

The Permian-Triassic Khuff Formation of central Saudi Arabia

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ABSTRACT

The Permian-Triassic Khuff Formation crops out in central Saudi Arabia along a N-S belt, some 1,200 km in length. It is 171.4 m (562.2 ft) thick in the type section and divided into five members; from oldest to youngest: Ash Shiqqah (formerly Unayzah member of the Khuff Formation), Huqayl, Duhaysan, Midhnab and Khartam. The base of the Khuff Formation is recognised as a regional unconformity (Pre-Khuff Unconformity), and the top of the formation is defined by the conformable contact with the overlying Sudair Shale. The Ash Shiqqah Member is tentatively dated as ?Middle Permian ?Capitanian (?Midian) based on the presence of the fusulinids *Monodiexodina kattaensis* and *Reichelina* sp. The Huqayl Member is tentatively dated as ?Late Permian ?Wuchiapingian (?Dzhulfian) based on an assemblage of smaller foraminifers dominated by *Pseudomidiella* cf. *labensis*, *Earlandia*? spp. and *Neodiscus* aff. *qinglongensis*. The Duhaysan Member is dated as Late Permian (Wuchiapingian-Changhsingian) based on *Hemigordius baoqingensis*, *Graecodiscus* cf. *kotlyarae*, "*Dentalina*" *hoi*, and *Colaniella* cf. *minuta*. The sMidhnab Member is dated as Changhsingian (Dorashamian) based on *Paradagmarita* sp. and "*Glomospirella spirillinoides*" and the disappearance of the genera *Nankinella* and *Globivalvulina*. Within the continental facies in the upper part of the Midhnab Member, incised channels facies yielded the Late Permian Midhnab Flora. The Lower Khartam Member is also dated as latest Permian (Dorashamian) based on the presence of several species of *Paradagmarita* and "*Nodosaria*" *dzhulfensis* in the lowest beds of the member, and the ostracods *Paraparchites* spp., *Knoxiella* spp. and *Kloedenellitina* sp. throughout the Lower Khartam Member. The Upper Khartam Member is assigned to an Early Triassic ('Scythian') age based on the occurrence of the characteristic annelid *Spirorbis phlyctaena*.

The Khuff Formation, in central Saudi Arabian outcrops, consists of four regional depositional sequences (DS PKh, DS PKm, DS PKk and DS TrS), each containing a maximum flooding interval (MFI, with the same designation). The oldest sequence DS PKh (named after Permian-Khuff-Huqayl) consists of the Ash Shiqqah and overlying Huqayl members. The basal sequence boundary corresponds to the Pre-Khuff Unconformity (PKU) and represents the onset of the first Permian flooding event recorded in the outcrops of Saudi Arabia. The massive gypsum, gypsiferous claystone, and solution breccias in the Ash Shiqqah Member are correlated to the subsurface Khuff-D Anhydrite. The MFI PKh is positioned in the basal part of the Huqayl Member, and is followed by the regressive evaporitic palaeoenvironments of the Huqayl Member.

The DS PKm (named after Permian-Khuff-Midhnab) starts with the subtidal to littoral deposits of the Duhaysan Member, over an erosive surface upon DS PKh; and ends with the regressive supratidal to continental deposits at the upper part of the Midhnab Member. The MFI PKm is located at the base of the Midhnab Member, where limestones yielded an abundant marine fauna including cephalopods and brachiopods. The terminal Permian DS PKk (Permian-Khuff-Khartam) corresponds to the Lower Khartam Member. The basal SB PKk is marked by a return to marine subtidal conditions after the continental break at the end of DS PKm. The MFI PKk is characterised by marine fauna including abundant Permian ostracods, bacrtrids, and locally cephalopods. The DS TrS (named after the Sudair Shale Formation) starts with the littoral, tidal to intertidal deposits of the Early Triassic Upper Khartam Member of the Khuff Formation, and ends with the closed basin, clayey to evaporitic rocks of the Early Triassic Sudair Shale.

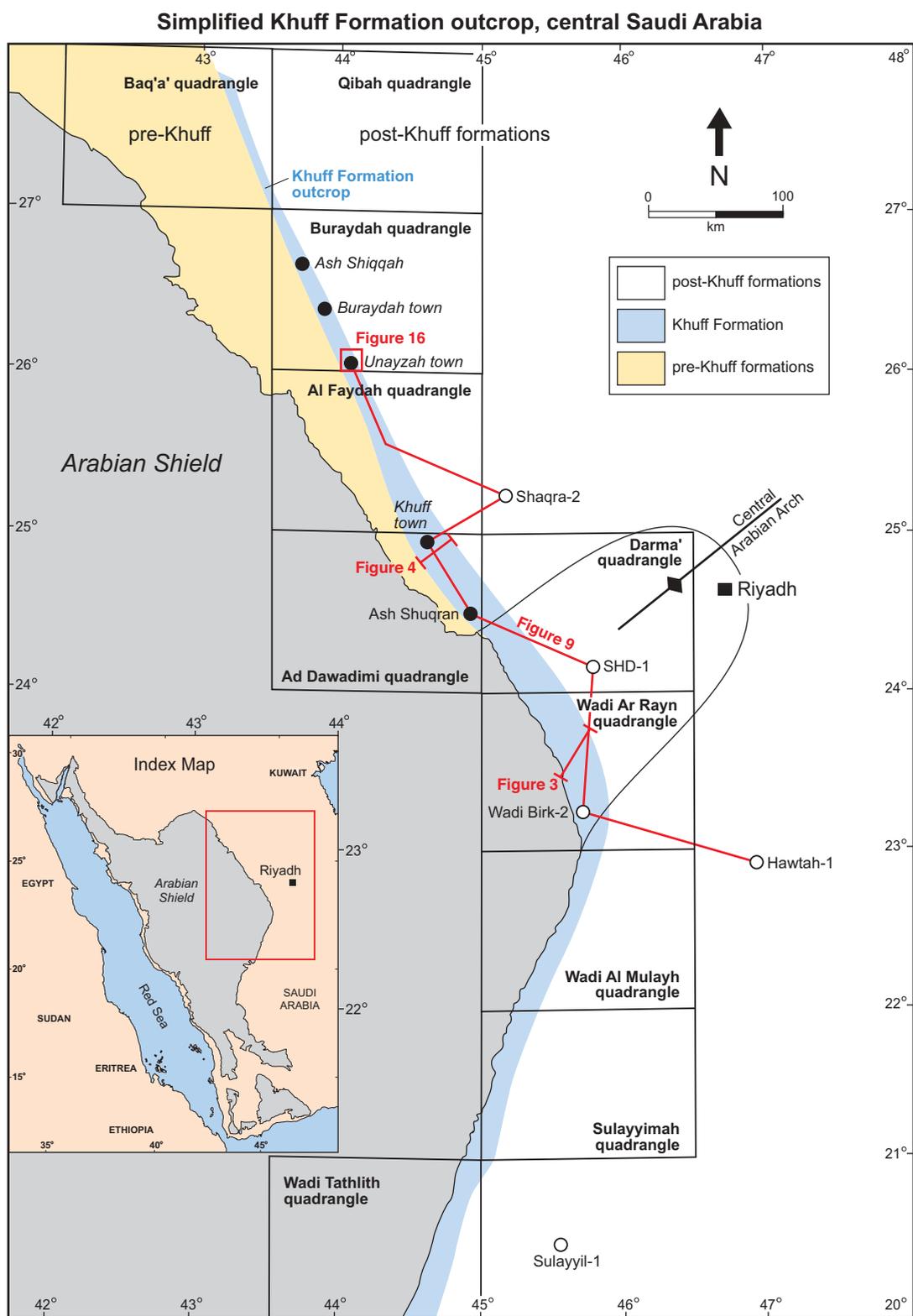


Figure 1: Simplified Khuff Formation outcrop, central Saudi Arabia. The reference and revised type sections of the Khuff Formation are shown in Figures 3 and 4, respectively. The reference sections of the Ash Shiqqah Member of the Khuff Formation and the Unayzah Formation are shown in Figures 14 and 16. Figure 9 shows a surface-subsurface traverse of the Unayzah Formation, Khuff-D, Ash Shiqqah and Huqayl members. The quadrangles with Khuff outcrops that were mapped by DMMR/BRGM authors are from north to south: Baq'a' (Vaslet et al., 1987); Qibah (Robelin et al., 1994); Buraydah (Manivit et al., 1986; Figures 5, 7, 9, 14, 15 and 16); Al Faydah (Vaslet et al., 1985a; Figures 5, 7, 9 and 19); Ad Dawadimi (Delfour et al., 1982; Figures 4, 5 and 7); Darma' (Manivit et al., 1983; 1985a; Figures 5, 7 and 23); Wadi ar Rayn (Vaslet et al., 1983; Figures 5 and 7); Wadi Al Mula'ayh (Manivit et al., 1985b; Figures 5, 7, 25 and 26); and Sulayyimah (Vaslet et al., 1985b).

INTRODUCTION

The Permian-Triassic Khuff Formation crops out in central Saudi Arabia along a N-S belt that is some 1,200 km in length (Steineke and Bramkamp, 1952; Steineke et al., 1958; Powers, 1968). The formation was mapped during the 1980s by the Deputy Ministry for Mineral Resources, Ministry of Petroleum and Minerals of Saudi Arabia (DMMR, now the Saudi Geological Survey – SGS), and the French Geological Survey BRGM (Figure 1). This paper provides a synthesis of these studies together with new data and interpretations. It starts with a description of the Pre-Khuff Unconformity (PKU) in outcrop and subsurface. Next the five formal members of the formation are described in the type section in the Ad Dawadimi quadrangle (Figures 1 and 4). The following section reconciles various conflicting lithostratigraphic definitions attributed to the names “Unayzah” and “Ash Shiqqah”. This is followed by a lateral correlation of the five members; first northwards and then southwards along the strike of the outcrops. The correlation includes several published well data from central Saudi Arabia.

The study next presents the palaeontology and ages of the five Khuff members and the underlying Unayzah Formation. This section includes ongoing biostratigraphic analysis of foraminifers and algae by D. Vachard and J. Gaillot (Vachard et al., 2002, 2005), of ostracods by S. Crasquin-Soleau (Crasquin-Soleau et al., 2004, 2006), and flora by J. Broutin and M. Berthelin (Broutin et al., 2002; Berthelin, 2002; Berthelin et al., 2005). Throughout the paper and figures, all stages and ages are related to the proposed global geological time scale of the Permian Period (Jin et al., 1997; Menning et al., 1997; Menning, 2001a, b; Gradstein et al., 2004) (Figure 2). The final section describes four regional Khuff depositional sequences (DS) and their corresponding maximum flooding intervals (MFI).

PREVIOUS STUDIES

The Khuff Formation, first recognised in publication by Steineke and Bramkamp (1952), was formally defined by Steineke et al. (1958) near ‘Ayn Khuff (between 24°58’36”N, 44°41’48”E and 24°53’12”N, 44°42’48”E) in the Ad Dawadimi quadrangle in central Saudi Arabia (Figure 1). The definition of the Khuff Formation was later amended by Powers et al. (1966) and Powers (1968). In the type section, the formation is 171.4 m (562.2 ft) thick, and its base is at the unconformable contact between a lower sandy phase of the Khuff and the underlying massive sandstone of the Saq. The top is placed at the level where Khuff limestone and dolomite are in sharp contact with red and green gypsiferous shale of the overlying Sudair Shale. A more complete reference section was documented in Wadi Ar Rayn quadrangle (Figures 1 and 3: between 23°32’45”N, 45°34’30”E and 23°43’N, 45°42’E; R.A. Bramkamp, E.L. Berg, R.L. Meyers and W.T. Short, *in* Powers et al., 1966). At this locality, the Khuff Formation overlies the Proterozoic Basement.

A revised type section of the Khuff Formation was proposed by J.M. Brosse, Y.M. Le Nindre and D. Vaslet (*in* Delfour et al., 1982) in the Ad Dawadimi quadrangle (Figures 1 and 4). They divided the formation into five informal members; from oldest to youngest (Figures 4 and 5): Unayzah (hereafter Ash Shiqqah Member of Khuff Formation), Huqayl, Dhaysan, Midhnab, and Khartam. These five Khuff members were adopted and mapped (at a scale of 1:250,000; Figure 1) across central Saudi Arabia by the DMMR and BRGM, during the exploration for minerals.

In 1987, Y. Le Nindre, J. Manivit and D. Vaslet synthesised the lithostratigraphic, sedimentologic and biostratigraphic results of the DMMR and BRGM mapping program, together with additional analytic data, in three PhD thesis at Paris University (in French), and in four BRGM publications (Le Nindre et al., 1990a, b; Manivit et al., 1990; Vaslet, 1990). These syntheses included revisions to the lithostratigraphic units, palaeoenvironments and sedimentologic interpretations, and biostratigraphic data that was published in the Explanatory Notes to the Geosciences Map series published by the DMMR (Figure 1).

The definition of the members of the Khuff Formation in Saudi Arabia varies according to author, and from the surface to subsurface (Powers et al., 1966; Powers 1968; Delfour et al., 1982; Le Nindre et al., 1990b; Al-Jallal, 1995; Alsharhan and Nairn, 1997; Alsharhan, 2006). This nomenclatural inconsistency causes confusion; especially in the case of the term “Unayzah” which is known as the

Khuff Formation outcrop, central Saudi Arabia

Ma	GTS 2004 Gradstein et al. (2004)		RUSSIAN	WEST TETHYS	LITHOSTRATIGRAPHIC UNITS	DEPOSITIONAL SEQUENCE			
250.0	EARLY TRIASSIC		Scythian		Sudair Formation				
251.0					Khartam Member	Upper	DS TrS		
	Lower	DS PKk							
253.8	LATE	Lopingian	Changhsingian	Dorashamian	Midhnab Member		DS PKm		
			Wuchiapingian		Duhaysan Member				
260.4			MIDDLE		Guadalupian	Capitanian	Midian	Ash Shiqqah Member (previously Unayzah)	DS PKh
265.8						Wordian			
268.0	EARLY	Cisuralian	Roadian	Kazanian	Unayzah Formation (outcrop and subsurface)				
270.6			Kungurian		Murgabian	Unayzah Formation (Subsurface)			
			Kungurian					Kubergandian	
275.6			Bolorian						
284.4	Artinskian								
294.6	Sakmarian								
299.0	Asselian								
	LATE CARBONIFEROUS								

Figure 2: Stratigraphy of the Khuff Formation, central Saudi Arabian outcrops and interpreted sequence stratigraphic framework of the Permian-Early Triassic of central Saudi Arabia. The geological time scale (Jin et al., 1997; and the ratified International Subcommission for Stratigraphy, Gradstein et al., 2004) shows the approximate relationships between the global scale and regional scales of Western Tethys, and eastern Europe-Russia. The Khuff Formation is divided into five members. Note that the term ‘Unayzah member’ of the Khuff Formation of Delfour et al. (1982) as adopted in the mapping of the cover rocks of Saudi Arabia by DMMR/BRGM, is here replaced where possible with the equivalent Ash Shiqqah Member of the Khuff Formation of Senalp and Al-Duaiji (1995, 2001; see Figure 16). In this study the oldest part of the Ash Shiqqah Member is tentatively dated as Capitanian. The Triassic/Permian Boundary is correlated to the Upper/Lower Khartam Boundary. The Khuff Formation is interpreted in terms of several depositional sequences (abbreviated DS) and Maximum Flooding Intervals. The age of the Unayzah Formation in the outcrops of central Saudi Arabia is interpreted as Middle Permian (Roadian-Wordian; J. Broutin, written communication, 2002) and corresponds to the "Surface Unayzah Formation" of Stephenson et al. (2003). In the subsurface the Unayzah Formation is dated as Late Carboniferous and Early Permian (e.g. Stephenson et al., 2003).

Khuff Formation, reference section, Saudi Arabia

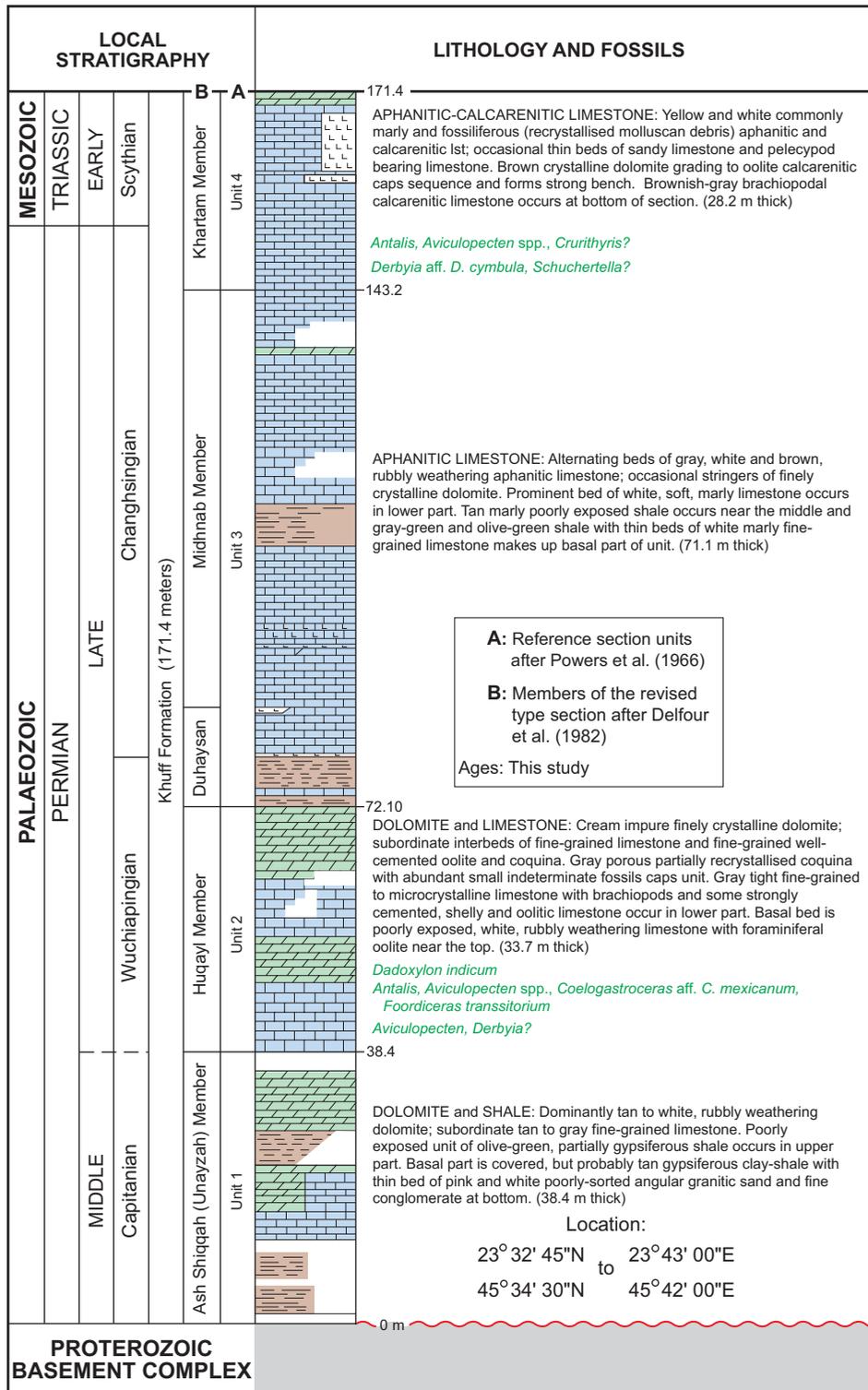


Figure 3: The type section of the Khuff Formation was originally defined by Steineke et al. (1958, in Powers, 1968) near the town of Khuff (Figure 1). A more complete Khuff reference section, shown here, was measured in the Wadi Ar Rayn quadrangle (Figure 1) by R.A. Bramkamp, E.L. Berg, R.L. Meyers and W.T. Short (in Powers et al., 1966; Powers, 1968). The correspondence between units 1 to 4 of Powers (1968) and the members of Delfour et al. (1982; see Figure 4) are shown in the vertical columns. Note the “Ash Shiqqah Member” replaces the obsolete “Unayzah member” of the Khuff Formation (see also Figure 16). At this locality the Khuff Formation lies on the Proterozoic Basement.

“Unayzah member of the Khuff Formation” (Delfour et al., 1982), as well as to the much older “Unayzah Formation” (Al-Laboun 1982, 1986, 1987; El-Khayal and Wagner, 1983, 1985; Senalp and Al-Duaiji, 1995). In order to avoid confusion, this paper will propose the “Ash Shiqqah Member” to replace the “Unayzah member of the Khuff Formation” of Delfour et al. (1982).

PRE-KHUFF UNCONFORMITY

The Khuff Formation in central Saudi Arabia unconformably overlies the Proterozoic Basement (Figure 6) or Lower Palaeozoic deposits (e.g. Powers et al., 1966; Powers, 1968; Le Nindre et al., 1990b). From north to south (see Figure 7 for longitude), the Pre-Khuff Unconformity (PKU) can be seen continuously between 27°40'N (Al Khuwayr, in the Baq'a quadrangle) and 19°57'N (Bani Ruhaya, in the Wadi Tathlith quadrangle). This angular unconformity reflects a period of regional uplift and compressional tectonic activity that occurred during the Carboniferous (Powers, 1968; Wender et al., 1998; Le Nindre et al., 2002; Al-Husseini, 2004).

Beds below the Pre-Khuff Unconformity in outcrop (Figure 7) are enhanced by a pedogenic lateritic alteration surface (Figure 8) that is developed over central Saudi Arabia (El-Khayal and Wagner, 1983, 1985; Le Nindre et al., 1990b; Senalp and Al-Duaiji, 1995). According to Le Nindre et al. (1990b), depending on the pre-Khuff substratum, this lateritic layer is represented either by a duricrust containing goethite pisoliths, or by an iron crust (10–80% silica, 2–15% Al_2O_3 and 4–76% Fe_2O_3). The main outcrops of the pisolitic duricrust are located between Jal al Khuffiyat (27°10'N) and Wadi Ar Rayn area (23°45'N), corresponding to a palaeohigh in the Khnaygu'iyah area where the Ash Shiqqah Member is locally reduced to a single sandstone bed (Figures 5 and 7).

The Khnaygu'iyah palaeohigh is located on the axis of the broader Central Arabian Arch (Figures 1, 7 and 9). The crest of the arch is expressed by the subcrop of the Pre-Khuff Unconformity, and consists of the Proterozoic Basement at its center and successively younger Palaeozoic formations along its flanks (Figure 7). In the subsurface, the Unayzah Formation was deposited around the periphery of the arch but not on its crest (Figure 9).

KHUFF FORMATION TYPE SECTION

In the north of the Ad Dawadimi quadrangle (Figure 1), Delfour et al. (1982) defined the informal Unayzah member (hereafter Ash Shiqqah Member) of the Khuff Formation above the Cambrian-Ordovician Saq Sandstone Formation (Figure 4). This definition was later revised by Le Nindre et al. (1990b). In the Khuff Formation type section, the Ash Shiqqah Member is 35 m (114.8 ft) thick, and consists of four subunits; from base up:

- (1) 10.5 m (34.4 ft) emerald-green, purplish red, or varicolored silty claystone, with secondary gypsum interbedded in its lower part by yellowish or gray silty dolomite;
- (2) 2.5 m (8.2 ft) white, fine-grained sandstone with cross-bedding;
- (3) 15 m (49.1 ft) red and green silty claystone interbedded with pinkish to yellowish dolomite, locally slumped and tinted red by iron oxides;
- (4) 7 m (22.9 ft) clayey, locally finely bioclastic dolomite, with beige patina, algal laminites, and fenestrate structures.

The Ash Shiqqah Member becomes thinner to the southeast, and along the eastern edge of the quadrangle it consists of only 2 m (6.5 ft) or less of sandy dolomite.

Overlying the Ash Shiqqah Member, the type section of the Huqayl Member of the Khuff Formation is also defined in the Ad Dawadimi quadrangle (Figures 4 and 5; Delfour et al., 1982, Le Nindre et al., 1990b) along a traverse at Safra Huqayl from 24°44'25"N, 44°39'08"E to 24°45'37"N, 44°39'15"E. In the type section (Figure 4), the Huqayl Member is 34.2 m (112.2 ft) thick, and elsewhere in the quadrangle ranges from 30–40 m (98.4–131.2 ft). This member is divided into lower and upper parts and six subunits. The Lower Huqayl Member consists of three subunits; from base up:

Khuff Formation type section, Ad Dawadimi quadrangle, Saudi Arabia

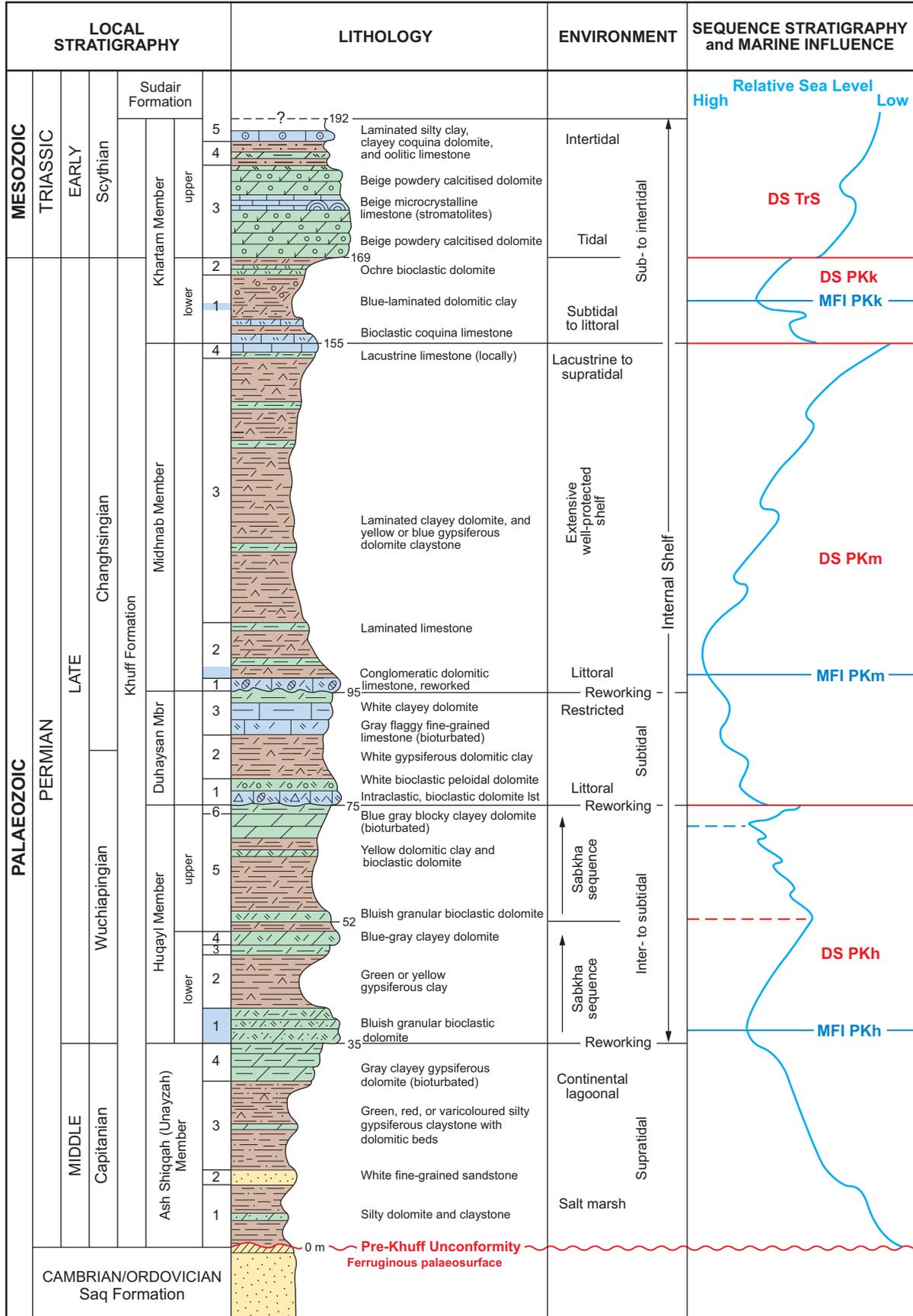


Figure 4: Composite type section of the Khuff Formation in the Ad Dawadimi quadrangle showing five members of Delfour et al. (1982): Ash Shiqqah (formerly Unayzah) Member, Huqayl, Duhaysan, Midhnab and Khartam members. The maximum flooding intervals (MFI) are shown in blue in the local stratigraphy column. See Figure 1 for location, and Figures 5 and 9 for regional correlation.

