JJEES

Volume 3, Number 1, June, 2010
ISSN 1995-6681
Pages 1- 16

Jordan Journal of Earth and Environmental Sciences

Lithostratigraphy and Microfacies Analysis of the Ajlun Group (Cenomanian to Turonian) in Wadi Sirhan Basin, SE Jordan

Mohamed Ka. Khalifa[a, b, *] and Abdulkader M. Abed [b]

[a] Geoscience & Petroleum Engineering Department, Universiti Teknologi PETRONAS Bandar Seri Iskandar, 31750 Tronoh, Perak Darul Ridzuan, Malaysia

[b] Department of Environmental and Applied Geology, University of Jordan, Amman, Jordan.

Abstract

The Ajlun Group of the Wadi Sirhan Basin, Jordan, of probable Cenomanian- Turonian age, consists of alternating beds of indurated marl, marly limestone and dolomitic limestone with violet friable phosphatic sandstone. The results were used to develop a new lithostratigraphic correlation of the undifferentiated Na'ur, Fuheis, Hummar and Shueib Formations and Wadi Sir Formation in the study area. The stratigraphic boundaries of these units were defined at marked changes in outcrop and borehole characteristics. They are 25.5 metres thick at outcrop of Zgaimat Al-Hasah and 147 metres in the Wadi Sirhan-2 well. Microfacies analysis indicates deposition in a near shore slightly restricted shelf lagoon (packstone-wackestone) to more restricted environment represented by pure micrite. They are arranged in four shallowing cycles of relative sea level change. The very low thickness of the Ajlun Group at Zgaimat Al-Hasah (25.5 metres compared with 100s m elsewhere in Jordan) as well as the restricted near shore environments are explained by deposition on the Bayer-Kilwa paleohigh which left little accommodation for the deposition of the Ajlun Group.

Keywords: Wadi Sirhan Basin, Jordan, Ajlun Group, lithostratigraphic correlation, petrography, microfacies analysis, Late Cretaceous, Cenomanian-Turonian and palaeogeography.

1. Introduction

This work deals with the geology of the Ajlun Group, Late Cretaceous (Cenomanian-Turonian) in the Wadi Sirhan Basin in the southeastern desert of Jordan, close to the Saudi Arabian border (Fig. 1). During the Early Cretaceous, most of the eastern Mediterranean was emergent and subjected to fluvial sandstone deposition (Powell, 1989). By the onset of the Cenomanian, the whole area was submerged by the southern continental shelf of the Tethys as a consequence of a major global eustatic sea level rise (Haq and Qahtani, 2005). Hundreds to 1000s m thick carbonates of various facies were deposited throughout the eastern Mediterranean (Bender, 1974). One of the major factors in the pattern of deposition (thickness and facies) was the ocean floor paleorelief. Basins and swells dominated the sea floor during the Late Cretaceous due to compression associated with northward movement of Arabia as part of the African Plate (Bowen and Jux, 1987). This compression is most conspicuous in what is known as "the Syrian Arc Fold System" running from northern Egypt through Sinai and into the eastern Mediterranean (Krnkel, 1924, Bowen and Jux, 1987). In Jordan, several of these basins and swells are recognized (Abed, 1994). One of the paleohighs is the Bayer-Kilwa high where Zgaimat al-Hasah is located (Fig. 1). Thicker and deeper carbonate facies can be found in the lows compared with the highs (Powell, 1989). The Ajlun Group at Zgaimat al-Hasah was studied in general works dealing with the geology of Jordan (Quennell, 1951; Bender, 1974; Powell, 1989).

The aims of this work are a) to study the microfacies of the Ajlun Group in the outcrop and subsurface, b) to deduce the depositional environments of the group and the factors controlling them, and c) to delineate the paleogeography of the Wadi Sirhan area in the Late Cretaceous.

2. Geological Setting

Integration of lineament data within the Wadi Sirhan Basin shows that the boundaries are marked by a complex of major structural features as shown in Fig. 1. The Wadi Sirhan Basin is a monocline which trends NW-SE. It is bounded on the north by the Suwaqa fault zone, which strikes S-E on Fig. 1; it seems to cross the monocline. It is a right lateral wrench system with a strong movement along the vertical down to the north margin of the Azraq Basin (Barjous, 1986). Another structural feature is the Zgaimat Al-Hasah fault zone which also trends E-W. It extends westward from Saudi Arabia for more than 250 kilometres, to the Jordan Valley (Fig. 1). It is represented by a narrow zone of discontinuous local faults. Local folding occurs in many places along this trend and the

* Corresponding author. Mohamed_kh@petronas.com.my.

  - Volume 3, Number 1 (ISSN 1995-6681)

