boundary SB 28.5. Murayr unit 2 (with 5-cycles, ?fourth-order) that culminated with an MFI in Murayr unit 3 (fish debris) could be a third-order cycle (28.5). Murayr unit 4 may represent the final third-order sequence (28.6) of the Jauf Formation. Alternatively, Murayr unit 4 could be the regressive highstand of DS 28.5 such that DS 28.6 is not represented (hiatus?).

The upper Subbat, Hammamiyat and Murayr members may constitute three or four orbital third-order sequences (Figure 2), and probably correspond to subsurface Sequence 2 of Rahmani et al. (2002) that consists of their 15 ‘fourth-order’ sequences.

The stratigraphic architecture of the Jauf Formation demonstrates a second-order transgressive-regressive cycle. The cycle can be characterized in terms of an initial Qasr flood, followed by a more regional Hammamiyat flood (maximum flooding interval MFI 28 in Figure 2). The Hammamiyat flood is recognized across Saudi Arabia by the D3B bioevent (Al-Hajri et al., 1999). The upper Hammamiyat units 3–6 represent the start of the second-order regression that gave way to the final Murayr Member regression.

In contrast to the sandstones of the underlying Tawil and overlying Jubah formations, the limestones of the Jauf Formation reflect an open-marine depositional environment. Y.-M. Le Nindre (written communication, 2005) notes that the Jauf Formation, in its own right, can be interpreted as a maximum flooding event of a much longer sequence (c. 40–50 my). This longer cycle started at the base of the underlying Tawil Formation (lowstand system tract, LST) and ended with the deposition of the overlying Jubah Formation (prograding highstand system tract, HST).

**CONCLUSIONS**

The Devonian Jauf Formation represents a regional marine flood of the Arabian Platform that is recognized in northwest and eastern Saudi Arabia, and correlated to the Misfar Group in Oman – a region of some 1,500 km in extent. The interpretation of this formation as a second-order, orbital-forcing depositional sequence (Al-Hussein and Matthews, 2005) seems possible based on sequence-stratigraphic criteria. (1) The upper and lower bounding regional discontinuities appear to be unconformities that are not associated with tectonism and qualify as second-order sequence boundaries. (2) In contrast to the upper and lower Jauf contacts, the intra-Jauf contacts are apparently conformable. (3) The formation constitutes a regional transgressive-regressive cycle with the internal architecture of five to possibly six third-order sequences. (4) Six fourth-order cycles in the main Hammamiyat Member flooding interval identify one probable third-order Emsian sequence. (5) The model age of DS 28 (407.6 to 393.0 Ma) is entirely in the Emsian Stage of Tucker et al. (1998) and Kaufman et al. (2005) estimated as 409.5 to 391.8 Ma, but also to the late Pragian to mid Eifelian (Gradstein et al., 2004).
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