South

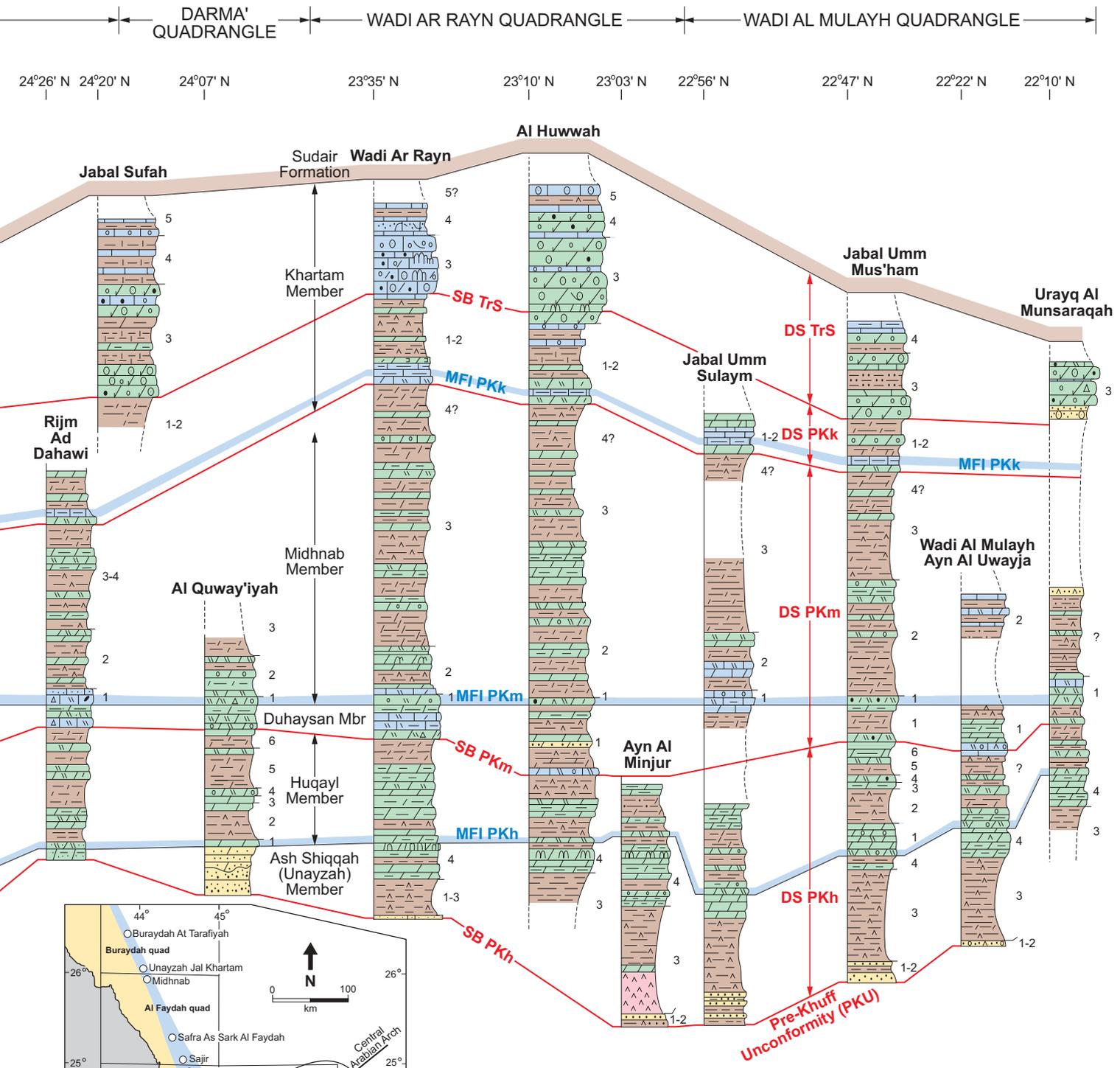


Figure 5: Regional correlation of five members and subunits of the Khuff Formation from the Buraydah to the Wadi Al Mula'iyh quadrangles in central Saudi Arabia. Note the Unayzah member of the Khuff Formation (Delfour et al., 1982) is renamed as the Ash Shiqqah Member of the Khuff Formation (Senalp and Al-Duaiji, 1995). The section is datumed at the boundary of the Du'haysan and Midh'nab members. Note the revised interpretation of the basal sections in the Buraydah quadrangle as the Ash Shiqqah (former Unayzah) Member (Al-Laboun, 1982, 1986, 1987; El-Khayal and Wagner, 1983, 1985; Senalp and Al-Duaiji, 1995, 2001).

- (1) 6 m (19.7 ft) of bluish bioclastic intraclastic dolomite with a cream patina, locally silty, and peloidal dolomite containing oolitized bioclasts, silty, bioclastic dolomite with a clear patina, overlying an intraclastic dolomitic bed;
- (2) 4 m (13.1 ft) of green or yellow gypsiferous clay;
- (3) 2.7 m (8.9 ft) of blue-gray clayey dolomite containing algal laminites and dolomite with a fenestrae structure containing pseudomorphs after gypsum and anhydrite.

The Upper Huqayl Member consists of three subunits; from base up:

- (4) 2.9 m (9.5 ft) bluish, intraclastic and bioclastic dolomite, commonly arranged in tidal channels, overlain by laminated dolomite;
- (5) 17.6 m (57.7 ft) white gypsiferous clay and fine-grained cherty dolomite, interrupted by a few bioclastic and oolitic dolomitic layers;
- (6) 1.0 m (3.3 ft) blue-gray clayey dolomite containing algal laminites with fenestrate structures, and showing very bioturbated beds (burrows), locally containing chert nodules or showing dissolution breccias or pseudomorphs of gypsum and anhydrite.

In outcrop, the benches of the Huqayl Member are locally dislocated and slumped due to collapse phenomena associated with the dissolution of anhydrite intervals known in the subsurface. Above the Huqayl Member, the type section of the Duhaysan Member is defined at Jabal Duhaysan (Delfour et al., 1982; Le Nindre et al., 1990b) where it is 13.4 m (44 ft) thick between 24°40'35"N, 44°45'58"E and 24°40'37"N, 44°47'46"E. The Duhaysan Member consists of three subunits (Figures 4 and 5); from base up:

- (1) 3.7 m (12.1 ft) gray dolomitic calcarenite, with pebbles, intraclasts, and bioclasts (Figure 10), overlain by white bioclastic peloidal dolomite showing current ripples and pseudomorphs of gypsum and anhydrite;
- (2) 5.6 m (18.4 ft) of white, gypsiferous, dolomitic clay;
- (3) 4.1 m (13.5 ft) blue-gray, fine-grained peloidal limestone with bioturbations, algal laminite, overlaid by white clayey dolomite with fenestrae structures.

The Midh nab Member, which is an approximate synonym of the Midh nab shale and informal unit 3 (Figure 3) that were discarded by Powers (1968), was reintroduced by Delfour et al. (1982) and emended by Le Nindre et al. (1990b) in the Ad Dawadimi quadrangle (Figure 1). The latter authors measured a type section along Wadi Maghib, near Khuff town, along a traverse from 24°55'28"N, 44°36'47"E to 24°58'20"N, 44°38'19"E, where it is 57.9 m (189.9 ft) thick (Figures 4 and 5). Throughout this quadrangle, the Midh nab Member is fairly uniform in thickness at about 60 m (196.7 ft), and consists from base up:

- (1) 2 m (6.6 ft) conglomeratic limestone with pebbles of dolomite and abundant bioclasts (bed-on-bed reworking) and bluish-gray platy limestone rich in marine fossils;
- (2) 9 m (29.5 ft) alternating gypsiferous platy dolomitic claystone and beds of blue-gray bioclastic limestone and dolomite;
- (3) 46 m (150.8 ft) yellow to blue gypsiferous clay, interspersed with beds of clayey dolomite;
- (4) 3 m (9.8 ft) light-gray, lacustrine limestone containing charophyte remains.

Delfour et al. (1982) adopted the Khartam Member (Figures 4 and 5), a synonym for the discarded Khartam limestone or unit 4 (Figure 3) of Powers (1968), to describe the mainly calcareous upper part of the Khuff Formation. The type section of the Khartam Member (Le Nindre et al., 1990b) is located northeast of Khuff town in the Ad Dawadimi quadrangle, where the member is about 37 m (121.3 ft) thick along a traverse from 24°58'20"N, 44°38'19"E to 24°59'52"N, 44°40'42"E.

The Lower Khartam Member, 14 m (45.9 ft) thick, comprises from base up:

- (1) 10.9 m (35.7 ft) coquina and peloidal limestone overlain by blue, laminated, dolomitic clay rich in pellets and terrigenous material;
- (2) 3.1 m (10.1 ft) ochreous, ferruginous, bioclastic dolomite and dolomitic claystone.



Figure 6: Khuff Formation lying over Proterozoic Basement rocks in Khnaigu'iyah area, Darma' quadrangle. The Ash Shiqqah Member (gray colour) and Lower Huqayl Member (light colour) overlie the Shield rocks (blackish colour). Photo from helicopter by D. Vaslet, 1979.

The Upper Khartam Member is at least 23 m (75.4 ft) thick, and the missing upper section is estimated at about 10 m (32.8 ft) thick, and comprises from base up:

- (3) 15 m (49.2 ft) cream oolitic and peloidal limestone with local megaripples and tidal channels (Figure 11). Stromatolitic constructions are locally developed in the middle part of the unit (Figure 12). This facies is entirely calcitized (the calcite ooids corresponding to rounded debris of entirely recrystallised dasycladacean algae) (Figure 13);
- (4) 6.5 m (21.3 ft) of alternating dolomitic coquina limestone and cream clayey dolomite;
- (5) 1.5 m (4.9 ft) massive oolitic limestone bed at the top of the outcrops. The upper 10 m (32.8 ft), which are probably clayey and soft, are hidden by Quaternary deposits.

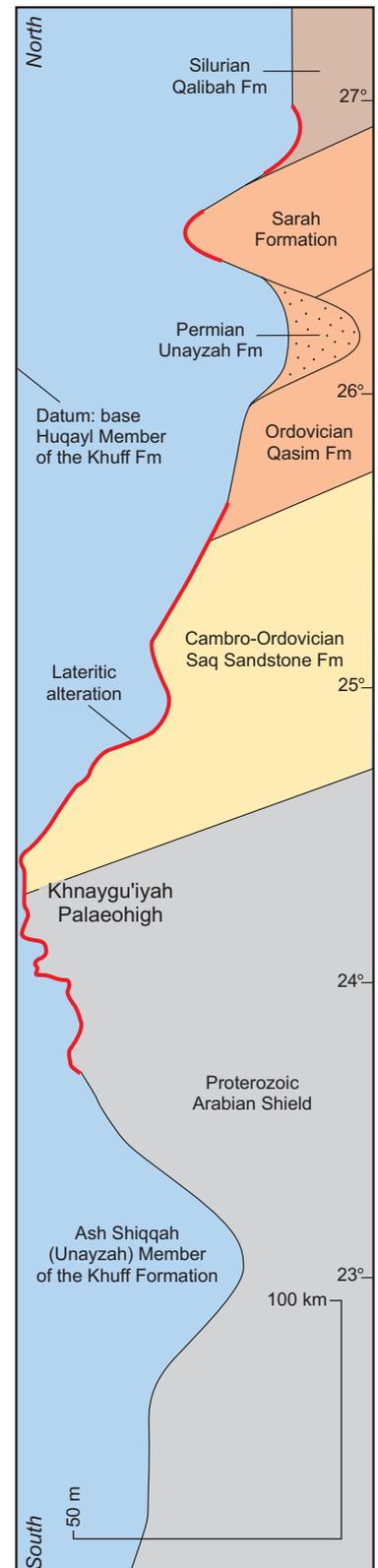
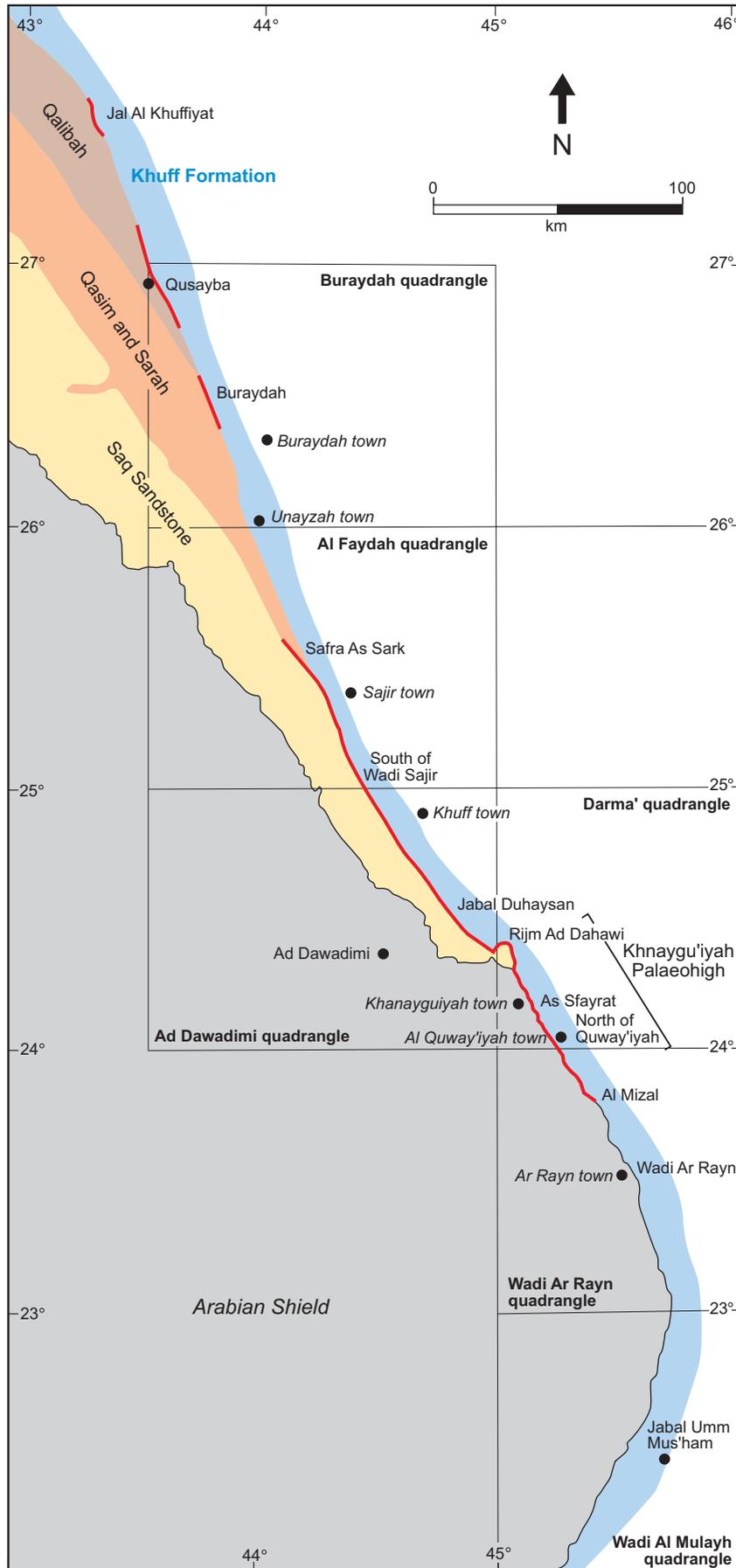
The boundary of the Khuff and Sudair formations is not visible in the type section (Delfour et al., 1982).

ASH SHIQQAH MEMBER REFERENCE SECTION

The reference section for the basal Ash Shiqqah Member (previously the 'Unayzah member') of the Khuff Formation is proposed near the town of Unayzah in the Buraydah quadrangle, some 150 km to the north of the Khuff type section (Figures 1, 14–16). At this locality (26°05'10"N, 43°59'24"E), Manivit et al. (1986) measured a 70-m-thick (229.6 ft) section above the Ordovician Qasim Formation. Manivit et al. (1986) and Le Nindre et al. (1990b) considered this section as the 'Unayzah member' (i.e. Ash Shiqqah Member), and divided it into four subunits (Figures 14–16). These authors considered the base of this section to be close to the base of the Khuff Formation.

In contrast, Al-Laboun (1982, 1987) interpreted part of the same section as the older Unayzah Formation (Figure 16) (26°06'N, 43°58'E). Senalp and Al-Duaiji (1995), also near Unayzah town (Figure 1), defined subunit 3 of Manivit et al. (1986) as the basal Khuff clastics or the Ash Shiqqah Member of the Khuff

Pre-Khuff Unconformity, Saudi Arabia



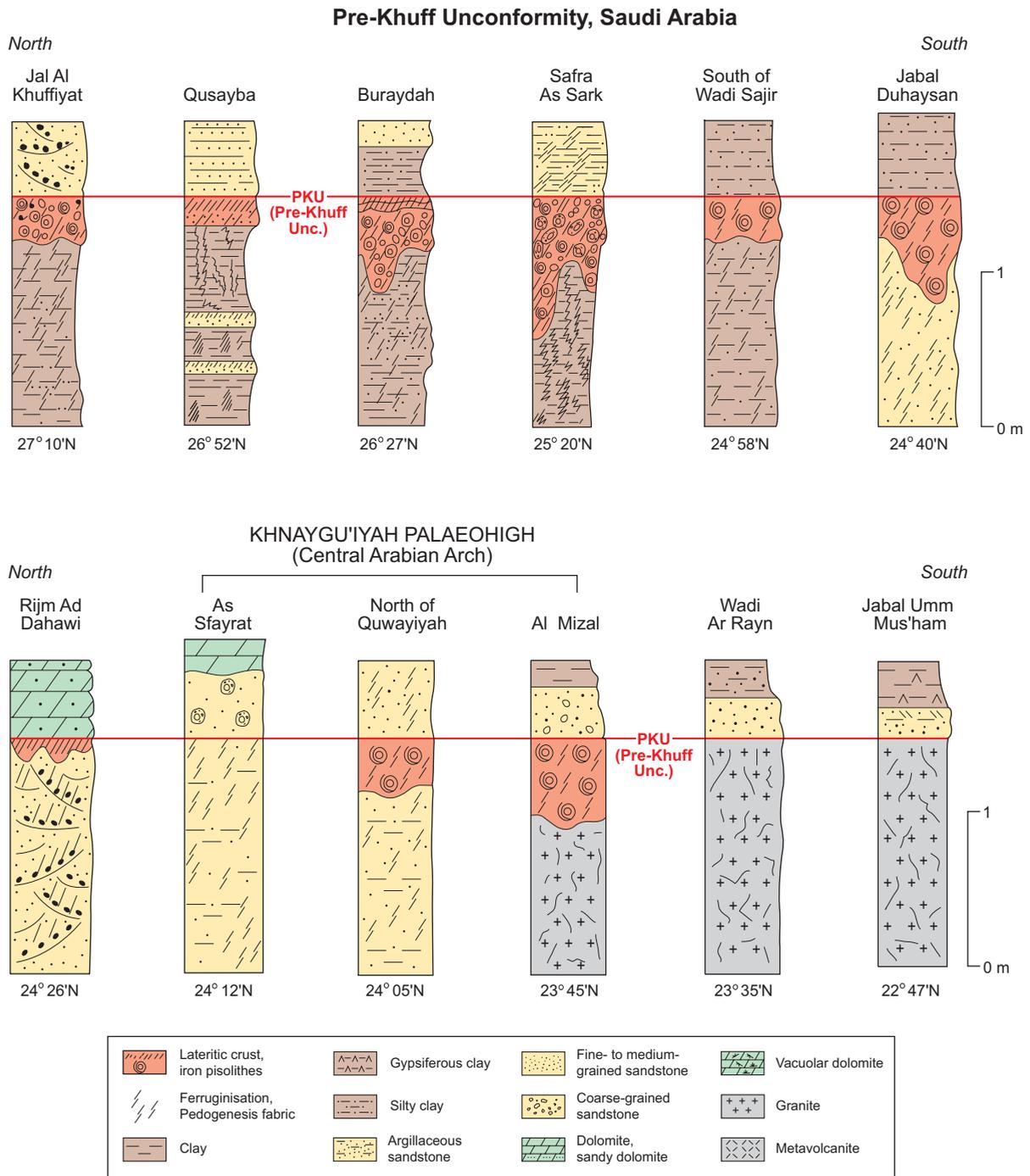


Figure 7 (facing page and this page): Regional correlation of the Pre-Khuff Unconformity in the outcrops of central Saudi Arabia. A pedogenic lateritic alteration surface (indicated in red) is developed over outcrops and enhances this unconformity. The lateritic layer is represented either by a duricrust containing goethite pisoliths or by an iron crust. The main outcrops of the pisolitic duricrust are located between Jal al Khuffiyat and Wadi Ar Rayn, corresponding to a palaeohigh in the Khnaygu'iyah area where the Ash Shiqqah Member is locally reduced to a single sandstone bed. The Khnaygu'iyah palaeohigh is located above the Central Arabian Arch (Figures 5, 6 and 9).

Formation (Figure 16). They assigned basal subunits 1 and 2 of Manivit et al. (1986) to the Unayzah Formation and subunit 4 to the Huqayl Member of the Khuff Formation. Senalp and Al-Duaiji interpreted a sequence boundary between subunits 1 and 2.

In a later study in the Ash-Shiqqah area of the Buraydah quadrangle, M. Senalp and A. Al-Duaiji (written communication, 2001) proposed the basal Khuff clastics (Ash Shiqqah Member of the Khuff Formation in their 1995 paper) as the Ash Shiqqah formation in a type section (26°22'44.6"N, 43°54'13.8"E; located 1.5 km south of the flour mill on the west side of the Buraydah-Hail highway). They divided the Ash Shiqqah formation into lower and upper units (Figure 16) separated by an unconformity associated with incised channels. They described the lower Ash Shiqqah Member to consist of argillaceous and extensively burrowed dolomitic algal limestone at the base (one metre thick) followed by 10.3 m (33.8 ft) of interbedded yellowish gray marl and dark gray, laminated, fissile, and organic-rich shale.

In 1997, a field trip by teams from Saudi Aramco and BRGM allowed D. Vaslet and M. Senalp to compare their observations. As a result, Vaslet proposed revising the lower boundary of the Khuff Formation in the Buraydah quadrangle, and to place it above the top of subunit 2 (Figure 16) at the change in colour between dark red for the lower part and yellowish or gray-green for the upper part. The Ash Shiqqah Member is thus limited to subunits 3 and 4, and only 42.5 m (139.4 ft) thick. This revision is supported by the presence of pedogenetised sandstone and claystone at the top of subunit 2 (Figure 16) as observed by Vaslet in 1996, while re-sampling the Khuff Formation for palaeomagnetic studies (Torcq et al., 1997), and in 1998 while re-sampling the Unayzah Flora with J. Broutin. D. Vaslet proposed correlating this pedogenetic event with the ferruginised crust observed southwards in other sections at the lowest part of the Ash Shiqqah Member (Figure 7).