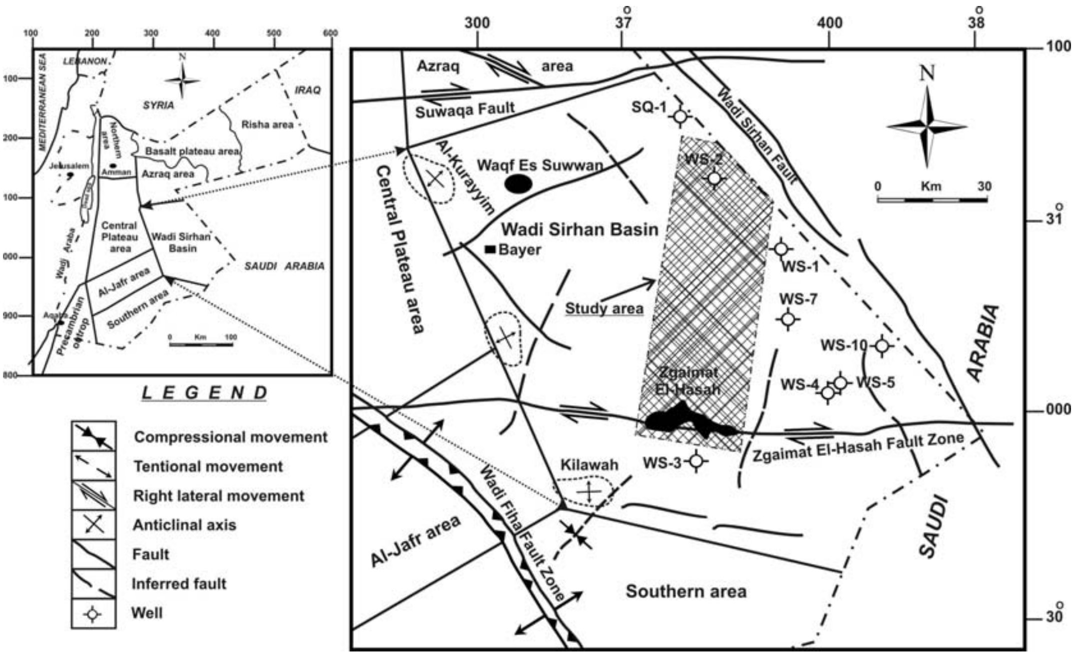

Fig. 1 Geographical location map of the study area within the Wadi Sirhan Basin (modified after Bender, 1968).

pattern of folding is indicative of (right-lateral) transcurrent movement (Holmes et al., 1989). The Zgaimat Al-Hasah outcrop is situated within one of these anticlines as an "inlier" where the Lower and Upper Cretaceous strata form its core (Qteishat, 1987; Abed and Amireh, 1999). Fig. 2 summarizes the Late Cretaceous stratigraphic framework of the Ajlun Group throughout Jordan (Wolfart, 1959; Marsi, 1963; MacDonald et al, 1965a, b; Parker, 1969; Bender, 1974; Powell, 1989; Amireh, 1997). The Ajlun Group is made of alternating limestone and marl horizons. It also thins southwards and becomes increasingly sandy in the extreme south of Jordan. It also thins eastwards and becomes sandy and phosphatic in Zgaimat Al-Hasah. The age of the group is Cenomanian-Turonian (Wetzel and Morton, 1959; Basha, 1978; Dilley, 1985).

AGE			GROUP	FORMATION	LITHOLOGY
CRETACEOUS	LATE	TURONIAN	AJLUN	Wadi Sir	Limestone, marly toward the base and massive shelly at the top increasingly sandy southwards.
				Shueib	Alternating nodular limestone with soft thinly bedded marl. Large ammonites are present.
		CENOMANIAN		Hummer	Limestone, micrite and shelly wackestone.
				Fuheis	Dominantly marly with marly limestone.
				Naur	Alternating limestone/dolomite with soft marl, increasingly sandy southwards.

Fig. 2 Stratigraphic units of the Ajlun Group throughout Jordan.

3. Lithology and Stratigraphy of the Ajlun Group

Following is a description and correlation of the Ajlun Group units at the Zgaimat Al-Hasah outcrop in the south Sirhan Basin and the Wadi Sirhan-2 well (WS-2) further north.

4. Zgaimat Al-Hasah Outcrop

The outcrop of Zgaimat Al-Hasah is approximately 90 kilometres south of the WS-2 (Fig. 1). The total thickness of the Ajlun Group in the measured outcrop is 25.5 metres. The lithostratigraphic units are summarized in Table 1.

Table 1. Lithostratigraphic units distribution of Ajlun Group sequence in the studied section of Zgaimat Al-Hasah.

Age	Group	Formation	Thickness (metres)		Main Lithology	Remarks
Turonian	Ajlun Group	Wadi Es Sir Formation	5.5 metres		Formation consists mainly of phosphatic sandstone sequence occasional thin sandstone interbeds.	Mainly of violet friable phosphatic sandstone
		Undifferentiated Na'ur, Fuheis, Hummar and Shueib Formation	20 metres	9 metres	Unit consists mainly of marly limestone with interbedded limestone, yellowish-grey, medium- grained, massive; fossils: mollusc fragments. The marls are thin, light yellowish-grey, unstratified.	The unit is yellowish in colour. The centre has a thick bed of molluscan-rich coquinoidal limestone. The gastropods and pelecypods are abundant throughout Yellowish unit, with few ostracods.
Cenomanian				11 metres	Unit consists mainly of marl and marly limestone, with scattered grey, buff and tan, dolomitic limestone. Thin levels of secondary gypsum crystals are also found.	Common in the unit is white lithology. This unit is rich in fauna, in particular; echinoids, gastropods, cephalopods and pelecypods.

The Ajlun Group here can be divided into two units; the lower part of the section is composed of undifferentiated Na'ur, Fuheis, Hummar and Shueib Formations as one formation, with a thickness of about 20 metres, shown in Fig. 3. This formation clearly overlies the varicoloured Kurnub Sandstone Formation of Early Cretaceous age. This lower unit is most probably the equivalent of the marl, marly limestone, and limestone with a few dolomitic limestones in north and central Jordan. In other words, they are equivalent to Na'ur, Fuheis, Hummar and Shueib Formation, with greatly reduced thickness.

The upper unit of the section is believed to be equivalent to Wadi Es Sir Formation with a thickness of 5.5 meters (Fig. 3, Table 2). It consists of friable phosphatic sandstone to sandy phosphorite.