Based on the above considerations, the four subunits of Manivit et al. (1986) are here interpreted (Figures 14 and 16) from base to top:

- (1) Unayzah Formation: estimated as 23 m (75.4 ft) green and purplish-red very pedogenetised claystone; only the top 2 m (6.6 ft) of the claystone are visible in outcrop. The remainder of subunit 1 was observed over a thickness of 20 m (65.6 ft) in trenches dug to channel water (Figure 17). The claystone overlies very pedogenetised sandstone. The top part of the claystone is very

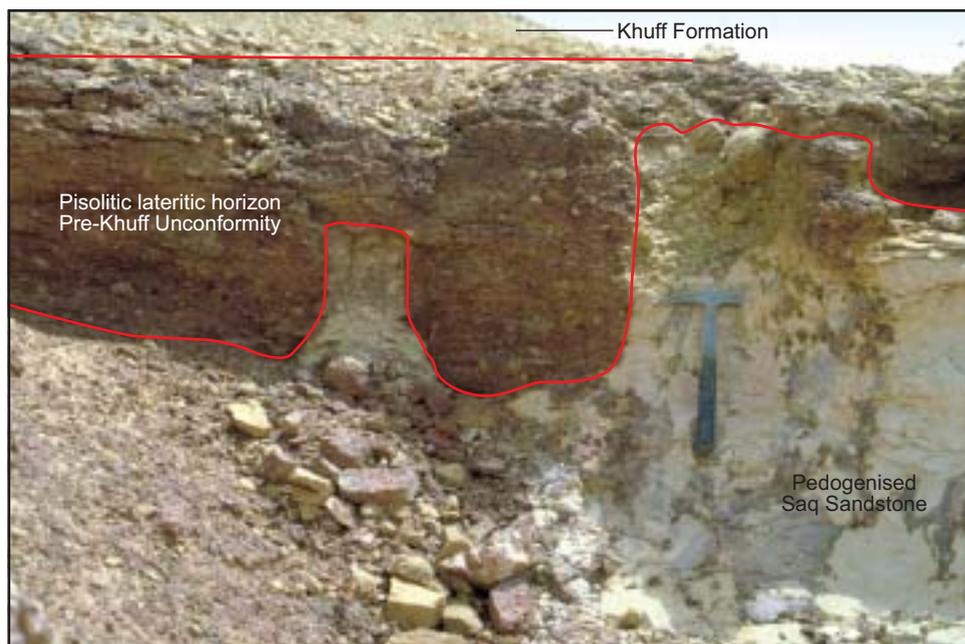


Figure 8: Pre-Khuff Unconformity (PKU) in Wadi Sajir area, Ad Dawadimi quadrangle. A pisolitic lateritic horizon (palaeosol), developed over Saq Sandstone, prior to deposition of the Khuff Formation. Photo by D. Vaslet, 1979.

laminated and has produced a rich flora (Unayzah Flora, described by El-Khayal et al., 1980; Lemoigne, 1981a, 1981b; El-Khayal and Wagner, 1983, 1985; Hill and El-Khayal, 1983; Broutin et al., 1995; and see section "Fossils and Age of the Khuff Formation");

- (2) Unayzah Formation: 4.5 m (14.8 ft) conglomeratic sandstone and medium-grained, slightly consolidated sandstone, channelled into subunit 1;
- (3) Ash Shiqqah Member: 32 m (105 ft) alternating gray claystone with gypsiferous intervals and green dolomitic claystone; the upper part displays intervals of fine-grained sandstone locally interpreted as tidal channels, and containing ligneous debris and ripple marks (Figure 18);
- (4) Ash Shiqqah Member: 10.5 m (34.4 ft) carbonate assemblage of beige laminated (possible algal films) dolomite and bioturbated and bioclastic clayey dolomite.

LATERAL VARIATIONS WITHIN THE KHUFF FORMATION

In this section, the lateral variations of the members of the Khuff Formation are described. The order of presentation proceeds member-by-member, and northwards from the type section in the Ad Dawadimi quadrangle (Figure 1), and then southwards (Figure 5).

Ash Shiqqah Member: Northwards of the Type Section

To the north, the Ash Shiqqah Member progressively increases in thickness. In the Al Faydah quadrangle (Vaslet et al., 1985a), the member is 47 m (154.2 ft) thick at 25°20'N (Safra as Sark-Al Faydah; Figures 5, 9 and 19). The lower half of the member comprises predominantly green silty claystone with secondary gypsum, but also contains dolomite beds and 5 m (16.4 ft) above the base, dark-gray fine-grained bedded sandstone with ripple marks. The upper half of the member is more calcareous, consisting in clayey algal laminated dolomite with fenestrate structures, finely bioclastic dolomite, and rare sandstone beds.

In the Buraydah quadrangle (Manivit et al., 1986), the Ash Shiqqah Member reaches a thickness of 42.5 m (139.4 ft) in the reference section at 26°05' (Unayzah, Figures 5, 14–16). Further north, at 26°27'N, in the Buraydah Ash Shiqqah-At Tarafiyah section (Figure 5), Manivit et al. (1986) identified four subunits (37.5 m or 123 ft thick) that they considered to be the "Unayzah member". Here subunit 1 (3.5 m or 11.5 ft thick), of which the basal contact with a ferruginous crust is visible, consists of reddish pedogenetised clay and sandstone. This subunit corresponds to the lower part (subunits 1–3) of the reference section near Unayzah town (Figures 5 and 16), and is here attributed to the Unayzah Formation (*sensu* subsurface). The Ash Shiqqah Member is limited to the subunits 2–4 of Manivit et al. (1986), consisting of:

- (2) 12 m (39.4 ft) thick, yellow to green clay and yellow dolomite;
- (3) 4 m (13.1 ft) thick microconglomeratic sandstone channel containing silicified tree trunks as much as 5 m (16.4 ft) long and aligned with the bedding;
- (4) 15 m (49.2 ft) alternation of green clay and yellow manganese rich dolomite which is locally collapsed and presents intense solution breccias (Figure 20).

Further north at 26°52'N (Figure 1), subunits 1–4 are about 60 m (196.8 ft) thick (Manivit et al., 1986). Sandstone facies clearly predominate over clay facies in the first 52 m (170.6 ft), occurring either as bedded sandstone or as channels of coarse-grained and microconglomeratic sandstone containing fragments of silicified wood. Fishbone structures and inclined overturned beds are observed in the bedded sandstone. The upper part is, however, finer grained (silty and sandy). The carbonate sequence (8 m or 26.2 ft thick) of subunit 4 at the top, is similar to the section at Unayzah town, but is interbedded with a layer of brown conglomeratic sandstone (2 m or 6.6 ft thick).

North of 26°55'N (Figure 1), in the Qibah quadrangle (Robelin et al., 1994) and in the Baqa quadrangle (Vaslet et al., 1986), outcrops of the Ash Shiqqah Member are rare (Jal al Khuffiyat at 27°10'N; Al Khuwayr at 27°40'N), but the facies remain comparable to those observed at the latitude of Qusayba.

Central Arabian Arch, Unayzah Formation, Ash Shiqqah Member, and Khuff-D Anhydrite

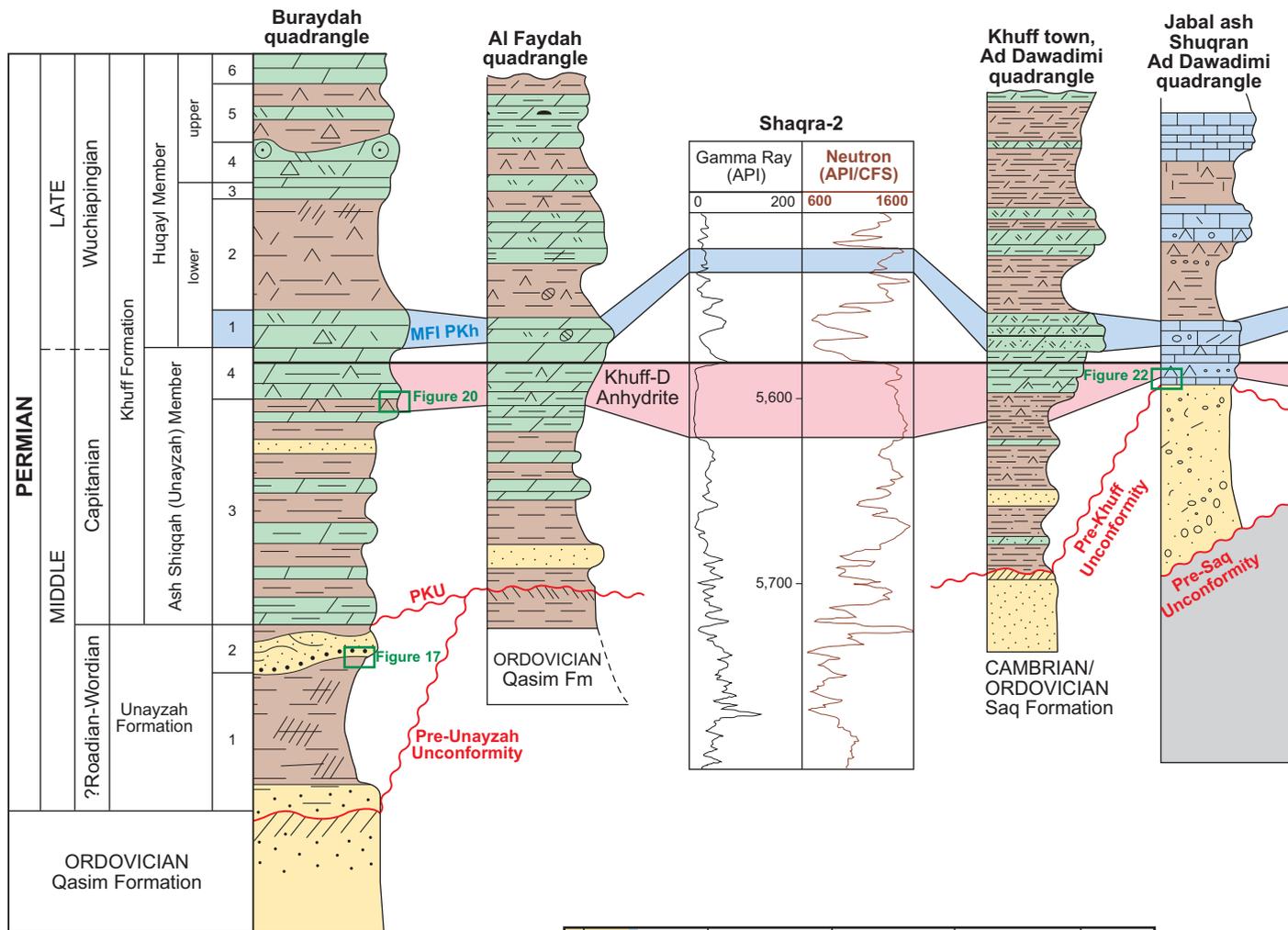
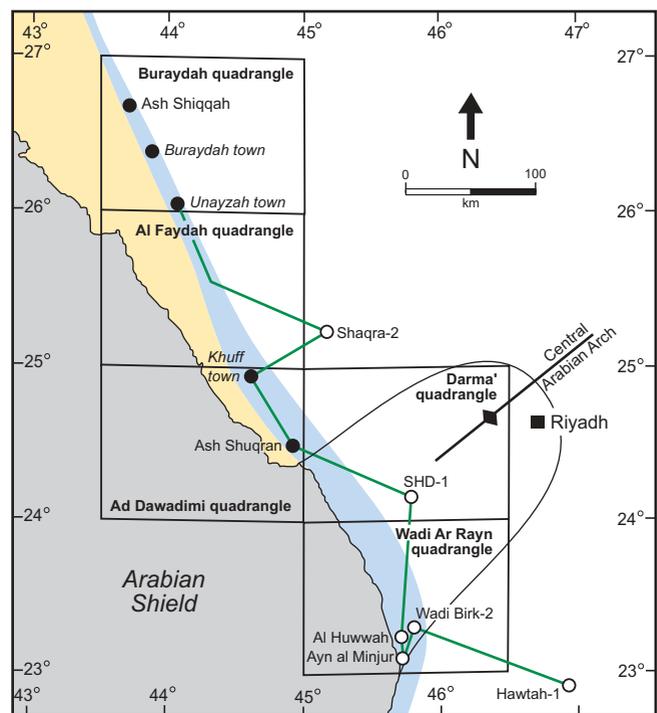


Figure 9: Regional traverse of the subsurface Unayzah Formation, Ash Shiqqah Member and Khuff-D Anhydrite (Shaqra-2, Wadi Birk-2 and Hawtah-1; modified after Ferguson and Chambers, 1991) is shown together with the Ash Shiqqah and Huqayl members in the Buraydah (Manivit et al., 1986), Al Faydah (Vaslet et al., 1985a) and Ad Dawadimi (Delfour et al., 1982) quadrangles, and SHD-1 well (Manivit et al., 1983, 1985a). The Al Huwwah field section measured south of the Wadi Ar Rayn quadrangle (Vaslet et al., 1983; Le Nindre et al., 1990a; Figures 1 and 5), and located close to the Wadi Birk-2 location is shown to correlate vertically between outcrops and subsurface. In this traverse the Khuff-D Anhydrite is correlated to the upper part of the Ash Shiqqah Member.



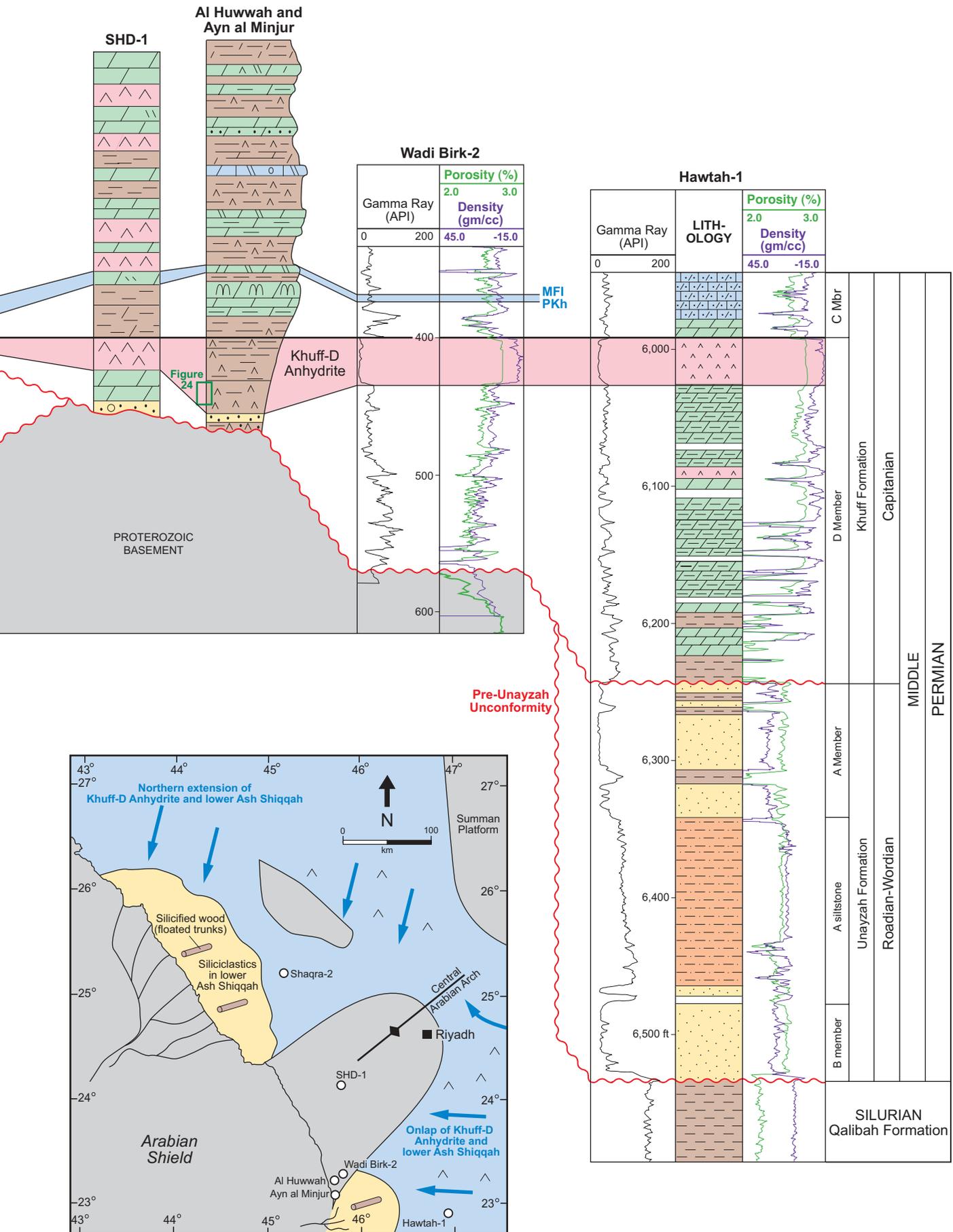




Figure 10: Duhaysan Member in Wadi Maghib area, Ad Dawadimi quadrangle. Bioclastic (nautiloids and gastropods) and reworked intraclastic calcarenite lying on an erosion surface over laminated limestone in the Duhaysan Member. Photo by Y.-M. Le Nindre, 1979.

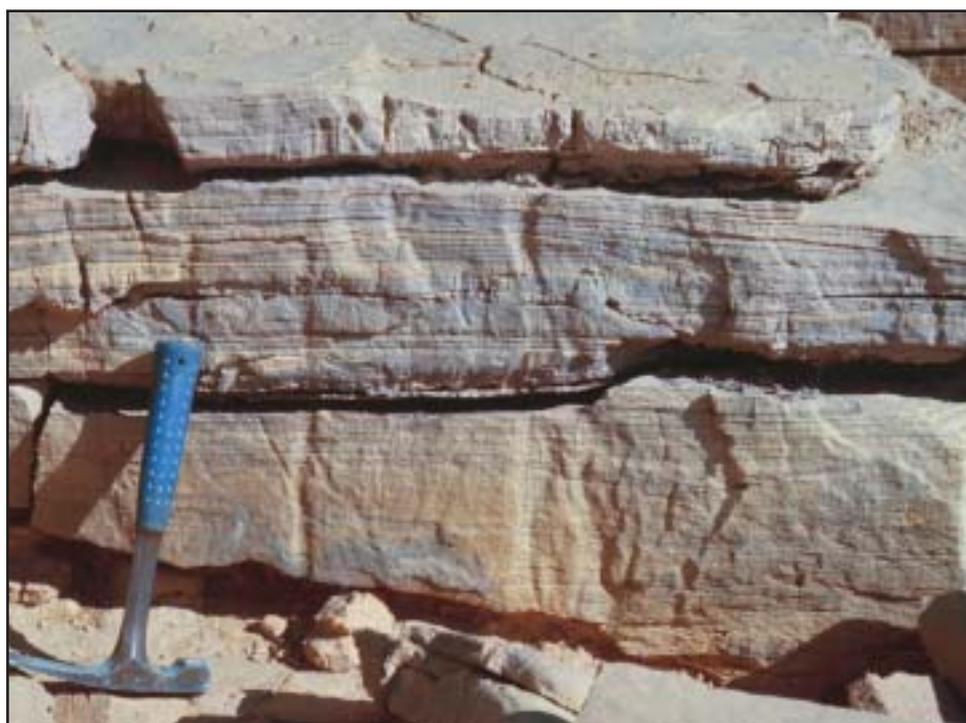


Figure 11: Khartam Member in Khuff town area, Ad Dawadimi quadrangle. Oolitic carbonate sand megaripple, in the Khartam Member. Photo by Y.-M. Le Nindre, 1979.

Ash Shiqqah Member: Southwards of the Type Section

Southwards from the type section, the clayey component of the Ash Shiqqah Member decreases abruptly, and is only 10 m (32.8 ft) thick at the latitude of Jabal Duhaysan ($24^{\circ}40'N$; Figures 5 and 21). The clayey facies completely disappears at $24^{\circ}27'N$ (Jabal ash Shuqran-Rijm ad Dahawi), where the member is only represented by 2 m (6.5 ft) of intraclastic dolomite alternating with sandstone beds and solution breccia horizons together with pseudomorphosed gypsum nodules (Figures 9 and 22). This thinning occurs over the Central Arabian Arch (Powers et al., 1966). South of the Arch, the member again increases in thickness and clayey facies.



Figure 12: Khartam Member in Khuff town area, Ad Dawadimi quadrangle. Domal columnar stromatolite in the Khartam Member. Photo by Y.-M. Le Nindre, 1979.

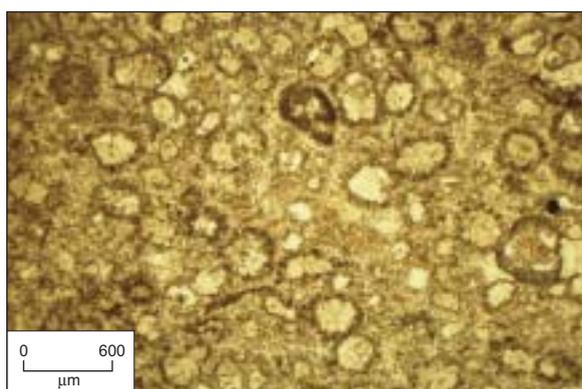


Figure 13: Microfacies of the Khartam Member in SHD-1 well, Darma' quadrangle. Oolitic limestone facies of the Khartam Member. The ooids in the centre of the photo are calcitized former dolomite. The external part of the ooids present former structures of dasycladacean algae (*Aciculella* sp.), indicating that the limestone was made by accumulation of rounded dasycladacean ooids. Photo by Y.-M. Le Nindre, 1985.

In the Ad Dawadimi quadrangle (Delfour et al., 1982), between 24°25'N and 24°10'N (in the vicinity of the Central Arabian Arch), the thickness of the member is 1.5–3.25 m (4.9–10.6 ft). Here, the substratum displays complex horst and graben structures, variably covered by detrital deposits attributed to the underlying Unayzah Formation (coarse- and medium-grained bedded sandstone, locally bioturbated), pre-dating the lateritic episode. The Khnaigu'iyah area contains copper and zinc mineralisation (Le Nindre et al., 1990b), local copper occurrences being located in the Ash Shiqqah Member at As Sfayrat (24°12'N). In this locality, the member comprises:

- (1) 2 m (6.5 ft) sandstone containing rounded fragments of malachite-bearing clayey tuffite that channels the underlying bedrock also composed of cupriferous tuffite;
- (2) 0.5 m brown sandy dolomite;
- (3) 0.75 m brown crystalline dolomite containing columnar stromatolites about a metre wide, capped by a layer showing mud cracks; these stromatolites are impregnated with copper mineralisation, and the dolomitic layers show marked Sr and Ba anomalies.

South of the Central Arabian Arch, the thickness of the Ash Shiqqah Member progressively increases to 10 m or more. In the Darma' quadrangle (Manivit et al., 1985a), the member is 12 m (39.4) thick at Al Quway'iyah (24°07'N, Figure 5), beginning with fine-grained sandstone with a sparitic cement and ended with green silty claystone, clayey dolomite, and pitted sparry dolomite.

Khuff Formation, Buraydah quadrangle, Saudi Arabia

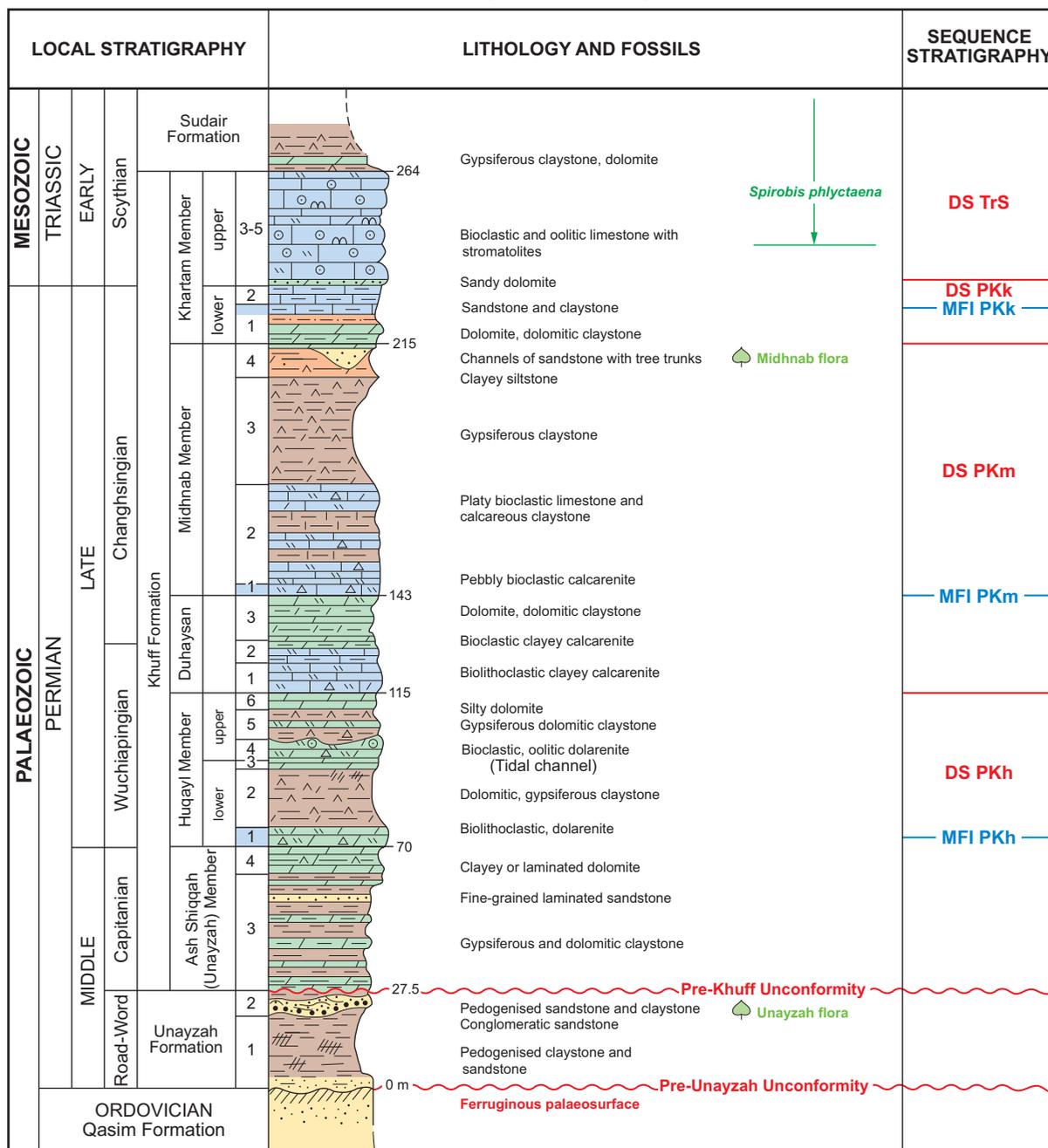


Figure 14: Composite section of the Khuff Formation in the Buraydah quadrangle (Manivit et al., 1986). See Figure 1 for location, and Figures 5 and 9 for regional correlation.

West of the town of Al Quway'iyah, Senalp and Al-Duaiji (1995) described a similar succession (8 m, 26.2 ft thick) to the one measured by Manivit et al. (1985a). The former authors considered this succession as the Unayzah Formation, and not the Ash Shiqqah Member. They attribute this interpretation to the detection of a red-coloured, oxidised, weathered zone at the top of the succession, below the Khuff limestone.

Also at the Quway'iyah area, Cole et al. (2000) describe a well-exposed section from basement to the uppermost part of the Huqayl Member in road cuts on the Riyadh-Mecca highway. Its basal clastic succession consists of well-developed, trough cross-bedded, red and green sandstone interpreted as point-bar deposits. The exposures oscillate between clastic and carbonate sedimentation. The overlying

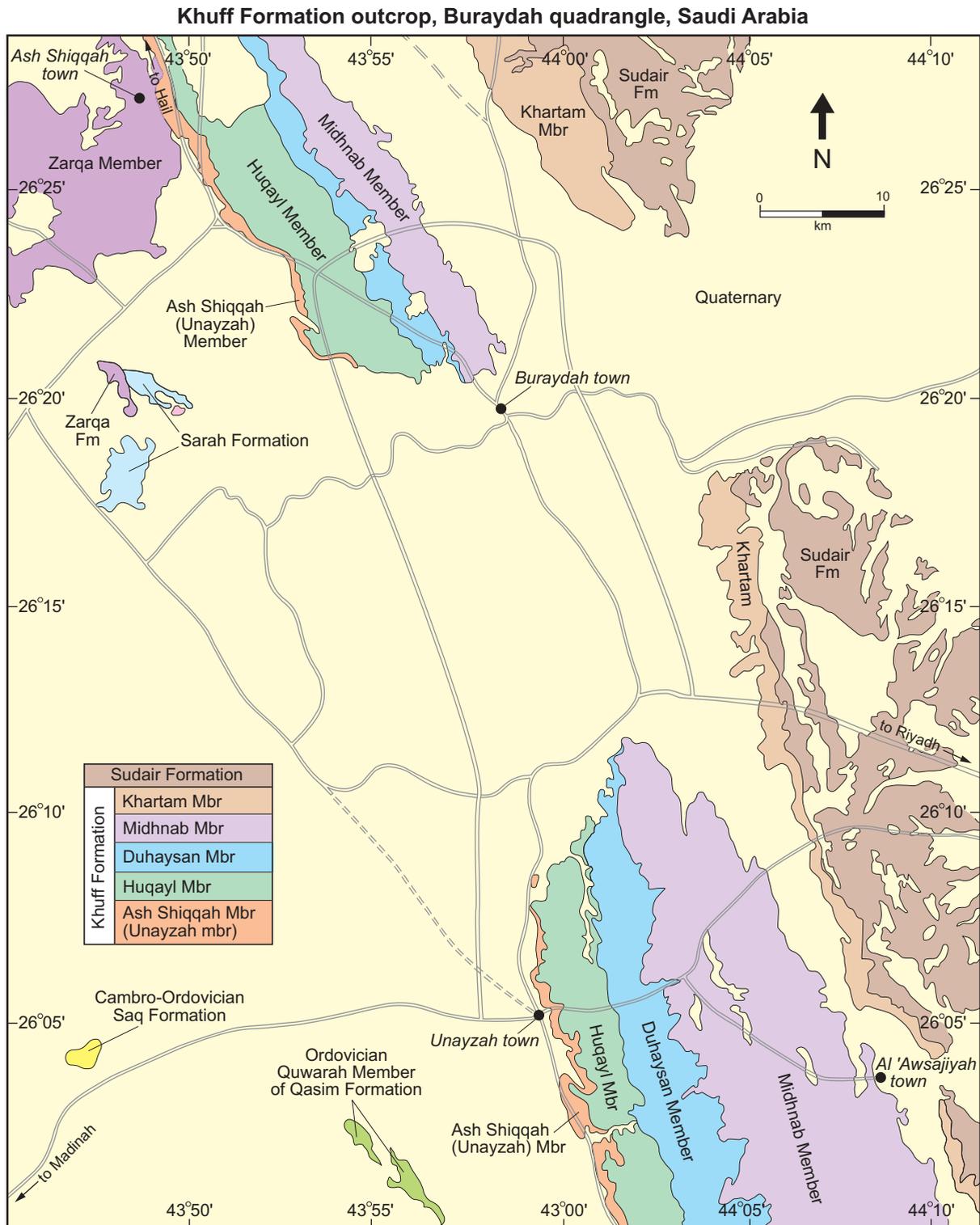


Figure 15: Outcrop of the members of the Khuff Formation of Delfour et al. (1982) in the Buraydah quadrangle (Manivit et al., 1986). See Figure 1 for location of Buraydah quadrangle.

3–5 m (9.8–16.4 ft) of cross-bedded, red and green feldspathic sandstones, coarse clastics, and marls contain interbedded dense, dolomitic mudstones 10 cm thick. Large salt hoppers are present in the marls.

Located in the Darma' quadrangle, the SHD-1 well (Figure 1; 24°13'40"N, 45°37'30"E; Manivit et al., 1985a; Le Nindre et al., 1990b) encountered the five Khuff members proposed by Delfour et al. (1982). The Khuff Formation in this well is 272.1 m (892.4 ft) thick (encountered between 413.0 m and 685.1 m),

"Ash Shiqqah" and "Unayzah" of central Saudi Arabia

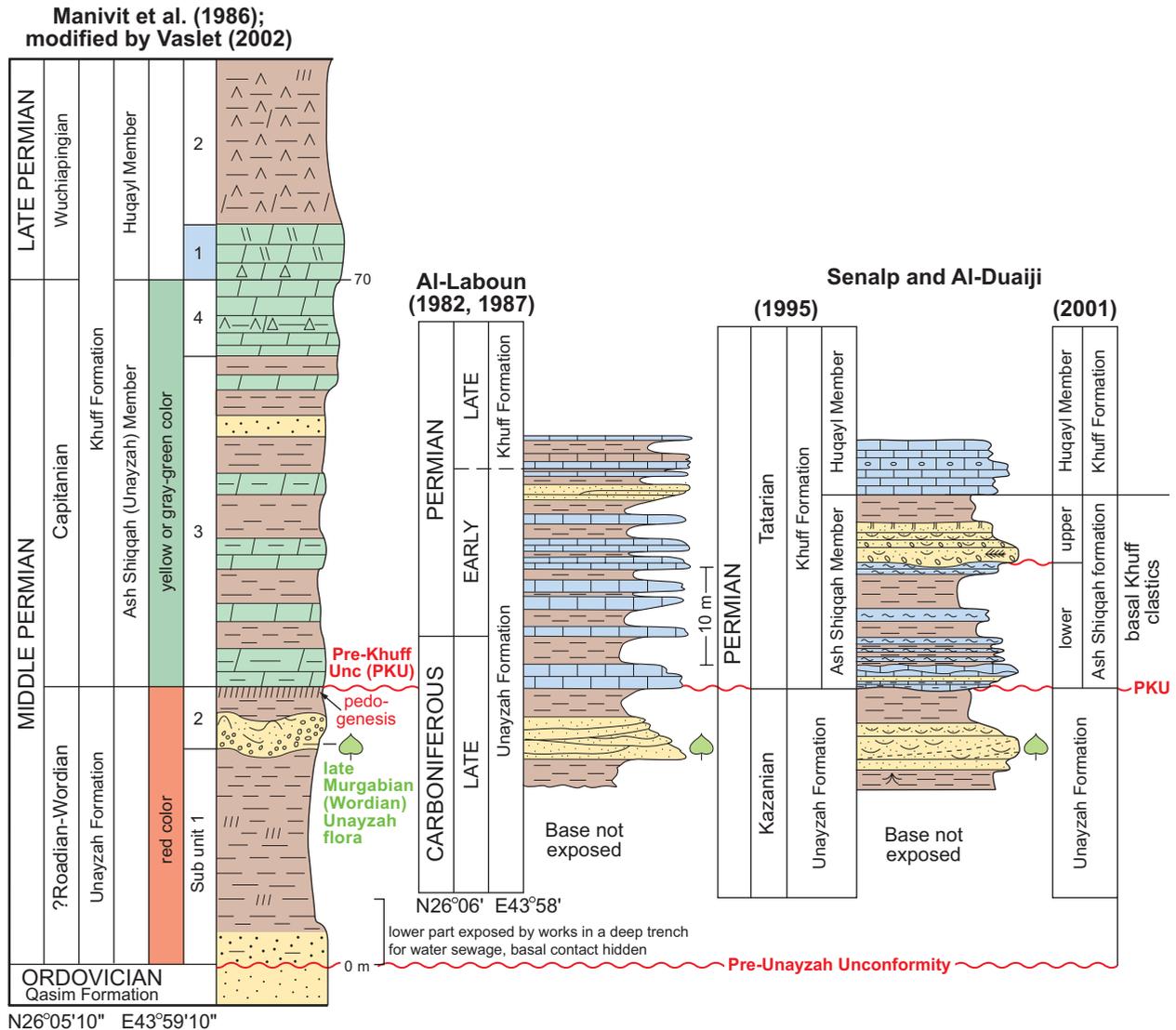


Figure 16: Comparison of the definitions of the succession near Unayzah town in Buraydah quadrangle: (1) Ash Shiqqah Member or previous 'Unayzah member' of Khuff Formation of Delfour et al. (1982) as measured by Manivit et al. (1986) in Figure 14 (modified by D. Vaslet); (2) Unayzah Formation of Al-Laboun (1982, 1987); and (3) Unayzah Formation and Ash Shiqqah Member or basal Khuff clastics (Senalp and Al-Duaiji, 1995, 2001). See Figures 1 and 9 for location of Buraydah and Unayzah towns.

and overlies the Proterozoic granodiorite basement (Figure 23). In this completely cored well, the Ash Shiqqah Member is 28 m (91.8 ft) thick and encountered between 657.0 m and 685.1 m. In this well the member is thicker than in nearby outcrops, some 40 km to the west and this may in part be due to the presence of undissolved evaporites (Manivit et al., 1985a). The member consists from base up of:

- (1) 1 m (3.3 ft) conglomerate and coarse sandstone in an argillaceous matrix, sometimes carbonaceous, with pyritic nodules and fine ligneous debris;
- (2) 10 m (32.8 ft) argillaceous dolomite with anhydrite nodules;
- (3) 7 m (23 ft) of massive anhydrite;
- (4) 10 m (32.8 ft) of emerald-green, dolomitic shale with fine beds of dolomite and anhydrite.

In the Wadi Ar Rayn quadrangle (Vaslet et al., 1983), the Ash Shiqqah Member is composed mainly of emerald-green silty, gypsiferous claystone (Vaslet et al., 1983). The total thickness ranges from 11–55 m



Figure 17: Unayzah Formation in Unayzah town, Buraydah quadrangle. Fluvial channel in pedogenised claystone in the upper part of the Unayzah Formation. The Unayzah Flora is located at the base of the channel. Photo by D. Vaslet, 1983.



Figure 18: Ash Shiqqah Member in Unayzah town, Buraydah quadrangle. Sandstone tidal channels with inclined bedding, in the upper part of the Ash Shiqqah Member. The pylone is located on the basal bed of the Huqayl Member. Photo by D. Vaslet, 1983.

(39.1–180.4 ft) depending on the development of the clay layers (Figures 1 and 5). The basal part of the member is 1–2 m (3.3–6.6 ft) thick, and consists of a sandstone bed. In the south of the quadrangle it yielded silicified fossil wood debris and has the characteristics of reworked granitic sand in a fluvial to littoral margin environment. In this southern area (Ayn al Minjur), a 3 to 4 m thick massive gypsum bed (?anhydrite at depth), occurs in the lower part of the gypsiferous claystone unit of the Ash Shiqqah Member (Figure 24). Locally, yellowish or gray, fine-grained dolomite occurs in rare layers in the lower third of the Ash Shiqqah Member, but the upper third of the member is dolomitic with cream coloured, dolomite; and gray, very bioturbated, granular dolomite. The top of the member is stromatolitic in the north and center of the quadrangle, and oncolitic in the south. In the southern area of Wadi Ar Rayn quadrangle, the upper part of the Ash Shiqqah Member is deformed by intense collapse structures and sliding.

Khuff Formation, Al Faydah quadrangle, Saudi Arabia

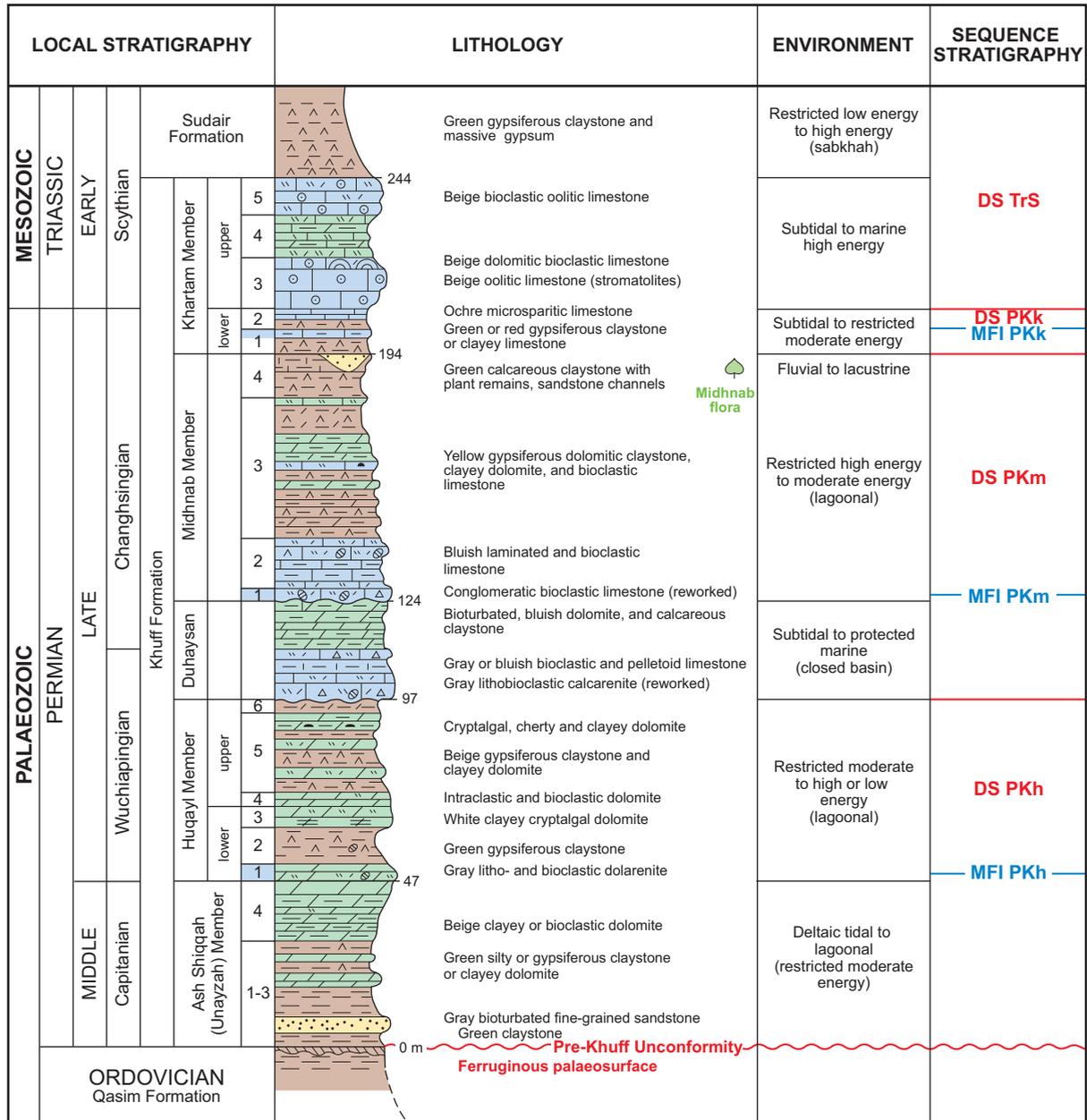


Figure 19: Composite section of the Khuff Formation in the Al Faydah quadrangle (Vaslet et al., 1985a). See Figure 1 for location, and Figures 5 and 9 for regional correlation.

Also in the Wadi Ar Rayn quadrangle (Figure 1), Cole et al. (2000) measured a section attributed to the Khuff Formation at 23°33'33"N and 45°33'14"E that overlies the weathered basement. The lowermost 38-m-thick (124.6 ft) unit consists of a thin (some inches to one foot thick, about several cm to 30 cm) basal conglomeratic sandstone overlain by green gypsiferous shales, and dolomite. At the nearby Gazelle Hill, the basal unit consists of 25–50 cm (about 1–2 ft) of red, poorly sorted, feldspathic, trough cross-bedded sandstone and coarse clastics that overlies a regolith of highly weathered granitic basement. These clastics are succeeded abruptly by 3–5 m (9.8–16.4 ft) of red and green marls overlain by 3 m (9.8 ft) of interbedded thin sandstones and sandy dolomites followed by 10 m (32.8 ft) of finely laminated dolomites.

Located in the Wadi Ar Rayn quadrangle, the Wadi Birk-2 well (Figures 1 and 7; 23°14'7"N, 45°47'13"E) was drilled directly in the Khuff outcrop. In this well, a section of about 21 m (68.9 ft) of clastics was



Figure 20: Ash Shiqqah Member in Ash Shiqqah area, Buraydah quadrangle. Collapse structures and solution breccias in the top most part of the Ash Shiqqah Member. Photo by Y.-M. Le Nindre, 2002.

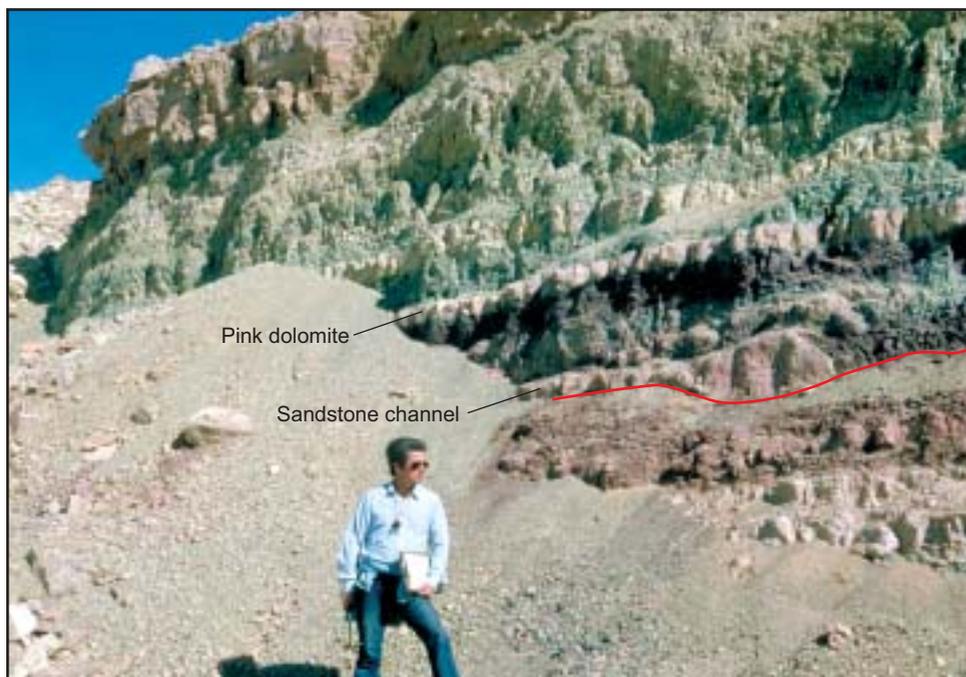


Figure 21: Ash Shiqqah Member in Jabal Duhaysan, Ad Dawadimi quadrangle. Salt marsh facies in the lower part of the member. Note the pink dolomite, mid-way to the top, and the fluvial sandstone channel in the first third. Photo by D. Vaslet, 1979.

encountered above the granitic Proterozoic basement. This section is referred to as the basal Khuff clastics, and from base up it consists of (Cole et al., 2000):

- (1) 5 ft (1.52 m; 570–565 ft) red siltstone;
- (2) 32 ft (9.8 m; 565–533 ft) green and black shales with a one foot sandstone stringer between 565–564 ft, and a 5 ft sandstone stringer between 562–537 ft;
- (3) 2 ft (0.61 m; 533–531 ft) friable red claystone;
- (4) 20 ft (6.1 m; 531–511 ft) mottled dolomudstone;
- (5) 10 ft (3 m; 511–501 ft) green and black shales.



Figure 22: Ash Shiqqah Member in Jabal Ash Shuqran, Ad Dawadimi quadrangle. The Ash Shiqqah Member is represented by few beds of dolomite, sandstone (Sst), solution breccia dolomitic beds (Br), and pseudomorphosed anhydritic nodules (N). Photo courtesy of B. Murat, 2002.

Above the clastic section another 10 m (32.8 ft) of bioclastic dolomites was encountered below an anhydrite bed, about 8 m (26.2 ft) thick, attributed to the Khuff-D Anhydrite (Ferguson and Chambers, 1991).

In the Wadi al Mulayh quadrangle (Figure 25; Manivit et al., 1985b) the Ash Shiqqah Member increases in thickness to 36 m (118.1 ft). This member was not recognised in the study by Al-Aswad (1997; Figure 26). Close to the Wadi al Mulayh (22°25'N), the lithology remains similar, with white sandstones with rare crustacean thoracic shields remains and abundant plant matter (Jabal Umm Mus'ham in Figure 5), and emerald-green claystone at the base (5-7 m, 16.4-52.5 ft) in which occur metre-thick beds of massive gypsum (anhydrite at depth?), and a succession of clayey or bioclastic dolomites, bioturbated and rarely stromatolitic (22°50'N).

The Ash Shiqqah Member is unknown in outcrop south of 22°10'N.

Huqayl Member: Northwards of the Type Section

In the Al Faydah and Buraydah quadrangles (Figures 1 and 5), the Huqayl Member maintains relatively homogenous lithology and thickness (33–51 m or 108.2–167.3 ft) and its division into the lower and upper units. Some minor changes of facies however do occur. For example, oncolites locally replace the oolites at the base of subunit 1. At 26°05'N (Unayzah town, Figure 27), traces of pedogenesis in claystone of subunit 2 are observed together with extensive solution breccias which yielded, locally, south of Unayzah town, some pinkish gypsum nodules of pseudomorphosed anhydrite. North of 26°05'N, subunit 3 contains local algal laminites, and the upper Huqayl Member contains a terrigenous fraction in the dolomites. Parts of the member (mainly subunits 3 and 6) are collapsed between 25°20'N (Al Faydah) and 26°25'N (Buraydah).

North of 26°40'N, in the Baqa quadrangle, the Huqayl Member is masked by surficial deposits. Only gray clayey dolomites crop out in disaggregated beds at 27°15'N (Shari) and east of Al Khuwayr (27°35'N).

Huqayl Member: Southwards of the Type Section

To the south in the Darma', Wadi Ar Rayn, and Wadi Al Mulayh quadrangles, the Huqayl Member is relatively constant in thickness (30–35 m, 98.4–114.8 ft) as far as 22°N. The lithologies are also very homogeneous, and the lower and upper parts of the member are everywhere clearly distinguished.

Khuff, Sudair and Jilh formations, SHD-1 well, Saudi Arabia

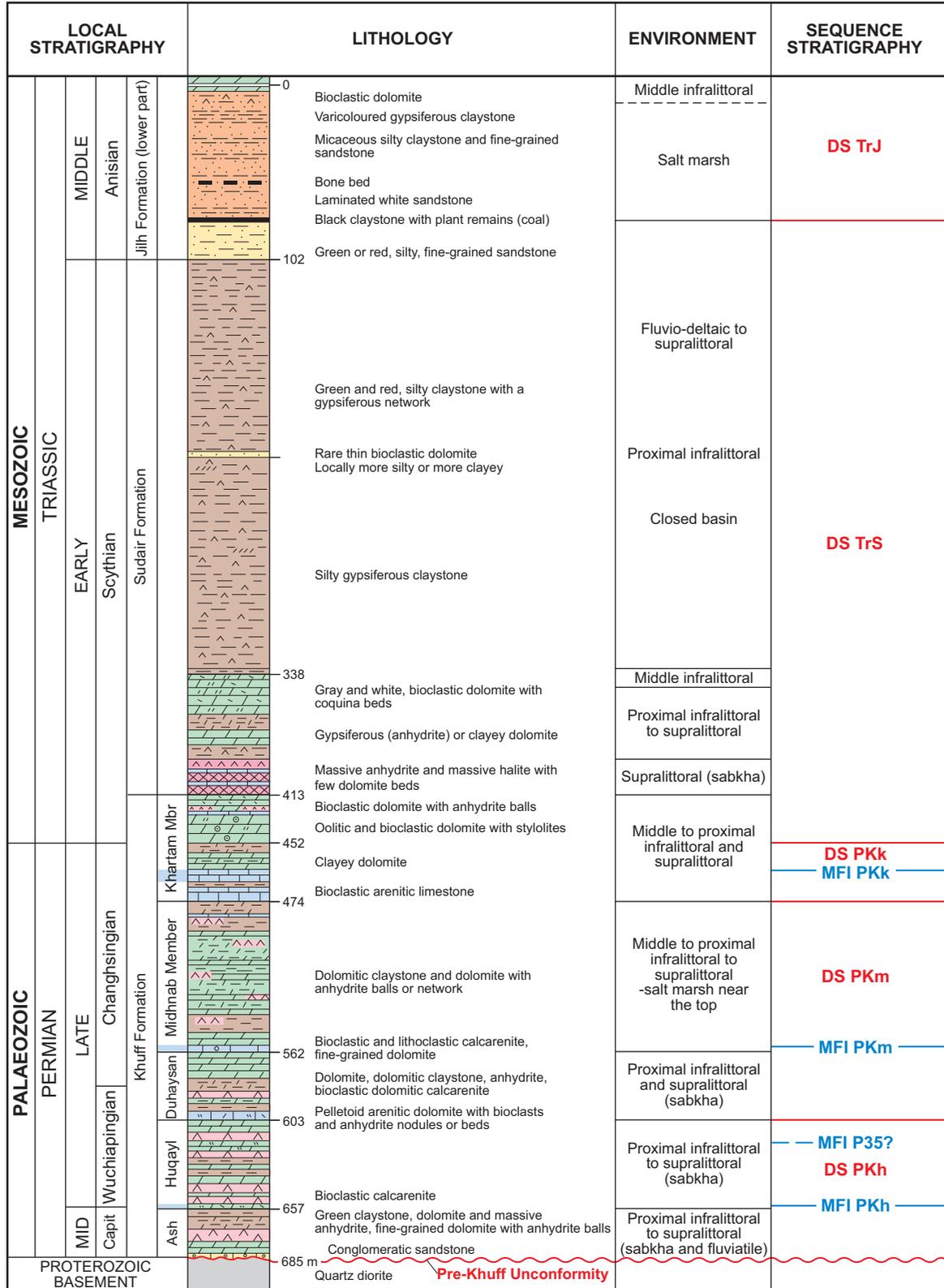


Figure 23: Lithology, environment (Manivit et al., 1983, 1985a) and sequence stratigraphy of the Khuff Formation in the SHD-1 well. See Figure 1 for location, and Figure 9 for regional correlation of lower Khuff members.



Figure 24: Ash Shiqqah Member in Ayn Al Minjur area, Wadi Ar Rayn quadrangle. Several meters thick massive gypsum, overlain by gypsiferous claystone in the lower part of the Ash Shiqqah Member. Photo by D. Vaslet, 2002.