5. Wadi Sirhan-2 well

The Wadi Sirhan-2 is situated in the eastern part of the Wadi Sirhan Basin (Fig. 1), 45 kilometres northeast of the outcrop at Zgaimat Al-Hasah. The report on the Wadi Sirhan-2 well (Qteishat, 1987) indicated that the Ajlun Group, Cenomanian to Turonian, extended from depths of 643 to 790 metres. However, the total thickness of the Ajlun Group in the measured section is 147 meters (Fig. 3). The undifferentiated Na'ur, Fuheis, Hummar and Shueib Formations at Wadi Sirhan-2 well are difficult to define in its boundaries and distribution. However, these descriptive undifferentiated formations can be resolved into a three intervals (Table 2). In the Wadi Sirhan-2 well, Wadi Es Sir Formation overlies undifferentiated Na'ur, Fuheis, Hummar and Shueib Formation, and it is overlain conformably by the lower part of the Belqa Group, the Amman Formation (B_2) (MacDonald, 1965a) (Fig. 3, Table 2).

6. Correlations with Other Areas

When correlating the Ajlun Group in the WS basin with two localities some 150 km further west (Fig. 4), the following points are evident:

1. The highly reduced thickness of the group in the WS basin, 25 meters in the former compared with around 450 meters in the latter. We did not see any erosional unconformities in the Zgaimat Al-Hasah outcrop. Thickness reduction might be non-depositional, or else a slower sedimentation rate will appear.
2. Despite the reduction in thickness, the lithology of the lower Zgaimat Al-Hasah unit is essentially the same as those in the west; i.e. fossiliferous marl, marly limestone and limestone. However, the upper unit is phosphatic in Zgaimat Al-Hasah compared with limestone in the west.

7. Petrography and Sedimentary Facies Analysis

The Aljun Group has been studied petrographically in outcrop of Zgaimat Al-Hasah (ZH series) and Wadi Sirhan-2 well (WS series). Standard microfacies types (SMF) have been established according to Wilson (1975) and Flugel (1982). The classification of limestone is that of Dunham (1962) and sandstone rocks of Pettijohn et al. (1973). Fig. 5 shows the MF types at Zgaimat al-Hasah outcrop while Fig. 11 is for the WS-2 well.

8. Microfacies and Depositional Environments of the Zgaimat al-Hasah Outcrop

Twenty thin-sections were studied from Zgaimat al-Hasah section (Fig. 5), 16 thin sections from the lower part, while the upper unit is represented by 4 thin sections. The description of these microfacies is shown in Table 3 and Figs 6 and 9.

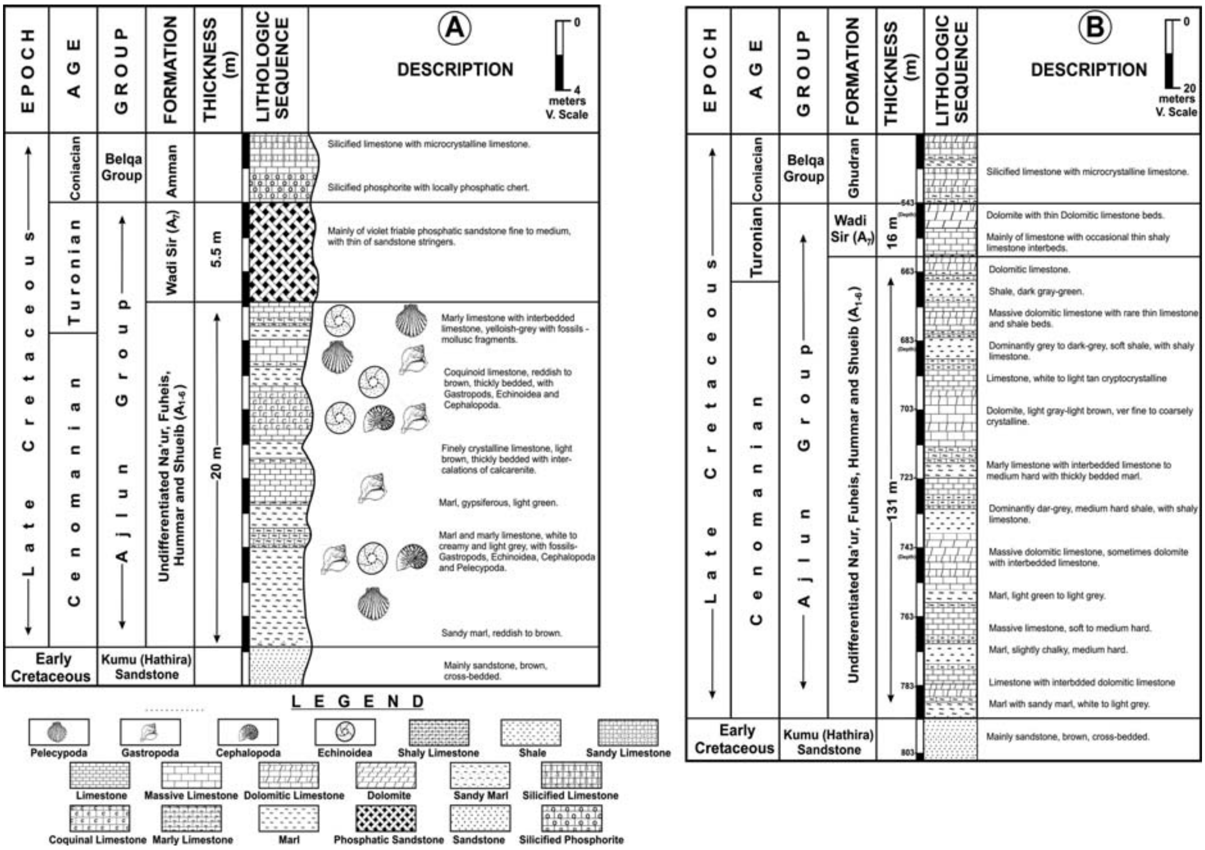

Fig. 3 Simplified lithostratigraphic column of Ajilun Group sequence in this study. **A** Representative measured section of the outcrop of Zgaimat Al-Hasah. **B** Representative measured section of the Wadi Sirhan-2 Well. (See Fig. 1 for column section location).