Variations in lithologies are minor: the Lower Huqayl becomes enriched in peloids, and the base (subunit 1) displays cross-bedding and reworked mud galls toward 23°40'N (Ar Rayn), with oncolitic bioclasts and algae toward 23°10'N. In the vicinity of Wadi Al Mulaḥ (22°22'N), subunit 4 at the base of Upper Huqayl, contains an accumulation of Gymnocodiaceae (red algae) layers, overlain by an assemblage of cream-colored, in place gypsiferous, dolomitic containing algal layers.

In the Sulayyimah quadrangle (Vaslet et al., 1985b), at 21°55'N, an outcrop of clayey gypsiferous dolomite and brown fine-grained dolomite containing peloids, lithoclasts, and algal films is also assigned to the Huqayl Member.

Khuff Formation, Wadi Al Mulaḥ quadrangle, Saudi Arabia

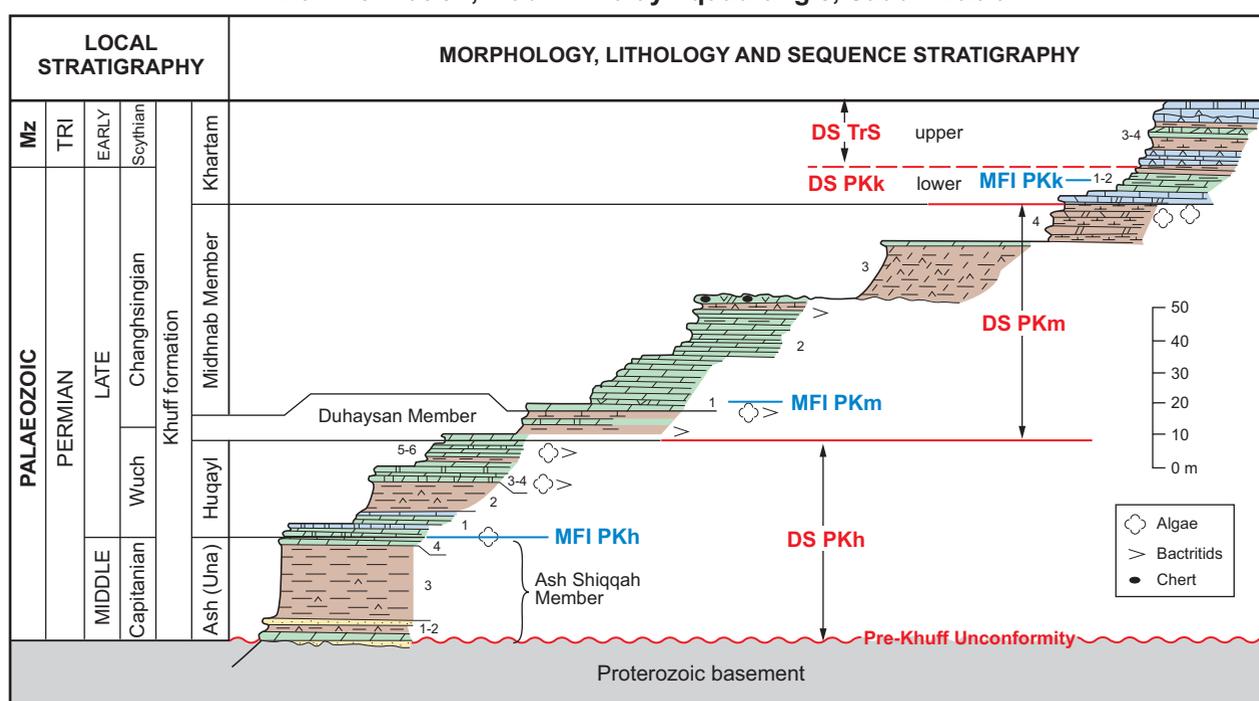


Figure 25: Composite schematic section of the Khuff Formation in Wadi Al Mulaḥ quadrangle (Manivit et al., 1985b). See Figure 1 for location, and Figures 5 and 9 for regional correlation.

Khuff Formation, Wadi Al Mulayh quadrangle, Saudi Arabia

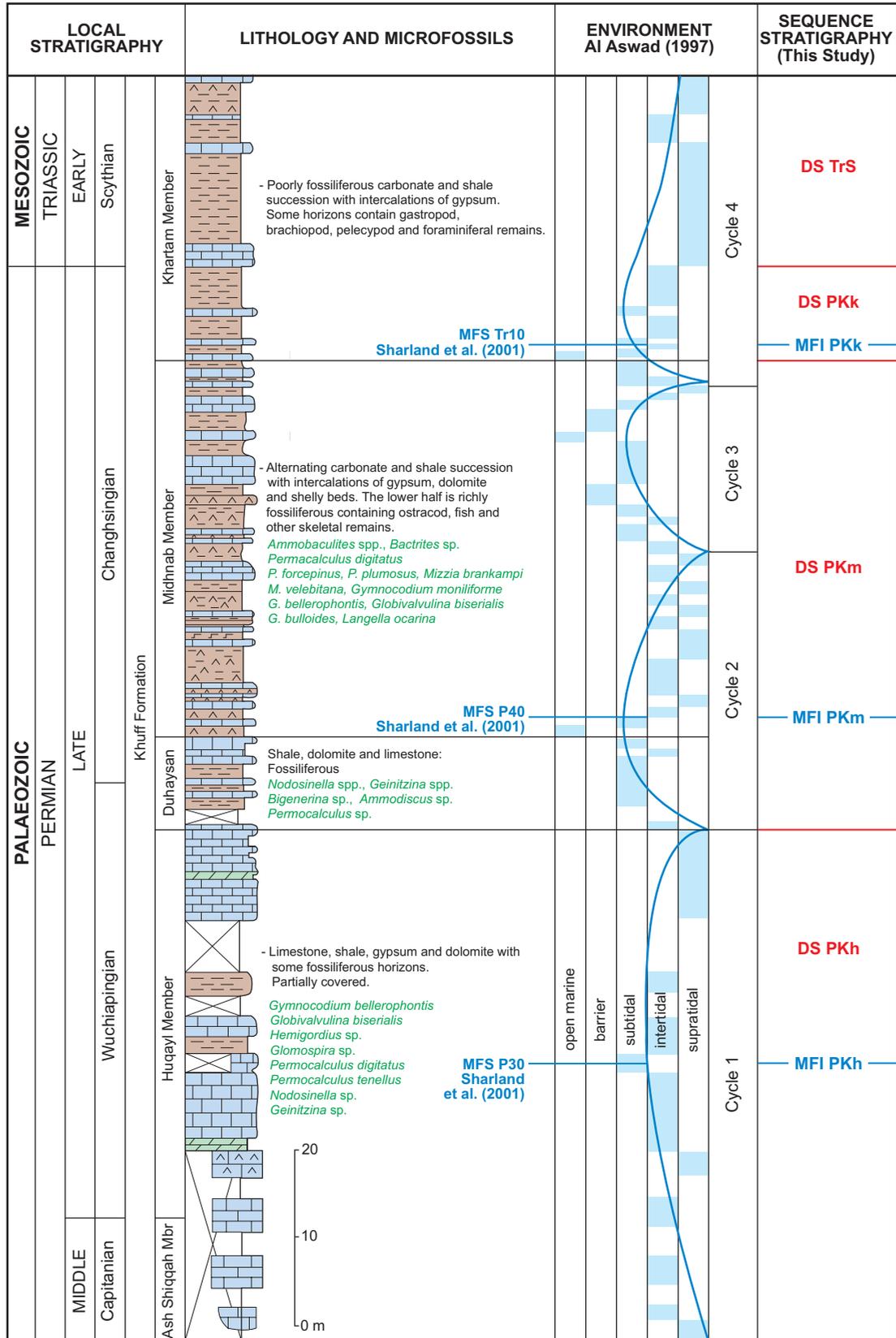


Figure 26: Composite section of the Khuff Formation based on 15 stratigraphic sections (Al-Aswad, 1997). Al-Aswad interpreted the Khuff Formation in terms of four transgressive-regressive cycles (shown as the blue line in "Environment" column). These cycles were adopted by Sharland et al. (2001) to tie maximum flooding surfaces MFS P30, P40 and Tr10. The interpretation shown in the right-hand column presents the new sequence stratigraphy interpretation. Note that cycle 3 of Al-Aswad that corresponds to the upper half of the Midhnab Member is not recognised as a depositional sequence by Manivit et al. (1985b) in the same quadrangle, nor elsewhere in outcrop. The list of microfossils has an historical interest but must be revised (see Vachard et al., 2005).



Figure 27: Huqayl Member in Unayzah town area, Buraydah quadrangle. Solution breccias and collapse breccias in the topmost part of the Lower Huqayl Member. Photo by D. Vaslet, 1983.

In the SHD-1 well (Figure 23), the Huqayl Member is 54 m (177.1 ft) thick and consists, as in outcrops, of two units (Manivit et al., 1983, 1985a; Le Nindre et al., 1990b). From the base, the lower unit consists of dolomite with bioclasts, dolomitic claystone and anhydrite, and fine-grained dolomite and massive anhydrite. The upper unit starts with intraclastic and bioclastic dolomite, argillaceous dolomite, followed by nodular dolomite with massive anhydrite.

Duhaysan Member: Northwards of the Type Section

The thickness of the Duhaysan Member varies from 25.5 m (83.6 ft) in the Al Faydah quadrangle, to 28 m (91.8 ft) in the Buraydah quadrangle (Figure 5). In many localities, the member is marked at the base (subunit 1) by a metre-thick layer of reworked lithobioclastic calcarenite (Figure 19). This layer is overlain by layers of laminated bioclastic peloidal limestone rich in marine fauna and peloidal calcarenite alternating with bioturbated clayey dolomite. At 25°55'N (Midhnab), bioclastic calcarenite forms tidal channels in subunit 3.

The Duhaysan Member is unknown in outcrop north of 26°40'N (north of Buraydah).

Duhaysan Member: Southwards of the Type Section

The Duhaysan Member is only 6 m (19.8 ft) thick between 24°30'N and 24°N over the Central Arabian Arch, in the Ad Dawadimi and Darma' quadrangles (Figure 5), where it appears to be



Figure 28: Midhnab Member in Al Faydah town area, Al Faydah quadrangle. Basal biocalcarenic bed of the Midhnab Member, reworking mudstone. Photo by D. Vaslet, 1982.

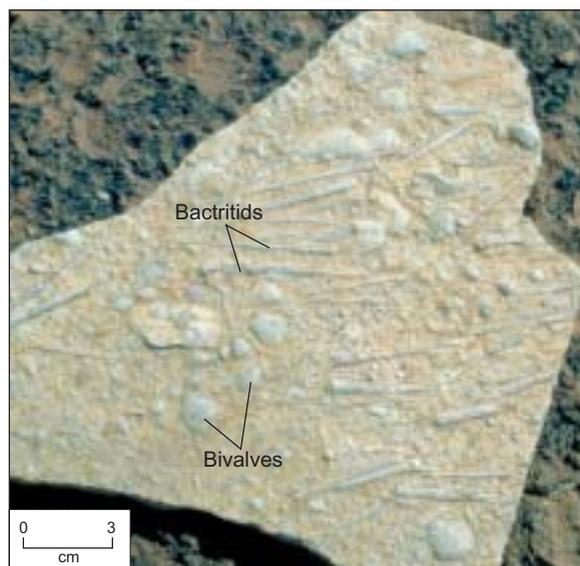


Figure 29: Midhnab Member in Al Faydah town area, Al Faydah quadrangle. Bactritids and bivalves in platy laminated limestone at the lower part of the member. Note the parallel orientation of the bactritids. Photo by D. Vaslet, 1982.

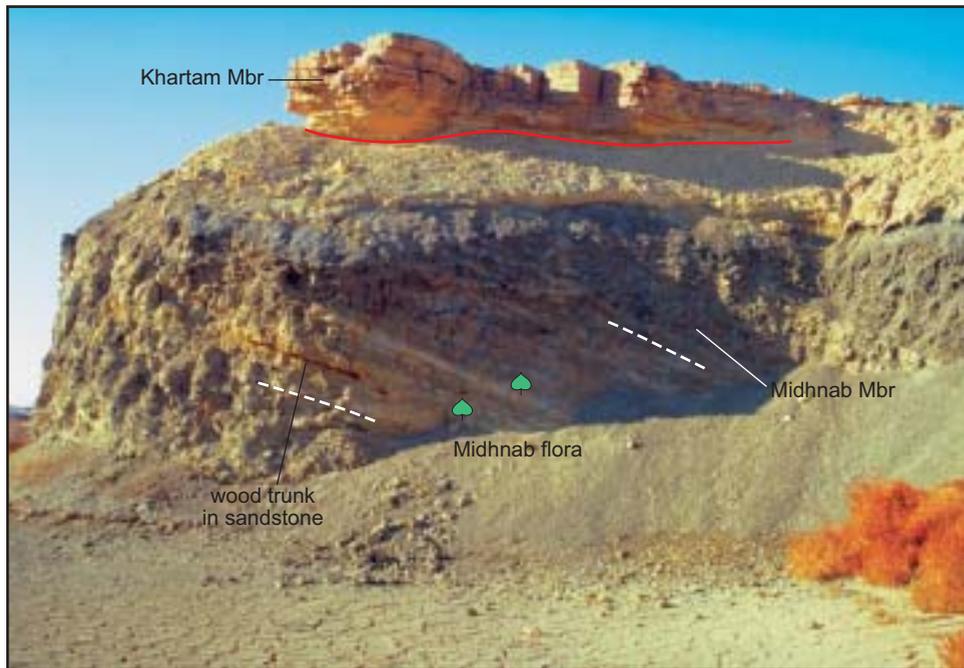


Figure 30: Midh nab Member at Jal al Khartam, Al Faydah quadrangle. Sandy oblique beds containing floated wood trunks, channelled into claystone. Both the sandstone and the claystone have yielded the Midh nab Flora, and are overlain by the basal dolomite of the Khartam Member. Photo by D. Vaslet, 1998.

mainly carbonate (bioclastic, dolomitic, and peloidal limestones; clayey limestone incorporating bioclastic dolomitic horizons). A number of benches of limestones contain marine fossils including conic-shaped fossils attributed to Bactritidae (Manivit et al., 1990).

In the SHD-1 well, the Duhaysan Member is 41 m (134.5 ft) (Figures 1 and 23; Manivit et al., 1985a). It comprises thin bioclastic limestone (3.5 m, 11.5 ft) that is overlain by marly dolomite interbedded with massive anhydrite beds.

In the Wadi Ar Rayn quadrangle (Vaslet et al., 1983), the member becomes thicker southwards, reaching 18 m (59 ft) at 23°N (Wadi Ar Rayn), where it is still essentially carbonate. The intraclastic and bioclastic dolomites, at the base, display cross-bedding; peloidal bioclastic dolomite dominates, and the succession ends with laminated, variably dolomitic gypsiferous claystone. The upper part of the member incorporates a layer of limonitic dolomitic sandstone south of 23°20'N.

The thickness of the member then decreases southwards in the Wadi Al Mulayh quadrangle, being only 6 m (19.7 ft) thick at 22°10'N. With the exception of the reworked layer at the base, the Duhaysan Member also becomes predominantly clayey and rich in gypsum, comprising gray-dolomitic and laminated-gypsiferous claystone.

Farther south, in the Sulayyimah quadrangle only one outcrop is attributed to the Duhaysan Member by Vaslet et al. (1985b) at 21°50'N. It comprises gray limestone containing rare phosphatic bioclasts and some rounded micritic lithoclasts.

Midh nab Member: Northwards of the Type Section

A section measured in the Al Faydah quadrangle (Vaslet et al., 1985a) at 25°55'N about 5 km north of Midh nab (Figure 5), enables comparison of the type section described at Khuff with facies in the area where the Midh nab shale was defined by Powers (1968). The member is 70 m (229.6 ft) thick, and the facies are slightly more clayey than in the type section. From bottom to top, it comprises:

- (1) 2 m (6.6 ft) conglomeratic limestone containing pebbles of dolomite and abundant bioclasts (bed-on-bed reworking) (Figure 28);
- (2) 16 m (52.5 ft) alternating bluish bioclastic platy limestone, rich in marine fauna (Figure 29), and yellow clayey limestone containing several layers of bioclastic, locally oolitic, cherty calcarenite;

- (3) 45 m (147.6 ft) yellow dolomitic gypsiferous claystone, incorporating beds of clayey dolomite, bioclastic dolomite containing chert nodules, and sandy layers less than one metre thick, showing inclined bedding toward the top;
- (4) 7 m of calcareous claystone and green claystone as well as sandy channels containing plant debris (Midhnab flora of Jal al Khartam, Vaslet et al., 1985a; Broutin et al., 2002) and floated tree trunks in the topmost part (Figure 30).

Further north, in the Buraydah quadrangle (Manivit et al., 1986), the facies of the Midhnab Member remain calcareous and clayey as far as 26°05'N (Jal Khartam) where the thickness is 72 m (236.2 ft). The topmost plant-bearing clayey facies (subunit 4), is locally eroded by megachannels of sandstone containing claystone galls, plant remains and silicified tree trunks (Figure 31).

At 26°30'N, along Jal al Khartam escarpment, the topmost clayey and sandy parts of the Midhnab Member contain the charophyte deposit described by Hill and El-Khayal (1983) in the upper part of the Khuff Formation.

The northernmost outcrop of the Midhnab Member is located at 26°55'N (An Naghabiq), where only the uppermost 8 m (26.2 ft) is visible. These comprise fine-grained sandstone (4 m, 13.1 ft) with inclined bedding, arranged in large festoon structures indicating a southeastward flow direction. The megachannels cut into green and blue-gray claystone (4 m, 13.1 ft) containing oxidised plant debris at the top.

Midhnab Member: Southwards of the Type Section

In the southern Ad Dawadimi quadrangle (Delfour et al., 1982), the Midhnab Member is 47 m thick at Rijm ad Dahawi (24°26'N) and further south in the Darma' quadrangle (Manivit et al., 1983) is estimated to reach 76 m (249.3 ft) with comparable facies to the type section.

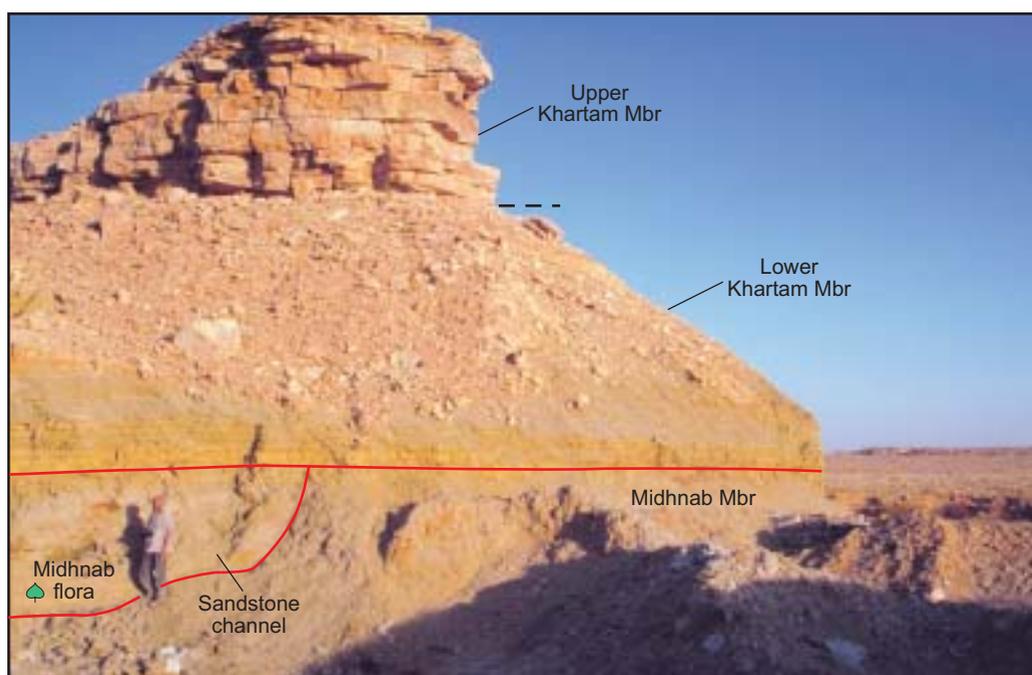


Figure 31: Khartam Member overlying Midhnab Member at Jal al Aswad, Buraydah quadrangle. In the lower half of the photo, the Midhnab Member shows sandy cross-laminated beds channelled into claystone. Both the sandstone and the claystone have yielded the Midhnab Flora. The Lower Khartam Member, including dolomite and clayey-limestone and part of the Upper Khartam Member made of oolitic limestone are seen in the upper half of the photo. Photo by D. Vaslet, 1999.

In the SHD-1 well, the Midhnab Member is 88 m (288.6 ft) thick (Manivit et al., 1983; 1985a), and consists from base up:

- (1) 2 m (6.6 ft) bioclastic and lithoclastic calcarenite;
- (2) 18 m (59 ft) dolomite and gray and black dolomitic claystone, with at the top fine-grained peloidal calcarenite;
- (3) 53 m (173.8 ft) of continuous dark gray dolomite and argillaceous dolomite with nodules of anhydrite (Figure 32) and gypsum; and 5 m (16.4 ft) fine dolomite with stylolitic joints;
- (4) 11 m (36.1 ft) bioclastic, fine-grained calcarenite with gray claystone at the top.

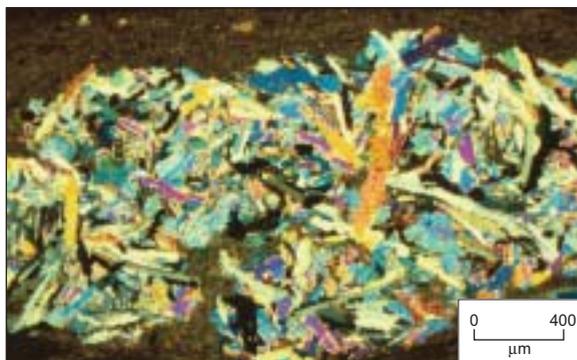


Figure 32: Midhnab Member in SHD-1 well, Darma' quadrangle. Anhydrite nodule in dolomitic facies of the lower Midhnab Member. Polarised light, depth 650 m (2,132 ft). Photo by Y.-M. Le Nindre, 1985.

The Midhnab Member becomes thicker in the Wadi Ar Rayn quadrangle (Vaslet et al., 1983), and is 92 m (301.8 ft) at 23°35'N. The lower 30 m (98.4 ft) is carbonate, comprising bivalve coquina and intraclastic limestone interspersed with gray dolomite, clayey dolomite, and laminated algal? dolomite. The upper 62 m (203.4 ft) is clayey and gypsiferous, and intercalated with thin layers of bioclastic dolomite, commonly very bioturbated.

In the Wadi Al Mulayh quadrangle (Manivit et al., 1985b) at 22°47'N (Jabal Umm Mus'ham), the carbonate unit at the base is 35 m (114.8 ft) thick, the facies remaining the same. It is overlain by 30 m (98.4 ft) of dolomitic and gypsiferous claystone containing beds of clayey or bioclastic dolomite. The succession is capped by gray vermiculate micritic limestone of lacustrine origin.

At 22°11'N (Urayq al Munsaraqah), the thickness of the Midhnab Member is reduced to 30 m (98.4ft). The clayey upper unit is only 22 m (72.1 ft) thick, and the top comprises beds of carbonate sandstone and siltite. Farther south, the few rare Midhnab Member outcrops in the Sulayyimah quadrangle (around 21°30'N) consist of yellow, red, and green, gypsiferous dolomitic claystone with rare beds of white or pink bedded dolomite.

Khartam Member: Northwards of the Type Section

In the Al Faydah quadrangle (Vaslet et al., 1985a), the Khartam Member becomes progressively thicker (Figure 5). At Khashm Khartam (25°57'N), the total thickness is 50 m (164 ft) and the Lower Khartam is comprised from bottom to top:

- (1) 10.5 m (34.4 ft) yellow dolomite overlain by green or dark-red gypsiferous claystone intersected in the middle by platy, and clayey limestone;
- (2) 3 m (9.8 ft) microsparitic limestone and silty claystone.

The upper Khartam is more massive and forms the carbonate frame of the cuesta of Jal al Khartam, and it consists of:

- (3) 14 m (45.9 ft) cream oolitic and peloidal limestone in massive beds with numerous pronounced stylolitic joints; and local stromatolitic patches;
- (4) 13 m (42.6 ft) bioclastic (coquina of bivalves) dolomitic limestone containing interbeds of clayey platy limestone and sparitised dolarenite (reddened surfaces);
- (5) 9.5 m (31.2 ft) cream oolitic and bioclastic limestone, and gray dolomite with clayey interbeds, and capped by gray / red bioclastic dolosparites.

Further north, in the Buraydah quadrangle (Manivit et al., 1986), the Khartam Member is uniform in thickness as far as 26°15'N; it then thins to 36 m north of Wadi ar Rimah (Jal al Aswad). The lower

clayey and dolomitic unit contains rare sandy beds, and from 26°05'N (Jal al Khartam) the upper unit begins with quartz dolomite and fine-grained sandstone in massive beds with clayey interbeds and sand-ball structures (Figure 31). Cross-bedding is observed in the overlying oolitic facies, the oolites being commonly weathered out in outcrop. Stromatolites patches are located from place to place in subunit 4 of the upper Khartam. At 26°30' N, the uppermost beds contain oncolites.

The northernmost outcrop identified as the Khartam Member is at 26°55'N (An Naghabiq), where the Lower Khartam (3.5 m, 11.5 ft) consists of green and red very silty claystone with exsuded gypsum; only the base (8 m, 26.2 ft) of the upper Khartam is visible, comprising cream oolitic limestone with inclined bedding and rare white clayey intercalations.

Khartam Member: Southwards of the Type Section

In the Darma' quadrangle (Manivit et al., 1985a), the Khartam Member increases slightly in thickness to about 60 m (196.8 ft) at Jabal Sufah (24°20'N) where the base is not seen in outcrop. The facies remain comparable to those in the type section, although the carbonate facies (upper Khartam) are thicker (52 m, 170.6 ft). The upper part of the Lower Khartam consists of blue claystone containing ammonoids and of ochre bioclastic dolomite.

In the SHD-1 well, (Manivit et al., 1983, 1985a; Le Nindre et al., 1990b), the Khartam Member is 61 m (200.1 ft) thick, and consists mostly of carbonates (Figure 23). The Lower Khartam consists of 14 m (45.9 ft) of bioclastic arenitic calcarenite. The upper Khartam consists of 30 m (98.4 ft) of clayey dolomite locally bioclastic, followed by a basal oolitic dolomite with anhydrite nodules (1 m or 3.28 ft), followed by 16 m (54.4 ft) of bioclastic dolomite.