Table 2. Lithostratigraphic units distribution of Ajlun Group sequence in the studied section of Wadi Sirhan-2 well.

Age	Group	Formation	Thickness (metres)		Main Lithology	Remarks
Turonian	------------------- Ajlun Group -------------------	Wadi Es Sir Formation	16 metres		Depths (643-659 metres) represent this formation. The upper formation consists of fine-crystalline dolomites with minor amounts of dolomitic limestone beds. Thin shale interbeds are rare. The lower formation consists mainly of a thick bedded to massive, hard, crystalline limestone.	The dolomite is often vugular, sometimes with few fractures filled with calcite or dolomite. The lower part of the formation is sometimes sandy indicating a local mixing with underlying sands and, quartz grains are found in the basal centimeters.
Cenomanian		Undifferentiated Na'ur, Fuheis, Hummar and Shueib Formations	----------131 metres ---------	28 metres	This upper undifferentiated formations from 659-687 meters depth is composed of shale with minor dolomitic limestone and very scattered thinly bedded shaly limestone.	The shale occurs in thin interbeds and is gray to green, soft, and calcareous.
				45 metres	This middle undifferentiated formations from 687-732 metres depth and consists of limestones, slightly-medium hard, fine crystalline, medium crystalline in part, massive crystalline dolomitic limestones and dolomite.	Thin interbeds of marly limestones are common especially in the lower of the interval.
				58 metres	The lower undifferentiated formations extend from 732-790 metres depth and consist predominantly of shale with thin limestone or dolomite and dolomitic limestone interbeds, from hard to soft.	Slightly marl at its base.

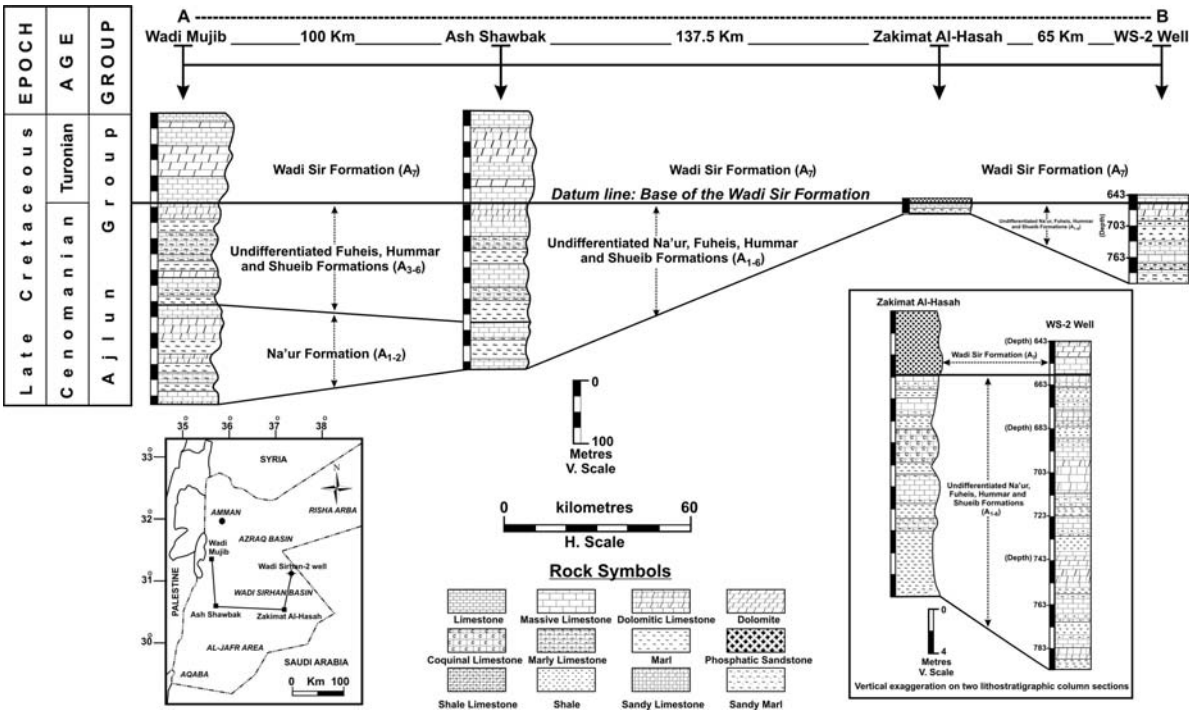

Fig. 4 Generalized lithostratigraphic columns of the Ajlun Group sequence between the Wadi Sirhan Basin (eg. outcrop of Zgaimat Al-Hasah and WS-2 well), Ash Shawbak and Wadi Mujib areas, showing the distribution of lithology, sedimentology and thickness from different lithostratigraphic units.

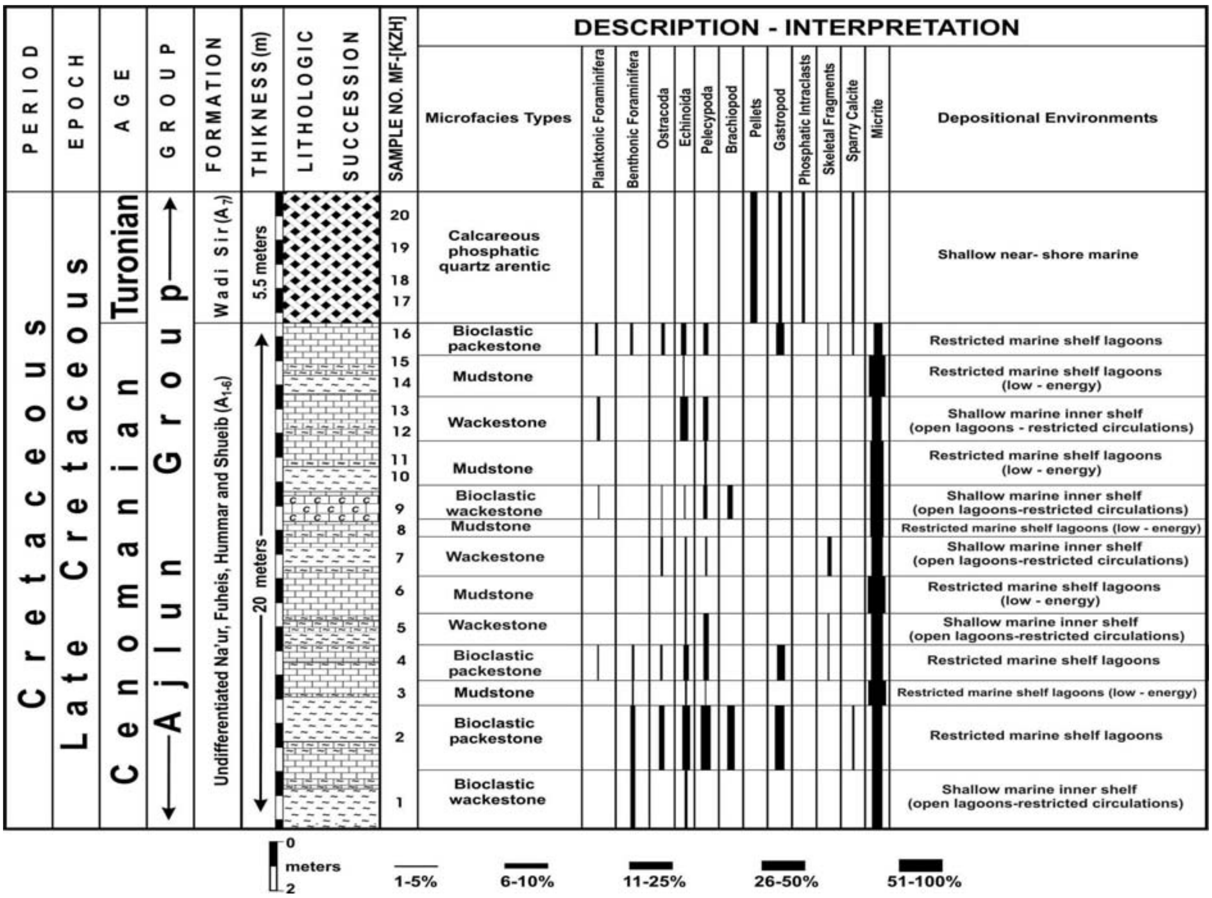

Fig. 5 Stratigraphic column of the undifferentiated Na'ur, Fuheis, Hummar and Shueib Formations and Wad Sir Formation in the outcrop of Zgaimat Al-Hasah showing microfacies types, particles and depositional environment distribution.

Table 3. Summary of the characteristics of the petrography for the Zgaimat Al-Hasah section.