Above the Khartam Member, the SHD-1 well encountered an undated section considered as the Sudair Formation by Manivit et al. (1985a); or the Khuff and upper part and Sudair Shale Formation by Al-Jallal (1995). It consists from base up: (1) 18 m (59 ft) of interbedded gray gypsiferous clay, sulfated dolomite, sulfurous gypsum, and massive halite in 1-m-thick beds; (2) 57 m (187 ft) of essentially dolomitic limestone with sandy layers containing bioclasts and inclusions of spheroidal anhydrite; and (3) 236 m (774.1 ft) of variegated green, or brick red and purplish, silty claystone and gypsum.

Farther south, the thickness of the member decreases progressively to 58 m (190.3 ft) at Wadi Ar Rayn (23°40'N), where the Lower Khartam (20 m, 65.6 ft) is clayey and carbonate, with bioclastic limestone intercalated in bluish carbonate, gypsiferous claystone, and brown dolomite. South of 23°15'N, the member becomes enriched in terrigenous material, such as purple claystone and micaceous sandstone. The Upper Khartam (38 m, 124.6 ft) consists of oolitic limestone (calcitized dolarenite), friable and cross-bedded, overlain by coquina, beige peloidal limestone with clayey interbeds, and a topmost bed of bioclastic oolitic limestone (Al Huwwah section, Figure 5).

In the Wadi Al Mulayh quadrangle, at 22°47'N (Jabal Umm Mus'ham), the Khartam Member is only 37 m (121.4 ft) thick. The Lower Khartam (15 m, 49.2 ft), entirely dolomitic and variably clayey or bioclastic, is rich in algae. The upper Khartam (22 m, 72.2 ft) is of oolitic facies.

Although of limited extent, the best outcrops of the Khuff Formation between 22°N and 21°N in the Sulayyimah quadrangle (Vaslet et al., 1985b), are those of the Khartam Member. Towards 21°55'N, in addition to carbonate oolites, ferruginous oolites and coquina facies occur. Towards 21°25'N, the member begins with a reworked layer of lithobioclastic calcarenite over the gypsiferous claystone of the Midhnab Member. It comprises bluish fine-grained laminated limestone, and ends with a gypsiferous clayey-dolomite unit.

Undifferentiated Khuff Formation, South of Latitude 21°N

In the Wadi Tathlith quadrangle (Figure 1), the Khuff Formation overlies the Juwayl Member of the Wajid Formation (Kellogg et al., 1986). Evans et al. (1991) correlated the Juwayl Member to the Unayzah Formation of subsurface (e.g. Ferguson and Chambers, 1991), and the Al Khlata Formation of Oman

Khuff Formation, Sulayyil-1 well, Saudi Arabia

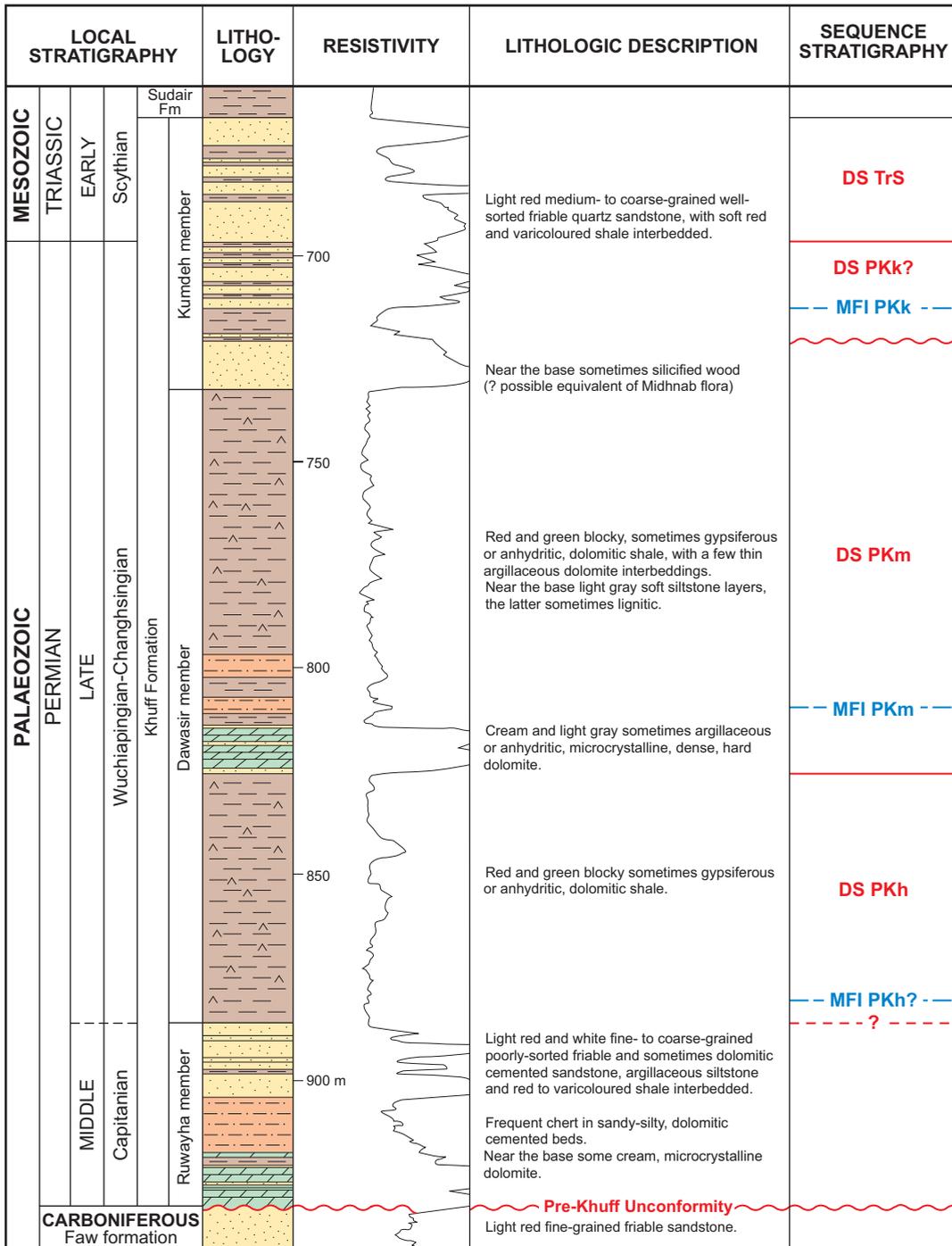


Figure 33: In the Sulayyil-1 well [referred to as Sulayyil D-1 in Evans et al. (1991); or also DEW-Su in unpublished 1969 Italconsult report, in Al-Laboun (1993)] the Khuff Formation is divided into three members. The lower Ruwayha member may correspond to the Ash Shiqqah (former Unayzah) Member, and the Dawasir to the Huqayl, Duhasan and part of the Midhnaab members. The basal sandstone of the Kumdeh member with silicified wood trunks may correspond to the Midhnaab subunit 4. The remaining part of the Kumdeh probably corresponds to the Khartam Member.

(Hughes Clark, 1988). Kellogg et al. (1986) noted that the Khuff Formation begins with 20 m (65.6 ft) of pale- to mouse-gray, fine-grained dolomite, poorly stratified and in places brecciated in appearance. This basal dolomite contains numerous diffuse occurrences of chert together with thin beds of pinkish, fine-grained sandstone, but contains no fossils.

A Khuff sequence that is several metres thick and probably fairly close to the unexposed contact with the underlying pre-Khuff strata, occurs at 20°49'20"N and 44°55'00"E. The lowest rocks consist of one metre (3.3 ft) of white marl, the base of which is not visible; overlain by a metre-thick layer of white dolomitic containing grains of silty quartz. This sequence is succeeded upwards by 3 m (9.8 ft) of beige or pinkish bioclastic dolomitic containing bivalve debris, algal fragments, rare foraminifers, and one cephalopod (orthoceratid), lithoclasts of dolomite fragments, and small grains of silty quartz. Overlying the dolomite is at least 70 cm (2 ft) of regularly bedded, fine-grained, feldspathic quartzarenite.

To the south of 'Irq al Wadi (20°06'30"N, 44°56'15"E), silicified tree trunks are exposed in an area mostly covered by superficial deposits.

The contact with the Early Triassic Lower Sudair shale is not exposed.

Located south of the Sulayyimah quadrangle, the Sulayyil-1 well (Figures 1 and 33; 20°27'40"N, 45°34'32"E; also Sulayyil D-1 in Evans et al., 1991; or DEW-Su, unpublished Italconsult report, 1969, in Al-Laboun, 1993), encountered the Khuff Formation. Italconsult divided this formation from base up into three members (Figure 33): (1) Ruwayha; (2) Dawasir; and (3) Kumdah.

The Ruwayha member unconformably overlies the Faw formation. Based on regional considerations, the Faw formation probably corresponds to : (1) Juwayl Member of the Wajid Formation of Kellogg et al. (1986); (2) subsurface Unayzah Formation in Evans et al. (1991); or / and (3) Ash Shiqqah Member of the Khuff Formation.

The lower Ruwayha member is about 50 m (164 ft) thick. Near its base it consists of cream, microcrystalline dolomite. The remaining Ruwayha section is described as interbedded, light red and white, fine- to coarse-grained, poorly sorted, friable, sometimes dolomitic cemented sandstone, argillaceous siltstone and red to varicolored shale. Frequent chert is found in sandy-silty, dolomitic, cemented beds in the Ruwayha member.

The Dawasir member is about 150 m (492 ft) thick and consists mostly of gypsiferous or anhydritic, dolomitic shale, except for a 20-m-thick (65.6 ft) dolomite bed in its middle part. The Kumdah member is about 50 m (164 ft) thick and, near its base it consists of sandstone with silicified wood trunks.

Summary of the Lithostratigraphy of the Khuff Formation

The Khuff Formation outcrops in central Saudi Arabia comprise five members. The Ash Shiqqah Member (formerly Unayzah member), consists of terrigenous sediments, generally fine-grained (claystone), interbedded with sandstone intervals, and give way upwards to bioclastic clayey dolomite. The greatest thicknesses are recorded to the north and south of the Central Arabian Arch (Khnaigu'iyah palaeohigh) a persistent relief of central Arabia at the beginning of the Khuff deposition. This palaeohigh is overlain by the stromatolite-bearing dolomite layers at the top of the Ash Shiqqah Member.

The lithology of the Huqayl Member is fairly homogeneous from north to south. The constant facies and thickness encountered are remarkable when compared to the variations in thickness observed in the underlying Ash Shiqqah Member. Two sequential units (calcarenite and gypsiferous claystone with subsurface evaporite) are clearly distinguished, marking the cyclic character of these deposits. The presence of marine fauna in calcarenite layers from the base of the lower unit, together with their extensive distribution, is indicative of the transgressive marine character of this member.

The Duhaysan Member contains the first truly calcareous or calcareous-dolomitic facies of the Khuff Formation. The base is marked by bed-on-bed reworking, accompanied by numerous marine fossils. Carbonate facies persist throughout the greater part of the member, giving way locally (southwards) to increasingly clayey facies. As in the case of the Huqayf Member, the effect of the Central Arabian Arch was a reduction in thickness, accompanied by a decrease in the claystone fraction throughout the middle outcrop sector. The terrigenous fraction of the Duhaysan Member is very weak.

The Midhnab Member is easily distinguishable in outcrop from north to south, and displays a rather homogenous vertical distribution of facies. It has been mapped continuously, for almost 700 km between 27°N and 21°N. All the sections yield at the base reworked calcareous or calcareous-dolomitic facies. These facies are accompanied by numerous marine fossils, and overlain by a fossiliferous carbonate succession evolving toward gypsiferous and dolomitic claystone facies. The upper part of the member locally displays plant bearing claystone, sandstone channels containing fossilised driftwood, or lacustrine limestone.

Over a total outcrop length of 700 km, the Khartam Member shows remarkably constant, thick oolite and peloid and bioclastic facies. The Lower Khartam Member is slightly clayey and dolomitic or sandy at the base, and overlies the detrital, gypsiferous, or lacustrine facies at the top of the Midhnab Member. The Upper Khartam Member represents a return to marine carbonate facies.

PALAEONTOLOGY AND AGE OF THE KHUFF FORMATION

In this section, the stages of the proposed global Permian System are tentatively adopted (Jin et al., 1997; Menning, 2001a, b; Gradstein et al., 2004). Where a stage is cited by an author, the approximate equivalent global stage or epoch (Late, Middle, Early) is added in parenthesis (Figure 2).

The biostratigraphic framework of the Khuff Formation, in central Saudi Arabia, is mainly based on small benthic foraminifers, algae and ostracods that were observed in the collected samples. These are the only organisms that establish a sufficiently detailed biostratigraphic framework. The following data pertaining to algae, foraminifers and ostracods represent a complete revision based on the ongoing systematic description by D. Vachard and J. Gaillot (Vachard et al., 2003, 2005) on foraminifers, and by S. Crasquin-Soleau on ostracods (Crasquin-Soleau et al., 2004, 2006). These data were acquired previously during the DMMR and BRGM mapping project of the Saudi Arabian outcrops (Figure 1), and recently in further studies of the Khuff Formation outcrops in central Arabia (D. Vaslet, J. Broutin and M. Halawani in 1999; D. Vaslet and Y.M. Le Nindre in 2002).

Other marine fossils are locally relatively abundant although of no stratigraphic value in dating the units of the Khuff Formation. They are, however, important for palaeoenvironmental reconstructions and sequence stratigraphic interpretations. These fossils include bivalves, nautiloids (Chirat et al., 2006), unidentified bactridids, orthocones, ammonoids, echinoderms, bryozoans, and gastropods. Rare brachiopods were recently discovered in the lower part of the Midhnab Member (Angiolini et al., 2006). Despite intensive searching, only a single specimen of a conodont has been recently discovered (Nicora et al., 2006) in a reworked calcarenite at the lower part of the Midhnab Member in Darma' quadrangle. Abundant microscopic fish teeth are found in the Khuff carbonates, but at the present time they have no stratigraphic significance.

The Khuff and pre-Khuff macroflora has important palaeobiogeographic significance but no chronostratigraphic value. The Unayzah Flora (El-Khayal, 1980; El-Khayal and Wagner, 1983, 1985; Hill and El-Khayal, 1983; Broutin et al., 1995) found in the Unayzah Formation, below the Ash Shiqqah Member (Figures 5, 14–16), and the Midhnab Flora (Hill and El-Khayal, 1983; Vaslet et al., 1985a; Broutin et al., 2002; Berthelin, 2002; Berthelin et al., 2006) in the upper part of the Midhnab Member (Figures 5, 14 and 19), do not provide precise ages. Most Khuff outcrops are too weathered to preserve microflora, and this type of data originated mainly from samples taken from boreholes.

Ash Shiqqah Member (formerly Unayzah member) of the Khuff Formation: ?Middle Permian Epoch, ?Capitanian Stage

The definitions and ages of the lithostratigraphic units within the Ash Shiqqah reference section, in the Unayzah locality, has been the subject of controversy during the past two decades (Figures 1, 14–16). This is mainly due to the lack of reliable chronostratigraphic controls based on: (1) plant remains in continental deposits of the lower part (Unayzah Formation); and (2) rare benthic foraminifers in the upper shallow-marine part (Ash Shiqqah Member of the Khuff Formation). In the following discussion, the fossils and age interpretations of Unayzah Formation and Ash Shiqqah Member are reviewed together.

In the Buraydah quadrangle, the Unayzah Flora from the clastic unit just below the Pre-Khuff Unconformity (Figures 5, 14 and 16), was tentatively dated as ?Late Carboniferous-?Early Permian by El-Khayal et al. (1980). Al-Laboun (1982, 1987) proposed this stratigraphic interval as the lower part of the Late Carboniferous-Early Permian Unayzah Formation (Figure 16). Later studies at the same Unayzah locality, based on additional plant material by Lemoigne (1981a, b) and El-Khayal and Wagner (1983, 1985), indicated that the age of the Unayzah Flora is probably Middle Permian, Murgabian (Wordian) (Lemoigne, 1981a, b; Broutin et al., 1995).

According to Broutin et al. (1995), the Unayzah Flora is a true Cathaysian-Euramerican mixed flora including important Cathaysian forms such as *Lobatannularia lingulata* Halle, *L. cf. heianensis* Kodaira, *Fasciopsis hallei* (Kawasaki) Lee et al., *Gigantonoclea* sp., *Pecopteris phegopteroides* Feistmantel, *Qasimia schyfsmae* (Lemoigne) Wagner and El-Khayal and associated with “northern elements” mainly belonging to Filicophyta and *Cordaites*. According to Broutin et al. (1995) the *Dadoxylon* spp., figured by Lemoigne (1981b), corresponds clearly to the Euramerican *Araucarioxylon* genus. Both macro- and microfloral data (Fauconnier in Le Nindre et al., 1990b) indicate a late Murgabian (Wordian) age. More recently, however, J. Broutin (written communication, 2002), reviewed all the former studies and concluded that Middle Permian, Kubergandian (Roadian) and/or Murgabian (Wordian) ages are both possible for the Unayzah Flora.

The Ash Shiqqah Member of the Khuff Formation is poorly dated. In the Buraydah quadrangle (Manivit et al., 1986), the carbonate subunit at the top of this member contain foraminifers, including *Paradagmarita flabelliformis* Zaninetti et al. This species was not encountered in our new investigation in the Huqayl Member. It can be confused with *Sengoerina argandi* Altiner, from the Midian (Capitanian) of northeastern Turkey (Altiner, 1999). Taxa of weak biostratigraphic value were identified in our samples: *Permocalculus* sp., *Globivalvulina* sp., *Nankinella* sp., “*Glomospira*” sp., *Cornuspira* sp., *Hemigordius* sp., *Pachyphloia* sp.

Near the Ar Rayn town locality (Figure 1), Vaslet et al. (1983) noted that the Ash Shiqqah Member is poor in benthic foraminifers (rare *Ammodiscus* sp., *Hemigordius* sp. and *Glomospira* sp.), in gymnocodiacean algae *Permocalculus* sp., and in microproblematica *Aeolisaccus* sp. Among the bioclasts are bivalves, gastropods, and rare phosphatic fish debris. A ?late Middle or early Late Permian age was assigned by Vaslet et al. (1983).

Near Wadi Al Mulayh (Figure 1), Manivit et al. (1985b) noted in the lowest sandstone unit of the member, some thoracic shields of palaeocrustaceans identified as *Tropidocaris* sp., bearing no age value. In the well SHD-1 (Manivit et al., 1985a), the top of the Ash Shiqqah Member is characterised by the appearance of abundant and varied (15 species) monosaccate and bivesiculate pollen, marking a renewal of the microflora.

According to G.W. Hughes (written communication, 2002) the Ash Shiqqah Member may pass in part to the Khuff-D Member in subsurface (Figure 9). Cuttings from the Khuff-D contain the foraminifers genus *Hemigordiopsis* dated as Middle Permian (late Capitanian) by Nestell (written communication to G.W. Hughes), but with an early Midian (early Capitanian) acme (Vachard et al., 2002, 2003). Fusulinids *Reichelina* sp. and *Monodioxodina kattaensis* (Schwager) recovered from the

Khuff-D Member in the Butabil well, located in Saudi Arabia near the Oman border, confirm this Midian age, although Nestell interpreted *Reichelina* spp. as late Capitanian to Dorashamian (Changhsingian) and *Monodiexodina kattaensis* as early Wordian. In fact, *Reichelina* is known from the base of the Midian (Leven, 1993), and *M. kattaensis* is associated with a *Codonofusiella* in the Pakistani Amb Formation (Mertmann and Sarfraz, 2000), which is Wordian in age according to conodonts (Wardlaw and Pogue, 1995; and L. Angiolini, personal communication, 2004) and to foraminifers (Vachard et al., 2002).

It therefore seems likely that the Ash Shiqqah Member (and the subsurface Khuff-D Member), is Capitanian (Midian, and probably early Midian). The Late Permian Wuchiapingian (early Dzhulfian) age, suggested by Vachard et al. (2002), seems unlikely due to the local presence of *Monodiexodina kattaensis*, compared to the complete absence of keriothecal fusulinids in the Late Permian (Sheng, 1992).

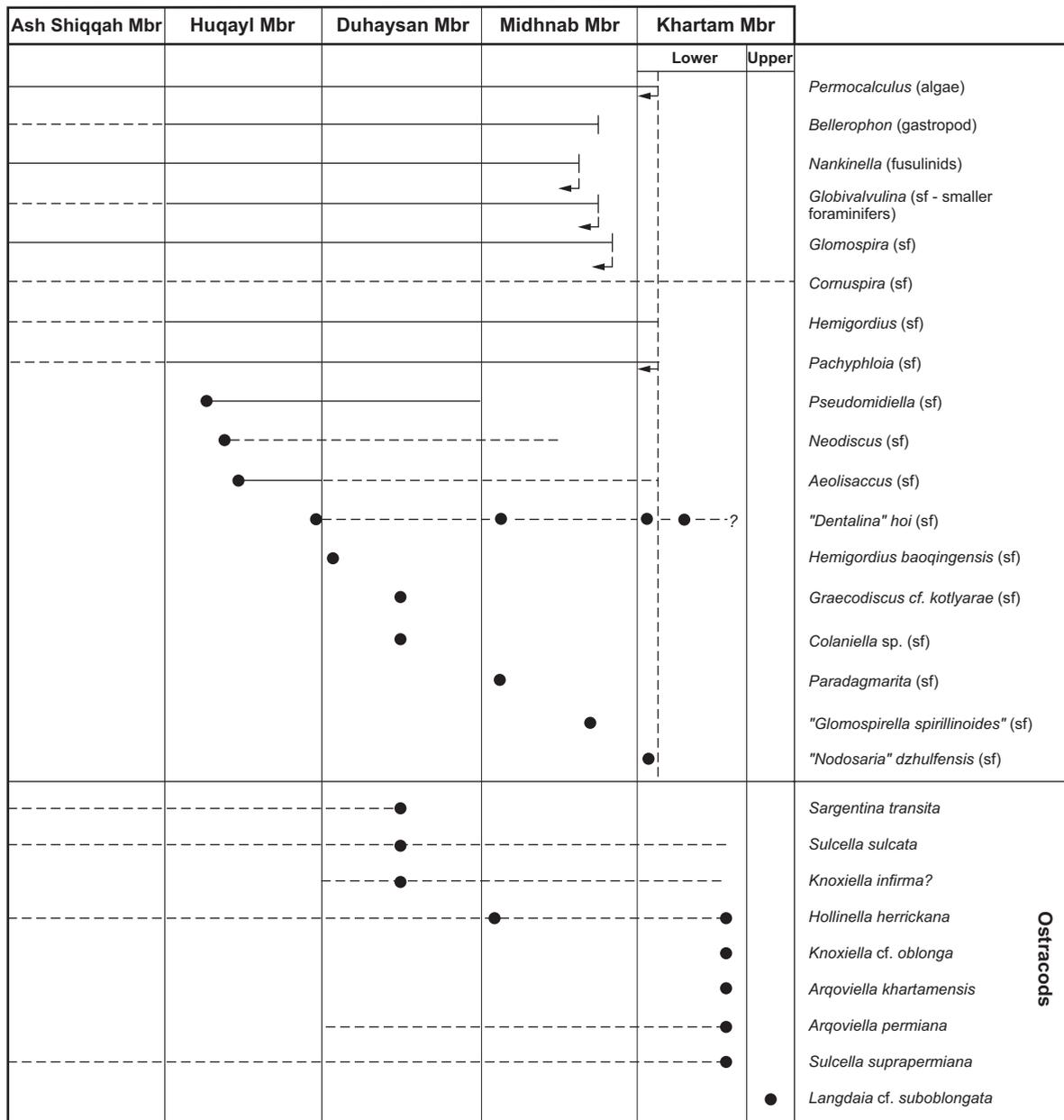


Figure 34: Middle and Late Permian main micropalaeontological components of Khuff Formation outcrop, central Saudi Arabia. Backward arrows indicate successive local LAD (last appearance datum) of selected foraminiferal trends.

Huqayl Member: Late Permian Epoch, ?Wuchiapingian Stage

The local appearances of new taxa or reappearances of Lazarus-taxa that are characteristic of the Huqayl Member (Figure 34) are *Pseudomidiella* cf. *labensis* Pronina-Nestell in Pronina-Nestell and Nestell, *Earlandia?* sp. and *Neodiscus* aff. *qinglongensis* Wang. *Neodiscus* is not significant since it appears in the Early Permian (Grozdilova, 1956). *Earlandia?*/*Aeolisaccus* are relatively common during the Changhsingian in Hungary (Berczi-Makk et al., 1995), and seem to reappear in the early Dzhulfian of Greece (L. Angiolini, personal communication, 2004; D. Vachard, personal communication, 2004). Although recently described, the genus *Pseudomidiella* might be a good marker of the late Changhsingian in the northwest Caucasus and in the Himalaya (Pronina-Nestell and Nestell, 2001). However, *Pseudomidiella* also appears in the early Wuchiapingian (early Dzhulfian) (sample GL252 of Hydra Island, Greece; D. Vachard, personal communication, 2004). Based on these considerations, the Huqayl Member may be Wuchiapingian (Dzhulfian) as suggested in Figure 34.

In the type section, the Huqayl Member sometimes contains algae *Gymnocodium bellerophontis* (Rothpletz) Pia and *Permocalculus fragilis* (Pia) Elliot, that reveal a Middle to Late Permian age (A. Roux, unpublished report in Delfour et al., 1982). Nevertheless, only *Permocalculus* were observed in our material, with the species *P. solidus* (Pia), *P. tenellus* (Pia) and *P. digitatus* Elliot. The common presence of *Earlandia?*, *Permocalculus*, and *Neodiscus*, in the Huqayl Member indicates high salinity, and emphasises the biologic confinement of this member (D. Vachard, oral communication in Vaslet et al., 1985; Vachard et al., 2003). A cone-shaped marine fossil identified as bacitrid, was also found in the upper subunit of the member, together with brachiopod debris, gastropods and bivalves.

To the north, in the Midhnaab section (Vaslet et al., 1985), the upper part of the member (subunit 5) yielded *Robuloides* cf. *gourisiensis* Reichel, a genus and species characteristic of the Dzhulfian-Dorashamian (Wuchiapingian-Changhsingian), accompanied by *Globivalvulina* cf. *graeca* Reichel, "*Glomospira*" sp., and *Nankinella* sp., the stratigraphic range of which is from the early Murgabian to the Dzhulfian-Dorashamian (early Wordian to Changhsingian).

In the Unayzah and Buraydah areas (Figure 1), the Lower Huqayl Member contains ostracods, calcareous algae, molluscs, and bryozoans and (in the Unayzah and Buraydah sections, subunit 1) the foraminifers *Pseudomidiella* cf. *labensis*. Another significant foraminifer, *Paradagmarita flabelliformis* Zaninetti et al., is located in this basal bench of the Huqayl Member in the Buraydah section (Manivit et al., 1986). *Paradagmarita flabelliformis* is late Dzhulfian (Wuchiapingian) to early Dorashamian (Changhsingian) in age (Altiner, 1981; Lys, 1984). The genus is only considered as early Dorashamian (Changhsingian) by Vachard et al. (2002), but is present up to the late Changhsingian with *Paradagmarita* sp. 1 (Pronina-Nestell and Nestell, 2001, plate 4, figure 12), and it can appear previously in the Dzhulfian (J. Gaillot, personal communication, 2004).

To the south, the Huqayl Member yielded limited biostratigraphic data. In the Wadi Al Mulayh section (Manivit et al., 1985b), the base of the Upper Huqayl (subunit 4) contains some foraminifers known from the entire Middle and Late Permian (e.g. Lys, 1984), including *Lasiodiscus minor* Reichel and *L. tenuis* Reichel, associated with a bacitrids-bearing bed.

In the well SHD-1 (Manivit et al., 1985a), the same pollen microflora prevails between the base of the Huqayl and the top of the Midhnaab members. At the base of the Huqayl Member, the occurrence of a microfloral association including *Lueckisporites virkkiae* Potonié and Klaus, *Klausipollenites schaubergeri* Potonié and Klaus, *Kraeuselisporites* cf. *wargalensis* Balme, and *Potoniesporites novicus* Bhardwaj as well as *Cordaitina gunyalensis* Pant and Srivastava in the Dhaysan and Midhnaab members supports the Late Permian Wuchiapingian (Dzhulfian) age (D. Fauconnier in Le Nindre et al., 1990b). The association is congruent with the presence of the foraminifers *Robuloides* cf. *gibbus* Reichel from the base of the member (subunit 1) and *Baisalina pulchra* Reitlinger in subunit 2.

Duhaysan Member: Late Permian Epoch, Wuchiapingian or Changhsingian Stages

The biozonal characteristics of the Duhaysan Member are as follows: “*Dentalina*” *hoi* Trifonova, *Hemigordius baoqingensis* Wang in Zhao et al., *Graecodiscus* cf. *kotlyarae* Pronina-Nestell in Pronina-Nestell and Nestell, and *Colaniella* cf. *minuta* Okimura (Figure 34). Locally, “*Dentalina*” *hoi* is present up to the Triassic. *Hemigordius baoqingensis* and *Graecodiscus* cf. *kotlyarae* were described in the late Changhsingian, but the exact range is poorly known due to numerous convergences for the Miliolida during the Late Permian. The exact range of *Colaniella* is discussed by several authors. It is restricted to the Changhsingian (Zhao et al., 1981; Lin et al., 1990), or appears before, i.e. in Midian or Dzhulfian (Capitanian or Wuchiapingian) (Jenny-Deshusses and Baud, 1989; Mertmann and Sarfraz, 2000; Vachard et al., 2002, 2003).

The Duhaysan Member also contains the foraminiferal association of *Lasiodiscus minor*, *Globivalvulina kantharensis* Reichel, *Hemigordius* sp., *Pachyphloia* sp., and *Robuloides* sp., *Paradagmarita monodi* Lys and *P. flabelliformis* of Dzhulfian-Dorashamian (Wuchiapingian-Changhsingian) age. *Nankinella* sp. is reworked in the lowest bed of this member. Ostracods have recently been described in the middle and upper parts of the Duhaysan Member (Crasquin-Soleau et al., 2004, 2006) including: *Knoxella* cf. *infirma* Shi, *Sulcella sulcata* Coryell and Sample, and *Sargentina transita* (Kozur). The latter two were described in the Wordian Khuff Formation of Oman (Crasquin-Soleau et al., 1999). The rest of the biozone bears no stratigraphic precision and is made of debris of algae (see Okla, 1992), gastropods (*Bellerophon* sp.), bryozoans, echinoderms, fish teeth, and small nautiloids of the genus tentatively attributed to *Caelogastroceras* aff. *mexicanum* (Girty) (written communication, J. Roger, 1985, in Le Nindre et al., 1990b).

In the well SHD-1 (Manivit et al., 1985a), the foraminifers (*Geinitzina postcarbonica* Spandel and *Hemigordius permicus* Grozdilova), and the microflora association (including five additional species compared to the Huqayl Member) suggest no precise age.

The Duhaysan Member, due to its position between the ?Wuchiapingian Huqayl Member and the Changhsingian Midhnaab Member is here attributed to the Wuchiapingian or Changhsingian (Figure 34). In the middle part of the member, in the Buraydah area, the foraminifer *Graecodiscus* cf. *kotlyarae* is common as the whole porcelaneous foraminifers in the modern hypersaline environments. It is accompanied by rare very small, primitive *Colaniella* cf. *minuta*. The level might correspond to the base of the local Changhsingian.

Midhnaab Member: Late Permian Epoch, Changhsingian Stage

The Midhnaab Member is characterised in its lower part by the foraminifer *Paradagmarita* and in its upper part by a level with “*Glomospirella spirillinoides*” (Grozdilova and Glebovskaya) *sensu* Wang in Zhao et al. (1981). This taxon of Miliolida must be created, because it is structurally different from the fusulinid *Brunsia spirillinoides* (Grozdilova and Glebovskaya), although perfectly homeomorph. The Midhnaab Member is also characterised by successive disappearances: e.g. *Globivalvulina* spp. and *Nankinella* sp. (Figure 34). According to the foraminifer association, the Midhnaab Member is tentatively attributed to the Changhsingian (Dorashamian) (Figure 35). The Midhnaab Member also yielded an ostracod assemblage including *Hollinella herrickana* (Girty) (Crasquin-Soleau et al., 2004 and 2006) of imprecise Permian age.

In the type section and in the Midhnaab area (Vaslet et al., 1985b), the basal limestone (subunit 1) of the Midhnaab Member contains debris of echinoderms, gastropods (*Bellerophon* sp.), and ostracods associated with gymnocodiaceans and dasycladacean algae (*Permocalculus* sp. and *Mizzia* sp.; see Okla, 1992). This lowest unit of the Midhnaab Member has also yielded abundant small nautiloids (*Caelogastroceras* aff. *mexicanum* (Girty) and *Aphelaeceras* sp., according to Le Nindre et al., 1990b), bactritids (Figures 29, 36–38), and rare brachiopods. The brachiopods have been identified by L. Angiolini (Angiolini et al., 2006) as *Kotlaia* sp., and a new genus of the Terebratulida subfamily Dielasmatinae, very close to the genus *Dielasma*. The two taxa are also described in the Khuff Formation

LITHOSTRATIGRAPHY	BIOSTRATIGRAPHY		CHRONOSTRATIGRAPHY		
	Foraminifers - Annelids	Ostracods	stages	sub-systems	
Khartam Mbr	upper	<i>Spirorbis phlyctaena</i>	<i>Langdaia cf. suboblonga</i>	Scythian	Early Triassic
	lower	" <i>Dentalina</i> " <i>hoi</i>	<i>Arqoviella khartamensis</i> <i>Arqoviella permiana</i> <i>?Knoxiella infirma</i>	Changhsingian (= Dorashamian)	Late Permian
	lowermost	" <i>Nodosaria</i> " <i>dzhulfensis</i>			
Midhnab Mbr	<i>Paradagmarita</i> - " <i>Glomospirella spirillinoides</i> "				
Duhaysan Mbr	" <i>Dentalina</i> " <i>hoi</i> - <i>Hemigordius baoqingensis</i> - <i>Graecodiscus cf. kotlyarae</i> - <i>Colaniella</i> sp.	Wuchiapingian/ Changhsingian			
Huqayl Mbr	<i>Aeolisaccus</i> spp. - <i>Pseudomidiella cf. labensis</i> - <i>Neodiscus aff. qinglongensis</i>	Wuchiapingian (= Dzhulfian)			
Ash Shiqqah Mbr	<i>Monodioxodina kattaensis</i> - <i>Reichelina</i> sp.		Capitanian (= Midian)	Middle Permian	

Figure 35: Significant foraminifer and ostracod assemblages of the Khuff Formation outcrops, central Saudi Arabia. Composite table of the biostratigraphic and lithostratigraphic units of the Late Permian Khuff Formation of Saudi Arabia.

of Oman (Angiolini and Bucher, 1999; Angiolini et al., 2004), and are known from Middle to Late Permian ages. The gypsiferous clay of subunit 3 yielded several benthic foraminifers including *Globivalvulina graeca* Reichel, *G. vonderschmitti* Reichel, *Paradagmarita* sp., *Geinitzina* sp., *Pachyphloia* sp., *Calcitornella* sp., and *Pseudotrictix* sp., the latter assemblage being characteristic of the late Dzhulfian-Dorashamian (Wuchiapingian-Changhsingian) (Altiner, 1981; Lys, 1984). The lower Midhnab Member contains also rare fusulinid debris identified as *Nankinella minor* Sheng, as well as Lagenidae foraminifers such as *Protonodosaria* sp., "*Dentalina*" *hoi*, "*Nodosaria*" spp., etc.

The lower clayey and calcareous part of the Midhnab Member (subunit 3) is poorer in organisms, containing the foraminifers *Globivalvulina vonderschmitti* Reichel, and *Paraglobivalvulina mira* Reitlinger, associated with some other bioclasts. These species existed from the late Murgabian (Wordian) or early Dzhulfian (Wuchiapingian) until the late Dorashamian (Changhsingian).

The lacustrine limestone described locally at the upper part of the Midhnab Member (top of subunit 4) contains charophytes and gastropods (Delfour et al., 1982; Vaslet et al., 1985; Le Nindre et al., 1990b). Laterally in the sandstone and clayey facies at the Jal al Wata locality north of Buraydah, Late Permian plants were discovered at the top of the unit by Hill and El-Khayal (1983) who described the new species of charophyte *Palaeonitella tarafiyensis*. This Midhnab flora has been extensively studied by Broutin et al. (1995, 2002), Berthelin (2002), and Berthelin et al. (2006), along the Jal al Khartam escarpment in the Al Faydah and Buraydah quadrangles (Figures 1 and 3).

The Midhnab flora associations vary according to the different palaeoenvironments encountered in the upper part of the Midhnab Member. The flood plain environments contain associations of Euramerican elements such as vegetative and fertile shoots of conifers (*Pseudovoltzia liebeana* Florin, *Culmitschia* sp.), mixed with Cathaysian elements (*Discinites* sp. cf. *D. orientalis* Gu and Zhi, *Pelourdea* sp., *P. hallei* Gu and Zhi). They also contain (Wadi al Batin area, Buraydah quadrangle) typical leaves

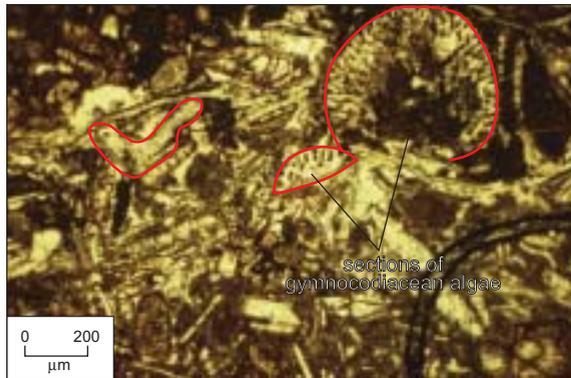


Figure 36: Microfacies of the Midhnaab Member in Al Faydah town area, Al Faydah quadrangle. Gymnocodiacean (*Permocalculus* sp.) biocalcarenite including also ostracods, foraminifers and other bioclasts. Basal bed of the Midhnaab Member (natural light). Photo by Y.-M. Le Nindre, 1985.

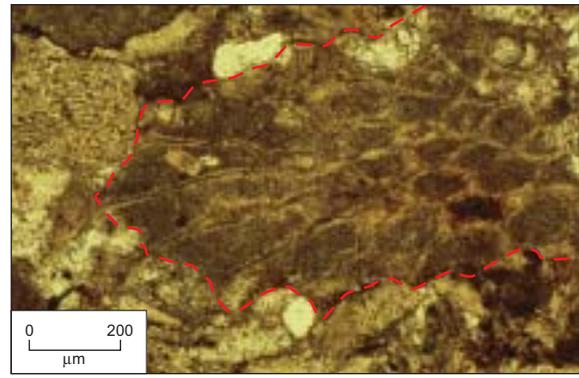


Figure 37: Microfacies of the Midhnaab Member in Al Faydah town area, Al Faydah quadrangle. Bryozoan in a biocalcarenite. Basal bed of the Midhnaab Member (natural light). Photo by Y.-M. Le Nindre, 1985.

and fructifications of Gondwanian glossopterids (*Glossopteris decipiens* Feismantel, *G. formosa* Feismantel, *Alberia* sp., *Phyllothea australis* Brongniart). The glossopterids were discovered for the first time in Saudi Arabia, where they occur intermingled with the Euramerican and Cathaysian representatives.

The deltaic environments of the upper part of the Midhnaab yielded flora associations dominated by sphenophytes including arborescent leaves and cones of lycophytes (*Lobatannularia multifolia* Kon'no and Asama; *L. heianensis* Kawashi), wood fragments of gymnosperms, and rare coniferous fertile shoots (*Voltzia* affinities). The swampy palaeoenvironments contain associations dominated by coniferous leafy shoots (*Ullmania bronni* Goeppert, *U. frumentaria* Goeppert, *Ullmania* sp., *Culmitzschia* sp.), and pteridophytes (*Pecopteris chihliensis* Stockmans and Mathieu, *Taenopteris* sp., and *Lepidostrobus* sp.).

The microfloral associations, dominated by gymnosperm bisaccate pollen, are in accordance with a Late Permian age and very similar in composition to the coeval palynologic assemblages described in the Salt Range in Pakistan (Balme, 1970) and Australia (Foster, 1979; Backhouse, 1991).

Floras and microfloras both confirm a Late Permian age for this part of the Khuff Formation.

To the north (Unayzah and Buraydah sections), the basal layers of the Midhnaab Member have also yielded *Paraglobivalvulina mira* Reitlinger, *Pseudotrictix solida* Reitlinger, *Geinitzina reperta* Bykova and *Pachyphloia pedicula* Lange known from the late Murgabian (Wordian) to the Dorashamian (Changhsingian). The carbonate marl in subunit 2 contains an abundant fauna. Foraminifers include *Hemigordius permicus* Grozdilova, *Pachyphloia pedicula* Lange, *Paradagmarita flabelliformis* Zaninetti and others, and *Robuloides lens* Reichel, all typical of the Late Permian.

To the south, in the southern part of the Ad Dawadimi quadrangle (Safra ad Dumaythiyat), a single specimen of a nautiloid described as *Tirolonutilus* gr. *hoernesii* (Chirat et al., 2006) was recovered from the bluish-gray clayey bioclastic limestone of subunit 2 of the Midhnaab Member. Other macrofauna includes baccritids, bryozoans, bivalves (Myophoridae) and gastropods. In the Darma' quadrangle (Jabal al Amshiyah), the reworked bioclastic and lithoclastic calcarenite of subunit 1 of the Midhnaab Member, has yielded a single specimen of a conodont described as "*Jinogondolella*" cf. *altaduensis* by Nicora et al. (2006). The Late Capitanian age recorded for some species of this genus is however questionable here due to the high probability of reworking of this corroded, broken and conferred species of conodont. In the Wadi Al Mulayh, the lowest unit of the member is a bioclastic limestone (phosphatic bone debris) containing foraminifers (*Cornuspira* sp., cf. *Meandrospira* sp., *Globivalvulina graeca* Reichel, and *Lasiodiscus minor* Reichel), associated with abundant gymnocodiacean algae and baccritids. Another abundant foraminiferal association is located in the clayey marl of subunit 2,

including *Pseudotrictix* cf. *solida* Reitlinger, *Geinitzina reperta* Bykova and *Nodosaria dzhulfensis* Reitlinger, and it is indicative of Dorashamian (Changhsingian) and Early Triassic. Midhnab subunit 2 also yielded the ostracod *Hollinella herrickana* (Girty) as well as numerous ostracod tests observed in thin sections.

In the well SHD-1 (Manivit et al., 1985a), the foraminiferal association includes: *Dagmarita chanakchiensis* Reitlinger, *Globivalvulina vonderschmitti* Reichel, *Hemigordius ovatus* Grozdilova, *Pachyphloia iranica* Bozorgnia and *Paradagmarita flabelliformis* Zaninetti from the base; and the microflora association (renewed with 14 species compared to lower units) includes: *Alisporites tenuicarpus* Balme and *Klausipollenites schaubegeri* Potonié and Klaus. These associations support a late Dorashamian (Changhsingian) age for the lower part of the Midhnab Member (J. Broutin, written communication, 2002). Manivit et al. (1985a) assigned the Midhnab Member to the Late Permian based on the microflora species *Alisporites tenuicarpus* Balme, *Klausipollenites schaubegeri* (Potonie and Klaus), and *K. wargalensis* Balme, together with *Densoisporites playfordii* (Balme), Dettmann.

Khartam Member: Late Permian Epoch (Changhsingian Stage) to Early Triassic Epoch ('Scythian' Stage)

In the Khuff type section, the coquina beds of the Lower Khartam Member contains debris of echinoderms, gastropods, bivalves, ostracods, algae, and fish teeth, together with phosphatic remains, and unidentified cephalopod in the subunit 2. A foraminiferal association found in the lowest intraclastic and bioclastic layer of the member includes *Nodosaria dzhulfensis* Reitlinger, "*Dentalina*" *hoi* Trifonova, *Geinitzina reperta* Bykova, and *Ichtyolaria latilambata* Sellier de Civrieux and Dessauvage and several species of *Paradagmarita* (Figures 34 and 35). This association of foraminifer and ostracods allow assigning a Late Permian (Changhsingian) age for the Lower Khartam Member.

The biophase of the Upper Khartam Member consists essentially in undetermined rounded carbonate algae and stromatolites.

To the north (Al Faydah and Buraydah quadrangles), the Lower Khartam contains bivalves, large bacrtrids, nautiloids and rare foraminifers (*Climacammina* sp.). According to (Crasquin-Soleau et al., 2004 and 2006) the presence of ostracods of the Paraparchitidae family (*Paraparchites* spp.) and Kloedenellacea superfamily such as *Knoxiella* sp., *Kloedenellitina* sp., and *K. infirma* Shi, are also in favour of a Late Permian age for the Lower Khartam Member. Other Permian ostracod forms are also found in the Lower Khartam, such as *Arqoviella permiana* Gerry and Honigstein and *Sulcella suprapermiana* Kozur. Crasquin-Soleau et al. (2004) described two new species of ostracods (*Arqoviella arabica* and *A. khartamensis*) from the Lower Khartam Member in the type section of Jal al Khartam.

The Upper Khartam (subunit 4) is characterised by the appearance of the annelid *Spirorbis*

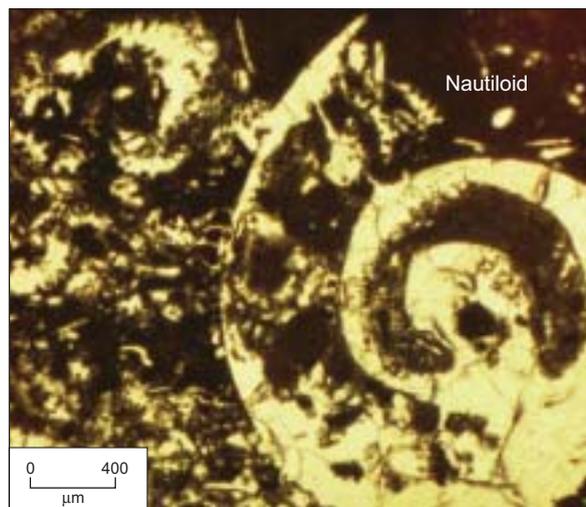


Figure 38: Microfacies of the Midhnab Member in Al Faydah town area, Al Faydah quadrangle. Nautiloid embryo. Basal bed of the Midhnab Member (natural light). Photo by Y.-M. Le Nindre, 1985.

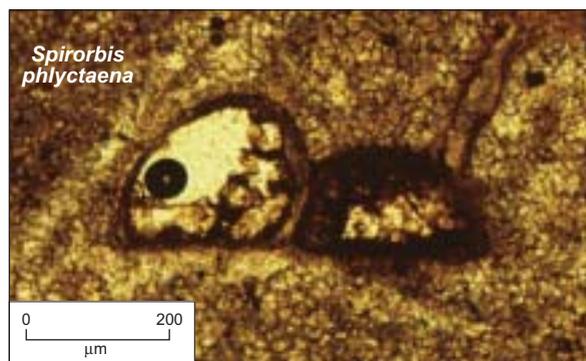


Figure 39: Microfacies of the Khartam Member in Safra adh Dumaythiyat area, Ad Dawadimi quadrangle. Thin section of *Spirorbis phlyctaena* (Brönimann and Zaninetti) (natural light). Photo by Y.-M. Le Nindre, 1985.

phlyctaena (Brönnimann and Zaninetti) (Figure 39) associated with bioclasts of brachiopods, bivalves, and rare ostracods including *Langdaia* cf. *soboblonga* Wang described in the Early Triassic of South China (Crasquin-Soleau et al., 2004). The annelid *S. phlyctaena* is characteristic of the Early Triassic (late Griesbachian substage of the Scythian according to Altiner et al., 1980; Zaninetti et al., 1981) (Figure 35). In the Buraydah quadrangle, ostracods with thick tests are present up to the top of the Midhnab, but are replaced by ostracods with thin tests in the Upper Khartam unit as described in thin sections by Manivit et al. (1986).

To the south, an isolated specimen of nautiloid found in the Ad Dawadimi quadrangle (Jabal al Amshiyah), described as *Tirolonutilus feltgeni* n. sp. (Chirat et al., 2006), occurred in the laminated dolomite of the subunit 1 of the lower Khartam. A genus recorded from the Dzhulfian and Dorashamian in the Tethyan areas. In the Darma' and Wadi Ar Rayn quadrangles, the Lower Khartam contains Late Permian foraminifers such as *Geinitzina* sp., *Lenticulina* sp., *Hemigordius* sp and *Robuloides lens* Reichel, associated with sponge spicules, ostracods, bivalves and large bacrtrids 10 to 15 cm long. The foraminifers *Pachyphloia* sp. and *Neohemigordius* sp. were found at the base of the Khartam Member in the south of the Wadi Ar Rayn quadrangle.

In the well SHD-1 (Manivit et al., 1985a), the microflora species that existed below the base of the Khartam Member completely disappear in it, and mark a rupture with earlier successions. The Upper Khartam yielded the Triassic Scythian serpulid *Spirorbis phlyctaena* Bronnimann and Zaninetti (Manivit et al., 1985a).

The boundary between the Permian (Changhsingian) and Triassic (Early Scythian) is thus located within the Khartam Member, and tentatively placed at the sequence boundary at the base of the Upper Khartam. This position for the Triassic/Permian Boundary remains identical to the boundary assigned by Le Nindre et al. (1990b) who placed this limit at the base of the Upper Khartam with the appearance of *Spirorbis phlyctaena*. The Khartam Member is thus assigned to a Late Permian (late Changhsingian) to Early Triassic (Early Scythian) age (Figure 35).

DEPOSITIONAL ENVIRONMENT AND SEQUENCE STRATIGRAPHY

The regionally transgressive Khuff Formation is dominated by low-energy carbonate and evaporite deposits that represent relatively confined environments of the mid-littoral domain (Figures 40 and 41). In outcrop, along a N-S strike in central Saudi Arabia, the formation is subdivided into four main depositional sequences (DS; see Figures 4 and 5), each characterised by: (1) a basal sequence boundary (SB) corresponding to a significant break in sedimentary deposition; (2) transgressive system tract (TST); (3) maximum flooding interval (MFI); and (4) highstand system tract (HST).

The first depositional sequence DS PKh (named after Permian-Khuff-Huqayl) includes the Ash Shiqqah and the Huqayl members. Its basal SB corresponds to the Pre-Khuff Unconformity (PKU). The Ash Shiqqah Member is interpreted as the TST, while the HST consists of two sabkha sequences that evolved from intertidal to subtidal environments (Lower and Upper Huqayl). The first Late Permian flooding event over central Arabia is represented by the flooding interval MFI PKh. The flood PKh (located in the basal part of the Huqayl Member, Figure 4) was followed by the regressive evaporitic palaeoenvironments of the Huqayl Member (Le Nindre et al., 1990b). The subtidal environments of the second sabkha sequence (Upper Huqayl Member) may represent a subsequence and contain a flooding interval of limited extent (Figure 4). The DS PKh corresponds closely with Khuff cycle 1 of Al-Aswad (1997), and may contain MFS P30 of Sharland et al. (2001) (Figure 26).