Formation	Thin-section	Description	Standard microfacies types
Wadi Es Sir Formation	ZH-17, 18, 19 & 20	*Microscopically this general thin-section is composed of 36% detrital quartz rounded to subrounded quartz grains (Fig. 8e). Phosphorite particles are about 21% (Fig. 8f) and are made of brown-coloured pellets anisotropic fish debris (bone fragments). Other minerals occur as accessory components including glauconite, heavy minerals such as tourmaline, and minor amount of rock fragments (chert). The chief cement component about 39% (Figs. 10a & 10b) in this rock is calcite occurring as recrystallized blocky grains within the detrital minerals. The calcite cement corrodes the detrital quartz grains. Other cements, as quartz overgrowth is also present in very small amount. Locally the calcite cement is growing at the expense of quartz overgrowth and the detrital quartz.*	MF (ZH-17, 18, 19 & 20) ~ calcareous phosphatic quartz arenite microfacies
Undifferentiated Na'ur, Fuheis, Hummar and Shueib Formations	ZH-2 ZH-4 ZH-16	This thin-section show different sizes of grains. This thin section is composed mainly of shell fragments of echinoids 29%, pelecypods 20%, gastropods 15% and brachiopods 14%, very limited of shell fragments of ostracods 10%, benthonic foraminifers 8% and dasycladcean algae 4% (Fig. 6b). Shell fragments embedding in matrix of micrite (Fig. 7a) and may be micritized skeletal fragments. It contains also some sparry calcite cement 4% (Fig. 7b). This thin-section similar to thin-section (ZH-2), but here it contains few amount of very fine detrital quartz 5% shown in Figs. 6c and 7d. It is similar to samples (ZH-2 and 4), but without brachiopod fragments. It contains also, a few detrital quartz small ranging from 0.3-0.1 mm in diameter.	MF (ZH-2, 4 & 16) ~ bioclastic packstone microfacies is similar to Wilson's belt 7 or 8, SMF 18 and 19.
	ZH-3 ZH-6 ZH-10 ZH-11 ZH-14	This thin-section is pure micritic limestone without fossils (Fig. 7c), sometimes a few ostracods 2%. It has same sparry calcite filling the fractures. This thin-section is made up of pure micrite (Fig. 7f) with about 1% of small amount of echinoids, matrix in fine-grained micrite lime mud. This thin-section is composed of pelecypod shell of fragments and few amount of algae, mixture of carbonate mud sediment and sparry calcite 7% (Fig. 10e). Skeletal algal and pelecypod fragments are often micritization. The thin-section characteristically consist specialized thin-section pure micrite and skeletal debris is not as abundant (e.g. foraminifers and gastropods) and some channels porosity are present in the section. Several channels are filled partially with calcite. It is similar to thin-sections (ZH- 3, 6, 8, 11 and 14), but in this sample the micrite shows recrystallization processes, also contains few amount 3% of detrital quartz, small ranging from 0.05-0.1 mm in diameter. The sample (ZH- 8) without echinoids and ostracods fragments.	MF (ZH-3, 6, 8, 10, 11, 14 & 15) ~ mudstone microfacies is similar to Wilson's belt 7, 8 or 9, SMF 19, 21 and 23.
	ZH-7 ZH-12 ZH-13	This thin-section is composed mainly of shell fragment of gastropods and foraminifers present and scattered embedded in fine grain matrix. Most of the section is made of micritized skeletal fragments shown in Fig. 8a. It thin-section with abundant shell debris and larger pelecypod and gastropod fragments and few amount of algae, and some of it reach detrital quartz that are embedded in a matrix of micrite. The micrite is recrystallized. Several channels are filled partially with calcite and few amount of silica are present in microfacies. Microscopically, this thin-section is composed mainly of shell debris and larger echinoids 34% pelecypods 19% and benthonic foraminifers 9%, with detrital quartz 7%, particles embedding in matrix of micrite (Fig. 9b). Sometimes particles are micritized shells. In addition, fractures are filled with calcite.	MF (ZH-7, 12 & 13) ~ wackestone microfacies is similar to Wilson's belt 7 or 8, SMF 19.

© 2010 Jordan Journal of Earth and Environmental Sciences . All rights reserved - Volume 3, Number 1 (ISSN 1995-6681)

	ZH-1	Microscopically, this thin-section is consists mainly of shell fragments jumbled of echinoids 63%, some miliolids of foraminifers 37%, and few amount 6% of detrital quartz shown in Fig. 6a. Quartz-size ranging commonly from 0.2-0.6 mm in diameter that is embedded in micritic matrix.	MF (ZH-1 & 9) ~ bioclastic wackestone microfacies is similar to Wilson's belt 7 and 8, SMF 9 and 19.
	ZH-9	This thin-section is dominated by shell of fragments pelecypods 42%, ostracods 28%, and echinoids 20% with some fragments of fenestrate bryozoans shown in Fig. 9a. Shell fragments embedding in matrix of micrite, the micrite is recrystallized (Figs. 8b and 8c). The In some sparry calcite cement fills the chambers and the surrounding sediment is micrite with a few thin ostracods and echinoidsd.	

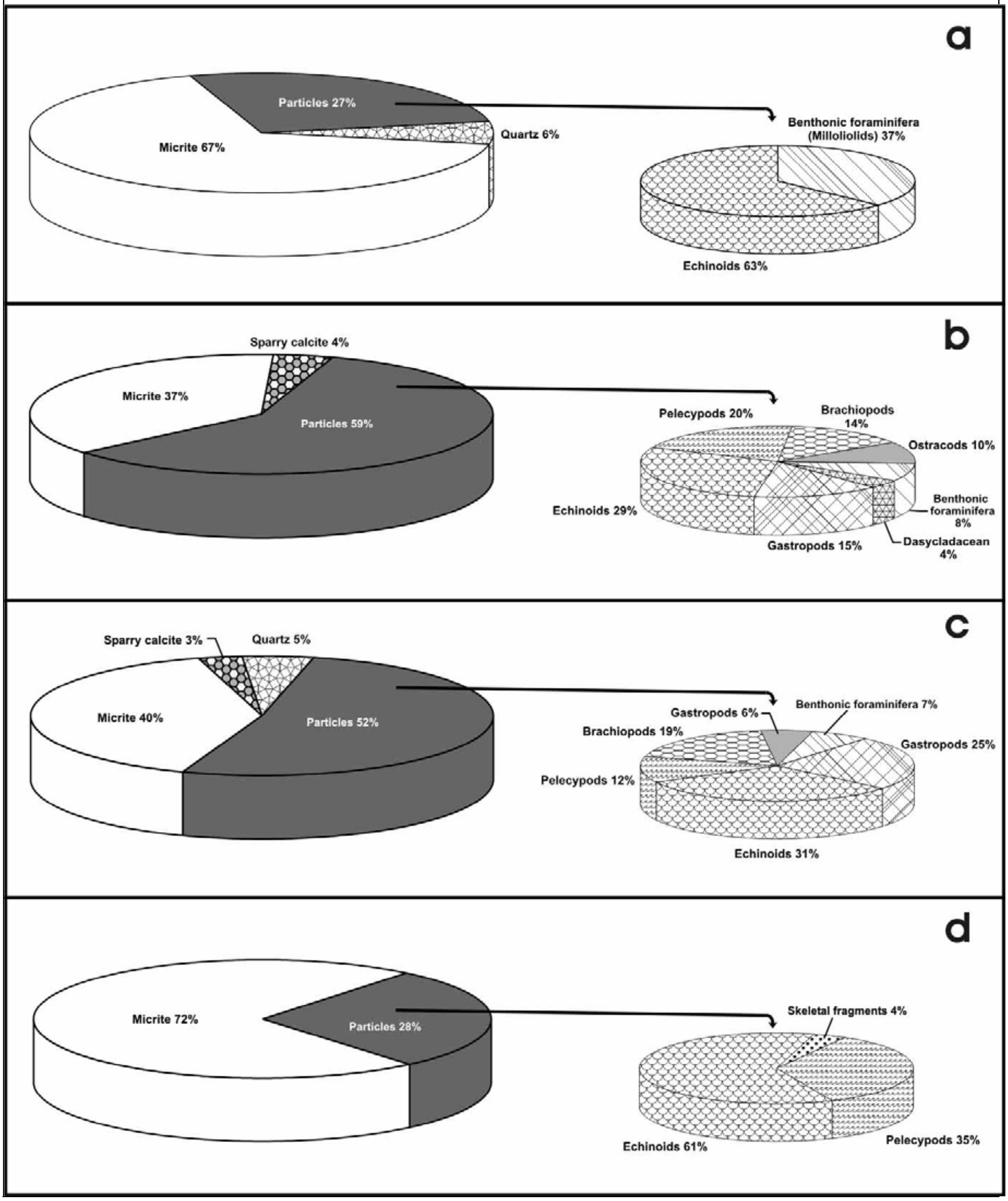

Fig. 6 Quantitative composition of the microfacies types within the outcrop of Zgaimat Al- Hasah. **A** MF (KZH-1): Bioclastic wackstone. **B** MF (KZH-2): Bioclastic packstone. **C** MF (KZH-4): Bioclastic wackstone. **D** MF (KZH-5): Wackstone.

Photomicrographs are shown in Figs. 7, 8 and 10. Four major microfacies types are recognized at the Zgaimat al-Hasah outcrop. These are (1) bioclastic wackestone/ wackestone microfacies; (2) bioclastic packstone microfacies; (3) mudstone microfacies; and (4) calcareous phosphatic quartz arentic microfacies.

Table 4. Summary of the characteristics of the petrography for the Wadi Sirhan-2 well.

Formation	Thin-section	Description	Standard microfacies types
Wadi Es Sir Formation		-- No thin-sections -- --	
Undifferentiated Na'ur, Fuheis, Hummar and Shueib Formations	WS-1	*This thin-section from depth 768 metres indicate the presence mainly of planktonic foraminifers 29%, benthonic foraminifers 21%, ostracods 15% and pelecypods 21% debris fragment, and few grains of glauconite and detrital quartz, embedded in a matrix of micrite (Fig. 9c). In some places, it is dolomitized, in other places recrystallized to sparry calcite.*	MF (WS-1) ~ foraminifera wackestone microfacies is similar to Wilson's belt 7 or 8, SMF 16, 18 and 19.
	WS-2	Microscopically this thin-section is best represented by depth 764 metres, which mainly consists of shell fragments (pelecypod and echinoid). Some foraminifers also present, dolomitization processes are also took place within this thin-section.	MF (WS-2 & 4) ~ wackestone microfacies is probably equivalent to the microfacies used as a similar to Wilson's belt 7 or 8, SMF 8, 9, 10, 17 and 19.
	WS-4	This thin-section about depth 763 metres and is represented by shell fragments of pelecypod 42% and echinoids 37%, and few benthonic foraminifers 21% (Fig. 9d). The matrix also contains some grains of quartz and glauconite. The matrix have been affected by two major processes, the first one is the recrystallization into sparry calcite, the other is the transformation of microsparrite into obvious dolomite grains (dolomitization), the last processes appears to be less obviously (Figs 10c and 10d).	
	WS-3	This thin-section is pure micrite limestone, without any fossils content. Small amount of quartz grains are present. Dolomatization has been detected but lesser, thin-section (WS-3), about 764 metres.	MF (WS-3 & 5) ~ mudstone microfacies is similar to Wilson's belt 8 or 9, SMF 23.
	WS-5	Microscopically, this thin-section similar to thin-section (WS-3), but matrix darker, about depth 762 meters.	

Interpreted depositional environment: this microfacies represents a shallow marine inner shelf (open lagoons-restricted circulation) environment. This is supported by presence in the sediment of fragments of diverse organisms. Wilson (1975) believed that these organisms may occur locally in great abundance in such facies. This microfacies occurs in an environment similar to Wilson's (1975) facies belt 7 or 8, SMF 8, 9 and 19.

9. Bioclastic Packstone Microfacies

This facies is composed mainly of marly limestone, light brown to dark grey, with yellow to cream, thin-medium bedded, interbedded with yellow marl. This belt has abundant bioclastic packstone textures that comprise 10-30% of the undifferentiated Na'ur, Fuheis, Hummar and Shueib Formations within of the Zgaimat Al-Hasah section.

Here macrofossils are restricted to only a few thin beds. The macrofossils present as whole shells; echinoids, cephalopods and gastropods are the most important fossil groups in this facies.

Microscopically, this section shows abundant bioclasts of brachiopods, echinoids, ostracods, mollusca (gastropods and pelecypods) all, dasycladacean algae, few benthonic foraminifers, and some detrital quartz, embedded in a matrix of micrite. The cement is mostly blocky sparry calcite and constitutes less than 10%. Fig. 5 shows the results of microscopic investigations of this microfacies bioclastic packstone were also given in thin-sections MF (ZH- 2, 4 and 16).