The second depositional sequence DS PKm (named after Permian-Khuff-Midhnab) starts with the subtidal to littoral deposits of the Duhaysan Member (TST), over an erosive surface (SB) upon DS PKh. The SB is marked by reworked deposits. DS PKm ends with the regressive supratidal to continental deposits of the upper part of the Midhnab Member (Figure 4). The MFI PKm is clearly located in the outcrops at the base of the Midhnab Member with abundant marine fauna (Le Nindre et al., 1990b): Changhsingian foraminifers (Vachard et al., 2003, 2005), brachiopods (Angiolini et al., 2006), nautiloids (Chirat et al., 2006), and bacrtrids. The MFI PKm represents the maximum extent of

Khuff Formation outcrop depositional environment, Saudi Arabia

North

← BURAYDAH QUADRANGLE | AL FAYDAH QUADRANGLE | AD DAWADIMI QUADRANGLE →

26°35' N 26°05' N 25°55' N 25°20' N 25°05' N 24°55' N 24°40' N

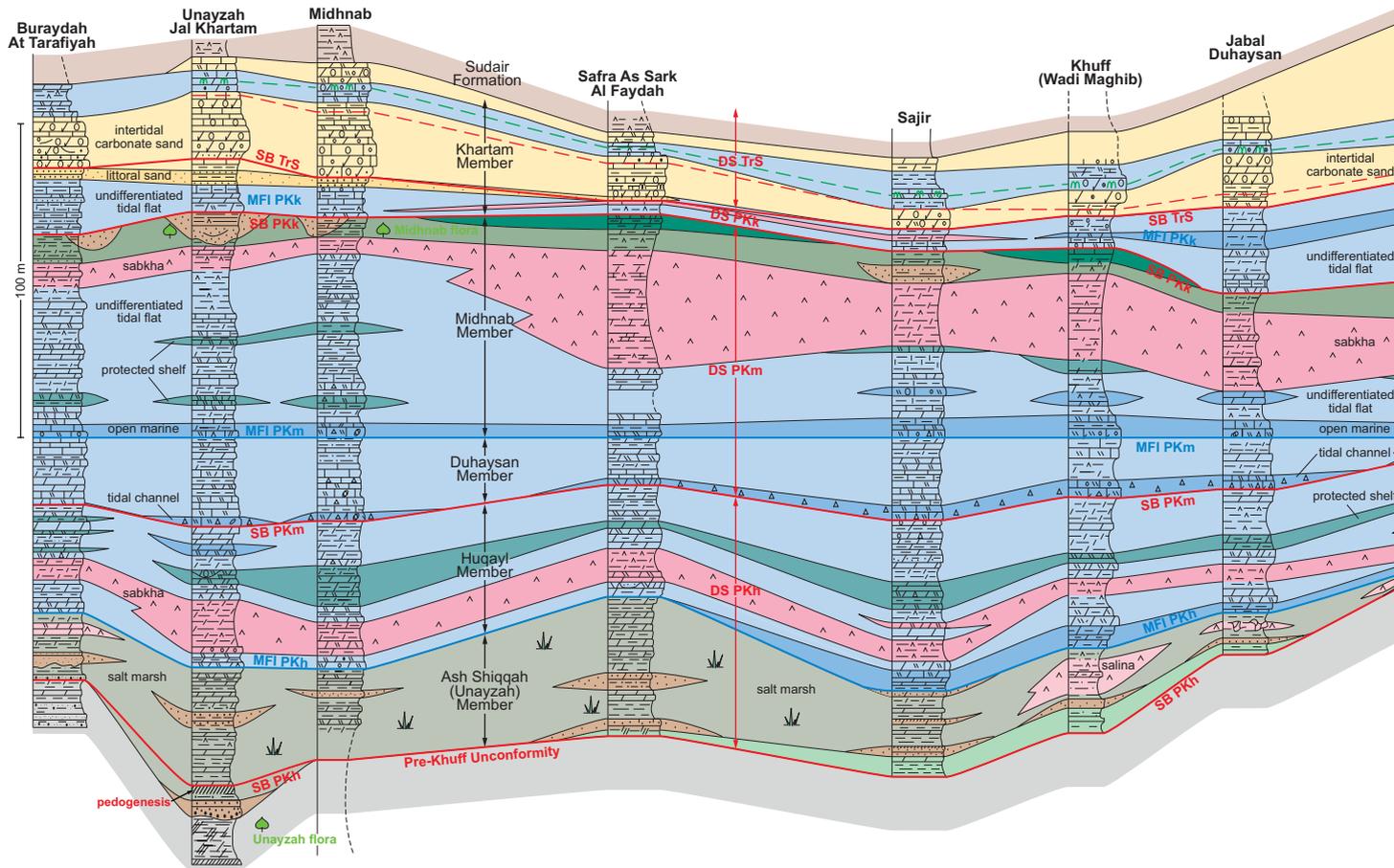
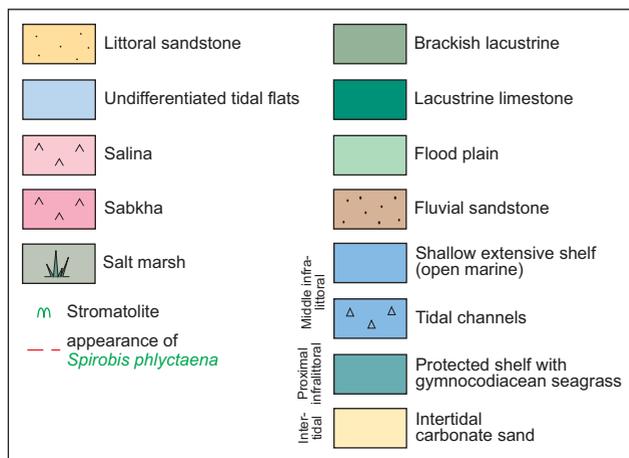
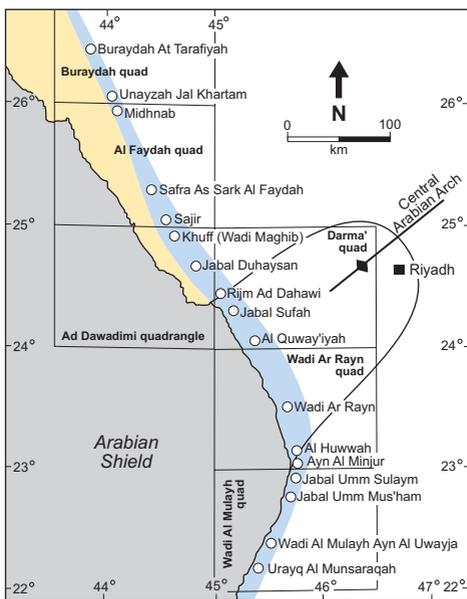
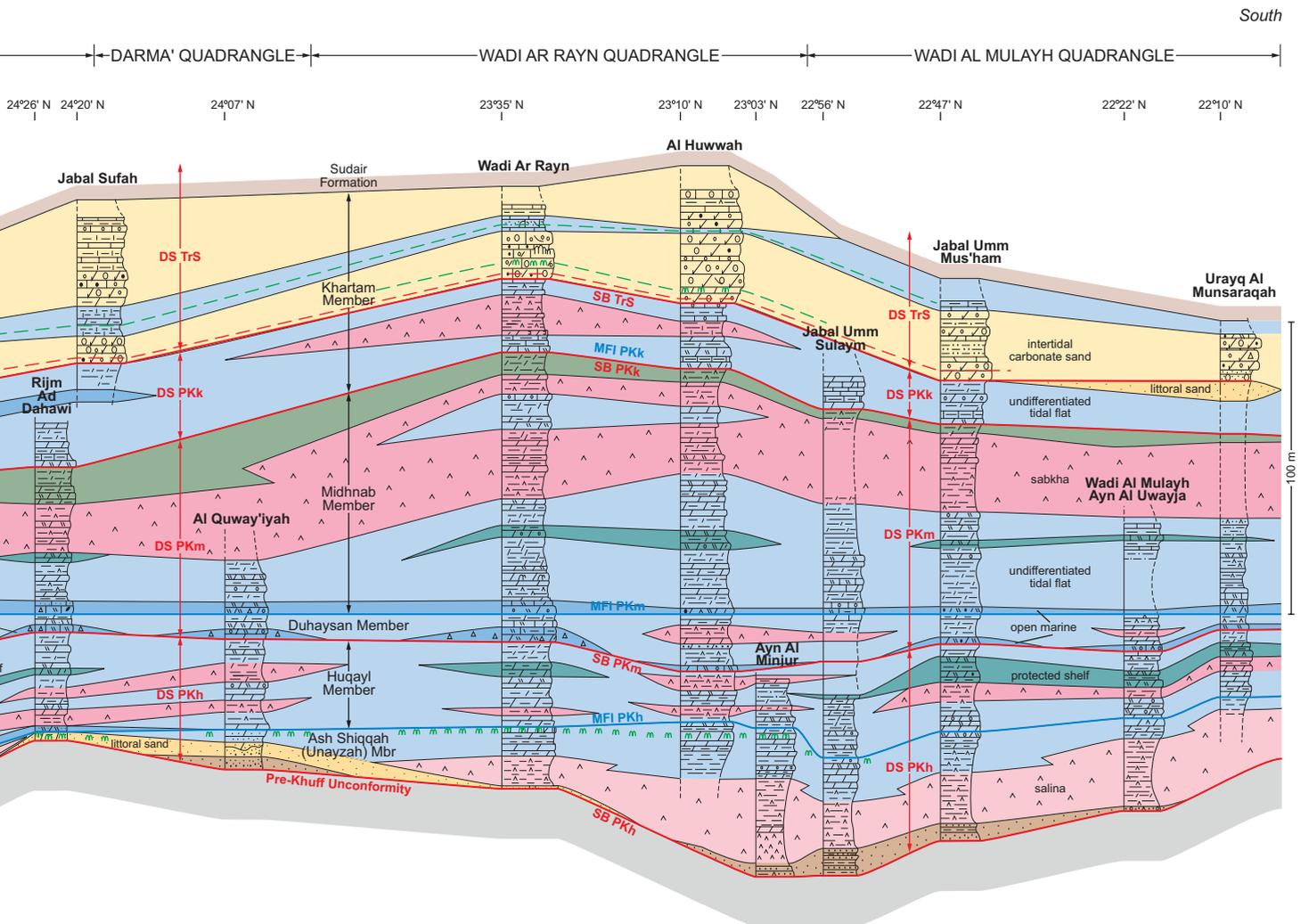


Figure 40: Depositional environments, Khuff Formation outcrops, Saudi Arabia are shown along the N-S strike of the outcrops (modified after Le Nindre et al., 1990b). Permian-Triassic depositional sequences (DS) PKh, PKm, PKk and TrS are shown together with Maximum Flooding Intervals (MFI).



the marine domain in central Saudi Arabia (Figures 4 and 41). The Midhnab MFI PKm is followed by the regressive HST that ends in the continental deposits at the upper part of the Midhnab Member. The DS PKm corresponds to Khuff cycles 2 and 3 of Al-Aswad (1997), and may contain MFS P40 of Sharland et al. (2001, 2004) (Figure 26).

The third depositional sequence DS PKk (named after Permian-Khuff-Khartam) corresponds to the Lower Khartam Member and represents the terminal Permian (Changhsingian) depositional sequence in the outcrops of central Saudi Arabia (Figure 4). The basal SB is marked by a return to marine subtidal conditions after the continental break at the end of DS PKm. The transgressive reworked facies at the base of the Khartam Member represents the TST and MFI PKk, with marine fauna including abundant Permian ostracods (Crasquin-Soleau et al., 2004), bactritids, and locally cephalopods (Chirat et al., 2006). The HST PKk is probably incomplete, being partly eroded by the dolomitic sands at the base of the Upper Khartam Member.

The DS PKk could be correlated with the lowest part of Khuff cycle 4 of Al-Aswad (1997; Figure 26). The MFI PKk has the same position as MFS Tr10 of Sharland et al. (2001), and so MFS Tr10 should be positioned higher in the section. The MFI PKk could correspond to a similar event recognised in the latest Permian of the Zagros Mountains (Insalaco et al., 2006).

The fourth depositional sequence (DS TrS, named after the Sudair Shale) starts with the littoral, tidal to intertidal deposits of the Early Triassic Upper Khartam Member of the Khuff Formation, and ends with the closed-basin, clayey to evaporitic rocks (HST) of the Early Triassic Sudair Shale (Le Nindre et al., 1990b). The Sequence Boundary is marked by an abrupt change in facies between the subtidal deposits of DS PKk and the intertidal to beach deposits of DS TrS (Figure 4). This erosional boundary could represent the Triassic/Permian Boundary in central Saudi Arabian outcrops. The MFS Tr10 is interpreted as an Early Triassic Scythian event (Stephenson, 2003; Sharland et al., 2004), and it should be positioned at least in the Upper Khartam Member or in the lower part of the Sudair Shale. This maximum flooding event has not been characterised clearly in the outcrops of central Saudi Arabia.

Depositional Sequence DS PKh: Ash Shiqqah and Huqayl Members

Above the Pre-Khuff Unconformity, the TST of DS PKh corresponds to Ash Shiqqah Member (Figures 40 and 41), which marks the progressive passage from the continental domain to lagoonal environment. In spite of the poor biofacies, the depositional palaeoenvironment and the polarity of the sequence still show the transgressive character of the Khuff Formation. The Ash Shiqqah Member exhibits very different facies north and south of the Central Arabian Arch (Figure 40). North of the arch, clastic coastal plain and salt-marsh environments dominated. South of the arch, brackish to evaporitic facies interpreted as salina deposits, correspond to the flooding of the former coastal plain.

To the north of the Central Arabian Arch, red and green claystone, fine-grained manganiferous, silty azoic dolomite and burrowed dolomite were successively deposited over a basal palaeosol. The first beds of carbonate mudstone are discontinuous, floating in clayey sediment, and display plastic deformation structures due to subsidence or slumping. In the Unayzah area, channels of quartzose sand channelled in coastal plain to lagoonal clayey unit, bearing gypsum pseudomorphs. The biophase is very rare, marked by benthic foraminifers, or poorly preserved. These facies are indicative of low-energy lagoonal-brackish environments with abnormal salinity under continental influences.

To the south, in the Darma', Wadi Ar Rayn, and Wadi Al Mulayh quadrangles, Manivit et al. (1985a, 1985b), Vaslet et al. (1983), and Cole et al. (2000) interpreted the basal clastics and mixed clastic and dolomite series of the Khuff Formation, to indicate a gradual environmental change from fluvial to shallow marine with intertidal influences (Figures 40 and 41). Between the continental and marine-end of the Ash Shiqqah Member, a transitional coastal plain environment with hypersaline lagoons was established. Conditions oscillated between peritidal marine (laminated dolomites) and marginal marine to coastal plain (marls and sandstones with salt hoppers). Continuing arid conditions led to the establishment of extensive evaporite platform deposits throughout the lower part of DS PKh. Passage to a supra- or medio-littoral domain at the top of the Ash Shiqqah Member, is shown by deposits locally progressing as far as constructed forms, such as columnar stromatolites.

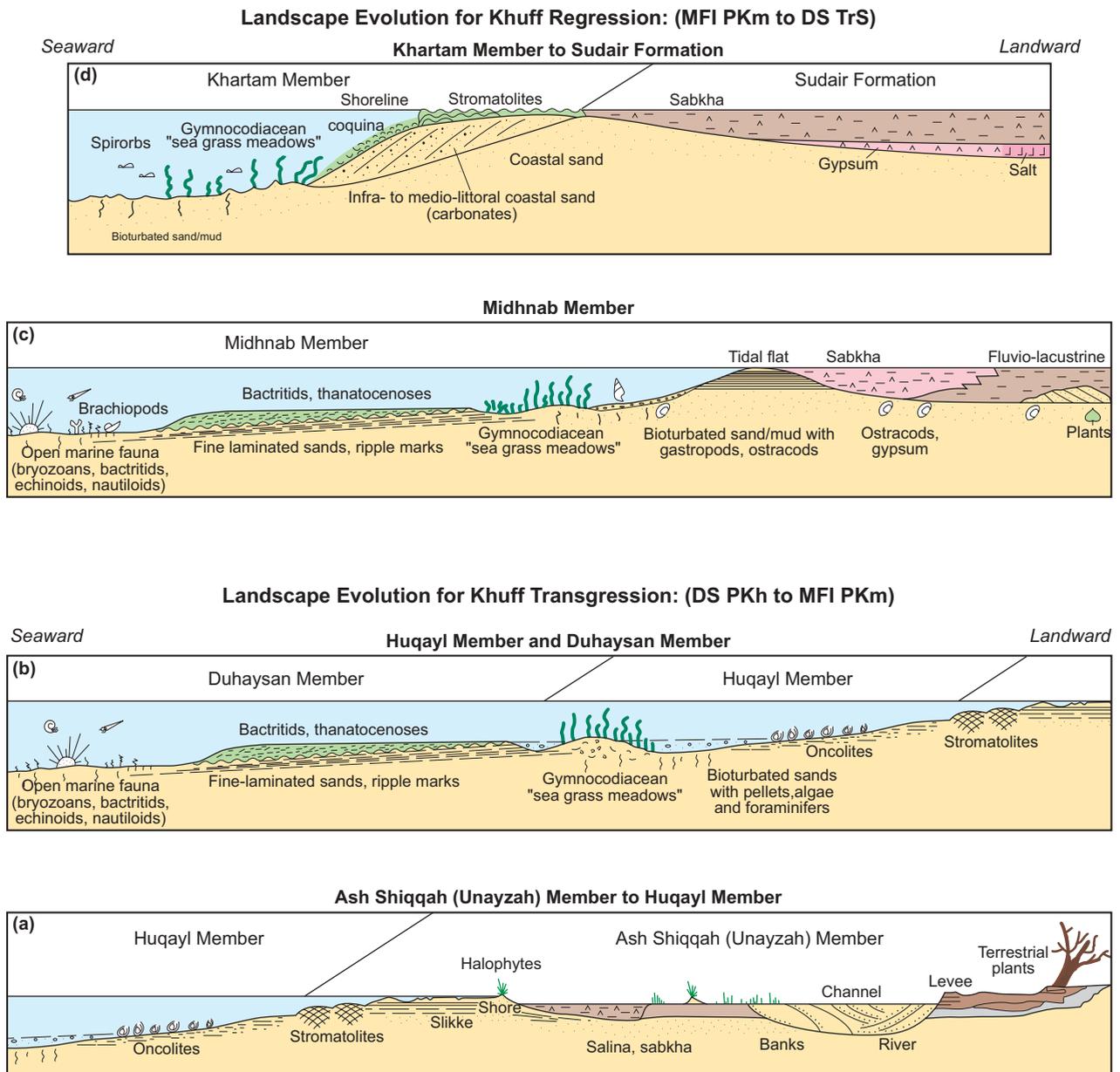


Figure 41: Landscape evolution for the Khuff transgression (DS PKh to MFI PKm) during deposition of: (a) Ash Shiqqah and Huqayl members; (b) Huqayl and Duhaysan members. Landscape evolution for the Khuff regression (MFI PKm to DS TrS) during deposition of: (c) Midhnbab Member; and (d) Khartam Member and Sudair Shale Formation (modified after Le Nindre et al., 1990b).

The marine bioclastic facies at the base of the Huqayl Member (Figure 40) corresponds to MFI PKh. It represents an intertidal domain with biocalcarene and locally intraclastic tidal channels. This marine interval represents the first transgressive deposits over the Central Arabian Arch. These carbonate beds are widespread and continuous. They represent a sharp break between the heterogeneous facies below and the homogeneous marine succession above.

The HST of DS PKh (Figures 4 and 40) corresponds to the Huqayl Member; it is composed of two higher-order sabkha sequences. Each of these two regressive sequences begins with marine bioclastic deposits and ends either with laminated mudstones containing gypsum pseudomorphs, or with anhydrite and solution breccias. The basal parts of both the Huqayl cycles are marked by a fairly rich microfauna. The base of the second sequence consists of an oncolitic marker layer. The alternation of facies is indicative of an oscillating depositional regime ranging from external lagoon to sabkha.

Carbonate sands, containing pellets and porcelaneous foraminifers, give way to deposits with a restricted fauna of molluscs that are silted up and encrusted by annelids. Abundant gymnocodiacean algae occupy an intermediate position, and tend to be reworked. Subtidal environment in the second sequence (Upper Huqayl) may represent a secondary flooding event (Figure 4). Burrowed mudstone commonly precedes paler-coloured laminated deposits. In the upper parts of the two sequences, sedimentary structures include laminations, mud cracks, mud chips, planar stromatolites, solution breccias, and sulfate pseudomorphs; all criteria suggest a low-energy mid-littoral zone such as a tidal flat and supra-littoral evaporitic domains.

Depositional Sequence DS-PKm: Duhaysan and Midhnab Members

The start of DS PKm is marked at the base of the Duhaysan Member by erosional and transgressive marine wedges (Figures 4 and 40). In this significant channelling phase, the underlying carbonate mud of the Upper Huqayl Member was reworked as mud galls in calcarenorudite, indicating an increased energy level (Duhaysan subunit 1). The sequence is marked by an abundant and varied, clearly marine fauna consisting of bryozoans, algae, echinoderms, brachiopods, gastropods, bacrtritids and cephalopods (nautiloid embryos). In north-central Saudi Arabia, the upper part of the Duhaysan displays a return to proximal and even supratidal conditions with carbonate claystone and dolomite. To the south of the Central Arabian Arch, terrigenous discharge and gypsiferous claystone reflect increased confinement.

The pelagic faunas (bacrtritids and nautiloids) associated with MFI PKm extended over considerable areas from north-central to south-central Saudi Arabia. Although this flood was the most widespread inundation of the Arabian Platform during Late Permian, it was very short-lived and followed by rapid confinement of the palaeoenvironments. In contrast to the TST of the Duhaysan Member, a new trend emerged in MFI PKm with the increased rareness or dispersion of the more-marine organisms (bryozoans) and the accumulation of bacrtritids. Measurements on thanatocenotic accumulations of the conic-shape bacrtritids, indicate a N175° direction, probably parallel to the palaeoshore. Wave ripples are commonly associated with these deposits.

Above MFI PKm, the rest of DS PKm indicates a clear regressive trend up to continental deposits in the upper part of the Midhnab Member. From the lower third of the Midhnab Member (subunit 2), the fauna becomes rarer but the algae persist, giving way upwards in the unit to rare fish debris and sulfate pseudomorphs. This general confinement was subsequently further manifested by the constant evaporitic character of the HST of DS PKm. At the top, very proximal facies containing intraclasts, fish debris, and stromatolites, is overlain by plant-bearing claystone (Midhnab flora) and sandstone channels in a swamp environment (Berthelin et al., 2006). In places, lacustrine limestone containing charophyta oogones, marks the continental trend at the top of DS PKm.

Depositional Sequence DS PKk: Lower Khartam Member

DS PKk corresponds to a terminal Permian marine incursion (Lower Khartam Member, Figures 4 and 40). It started with renewed open-marine influences followed by a rapid transgression that culminated with MFI PKk (located just a few metres above the major break between the Midhnab and Khartam members). The MFI PKk is characterised by echinoderms, bryozoans, and cephalopods associated with foraminifers (diversity of the genus *Paradagmarita*), ostracods and phosphatic debris. The extension of the marine episode (with cephalopods) is limited to the northern edge of the Central Arabian Arch. In the Buraydah area, according to Le Nindre et al. (1990b), the depositional environment of the Lower Khartam is interpreted from subtidal to lagoonal and mid-littoral.

Depositional Sequence DS TrS: Upper Khartam Member and Sudair Shale

The Depositional Sequence TrS starts with the Upper Khartam Member of the Khuff Formation and ends within the Sudair Shale Formation. In the Lower Khartam Member, the facies comprises

grainstone with commonly very planar oblique bedding, stromatolite mats (intertidal environments), and coquina. The dolarenites that predominate are composed of fine, sorted cortoids (proto-oolites) with a dolomitic bioclastic nucleus originating from biodegradation of undetermined carbonate algae. Several elemental sequences comprising the three facies are superposed, and indicate a beach environment extending from the upper part of the infralittoral domain to various levels of the midlittoral domain (foreshore to backshore), separating the lagoon from the sabkha. In the infralittoral deposits (Upper Khartam Member, subunit 4), *Spirorbis phlyctaena* is virtually constant. This sedentary annelid must have lived (much as the present-day genus) as an epiphyte over algae that are no longer preserved; it is associated with ostracods and, locally, with echinoderms. Also, due to a change in environment, a relatively abundant fauna of ostracods with a thin test appeared at this time.

The passage to a different type of sedimentation between the Lower and Upper Khartam members, underlines a discontinuity between the two depositional sequences. This change may be due to the progradation by beaches with recycling of locally available material (carbonate algae debris). Beach construction could have introduced an erosional unconformity and a change in the depositional mechanism. The diachronous aspect may have caused the depositional break to become even greater landward from the initial shoreline. This sequence boundary is believed to represent the Triassic/Permian Boundary in the outcrops of the Khuff Formation in central Saudi Arabia.

Although still showing marine influence (beds of bioclastic dolomite) in the lower part, the TST facies of DS TrS evolved throughout the remainder of the Early Triassic Scythian (Sudair Shale) towards supralittoral facies of sabkha type. These facies are essentially represented by transitional ostracod dolomite, then by gypsiferous claystone containing beds of massive gypsum, and in the SHD-1 well, some halite (Figure 23). The passage to the Sudair Shale Formation is progressive. Despite the presence of finely-oolitic and peloidal grainstone, an irreversible evolution continued toward sulfate deposits, initially interstratified in the algal mats, and subsequently as massive gypsum.

CONCLUSIONS

The Khuff Formation holds the world's largest non-associated gas reserves in many giant fields located in Bahrain, Iran, Qatar, Saudi Arabia and the United Arab Emirates (Al-Jallal, 1995). The Khuff outcrops in central Saudi Arabia offers one the most complete and representative exposures of this commercially important reservoir. This study presents a regional synthesis of previous and new lithostratigraphic and biostratigraphic data collected from this formation, and presents it in a chronostratigraphic and sequence stratigraphic framework. The study extends stratigraphically from below the Pre-Khuff Unconformity to the Sudair/Khuff Boundary, and geographically along the N-S outcrop region of about 1,200 km; the study also includes several wells.

The Khuff Formation consists of five members; from oldest to youngest: Ash Shiqqah (replaces the obsolete "Unayzah member"), Huqayl, Duhaysan, Midhnaab and Khartam. The Ash Shiqqah Member is tentatively dated as ?Capitanian (?Midian) based on the presence of the fusulinids *Monodiexodina kattaensis* and *Reichelina* sp. and appears to correlate to the subsurface Khuff-D Member. The overlying Huqayl Member is tentatively dated as ?Wuchiapingian (?Dzhulfian) based on an assemblage of smaller foraminifers dominated by *Pseudomidiella* cf. *labensis*, *Earlandia?* spp. and *Neodiscus* aff. *qinglongensis*. The Ash Shiqqah and Huqayl members constitute a depositional sequence (named DS PKh) with an age of ?Capitanian-Wuchiapingian (?late Middle Permian and Late Permian).

Another Late Permian Khuff sequence is represented by the Duhaysan and overlying Midhnaab members (DS PKm). The Duhaysan Member is dated as Late Permian (Wuchiapingian-Changhsingian) based on *Hemigordius baoqingensis*, *Graecodiscus* cf. *kotlyarae*, "*Dentalina*" *hoi*, and *Colaniella* cf. *minuta*. The Midhnaab Member is dated as Changhsingian (Dorashamian) based on *Paradagmarita* sp. and "*Glomospirella spirillinoides*" and the disappearance of the genera *Nankinella* and *Globivalvulina*. Incised channels at the top of the Midhnaab Member contain continental deposits that yielded Late Permian flora. The top of the Midhnaab Member corresponds to the maximum intra-Khuff sea-level lowstand but does not represent the Triassic/Permian Boundary.

The Triassic/Permian Boundary is positioned between the Upper and Lower Khartam members. The Lower Khartam Member is dated as latest Permian due to the presence of several species of *Paradagmarita* spp. and “*Nodosaria*” *dzhulfensis* in its lowest beds, and the ostracods *Paraparchites* spp., *Knoxiella* spp. and *Kloedenellitina* sp. throughout the unit. The Lower Khartam Member appears to represent a single sequence (DS PKk). The Upper Khartam Member is dated as Early Triassic (‘Scythian’) based on the appearance of the characteristic annelid *Spirorbis phlyctaena*. The Upper Khartam Member is interpreted as the start of Triassic sequence that extends into the Sudair Formation (DS TrS).

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