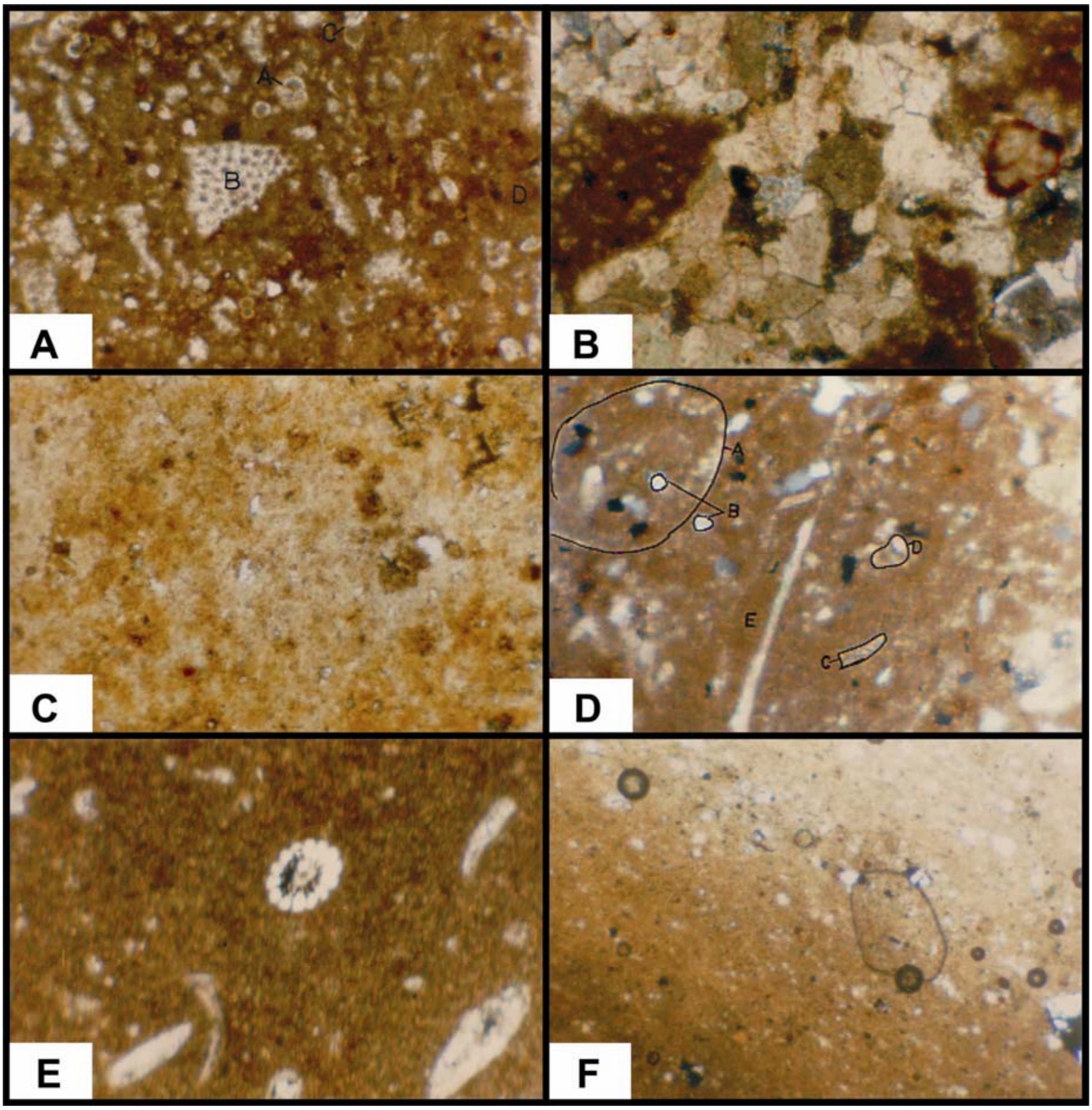

Fig. 7 Thin-section photomicrographs within the outcrop of Zgaimat Al-Hasah. **A** Bioclastic packstone showing benthonic foraminifera (*A*), dasycladcean algae (*B*), gastropod (*C*) and matrix of micrite - magnification X10/ XPL. **B** Bioclastic packstone with abundant blocky calcite cements - magnification X10/XPL. **C** Pure mudstone - magnification X10/XPL. **D** Bioclastic packstone shows gastropod (*A*) fossil filled with detrital quartz (*B*), pelecypod fragments (*C*), foraminifera (*D*) and matrix of micrite (*E*) - magnification X10/ XPL. **E** Wackstone shows echinoid spine and pelecypod (shell fragments) embedding in micrite - magnification X10/ XPL. **F** MF (KZH-6) is made up of pure micrite - magnification X10/ XPL.

Interpreted depositional environment: this microfacies is similar to SMF-19 of Wilson (1975), indicating a restricted marine shelf lagoon environment. This is supported by the very limited whole fossils, mainly cephalopods, echinoids and gastropods, which indicate a quiet environment, and the presence of shell debris of ostracods, brachiopods, mollusca (pelecypods and gastropods), dasycladcean algae and benthonic foraminifera is abundant. The detrital quartz possibly was originated from a sand bar producing this shelf lagoon (Selley, 1988).

10. Mudstone Microfacies

This facies contains marls, white to yellowish, with associated light brown, marly limestone and minor coarse shell debris. The facies is dominated by mudstone textures which comprise 40% or more of the total thickness of the undifferentiated Na'ur, Fuheis, Hummar and Shueib Formation in Zgaimat Al-Hasah section.

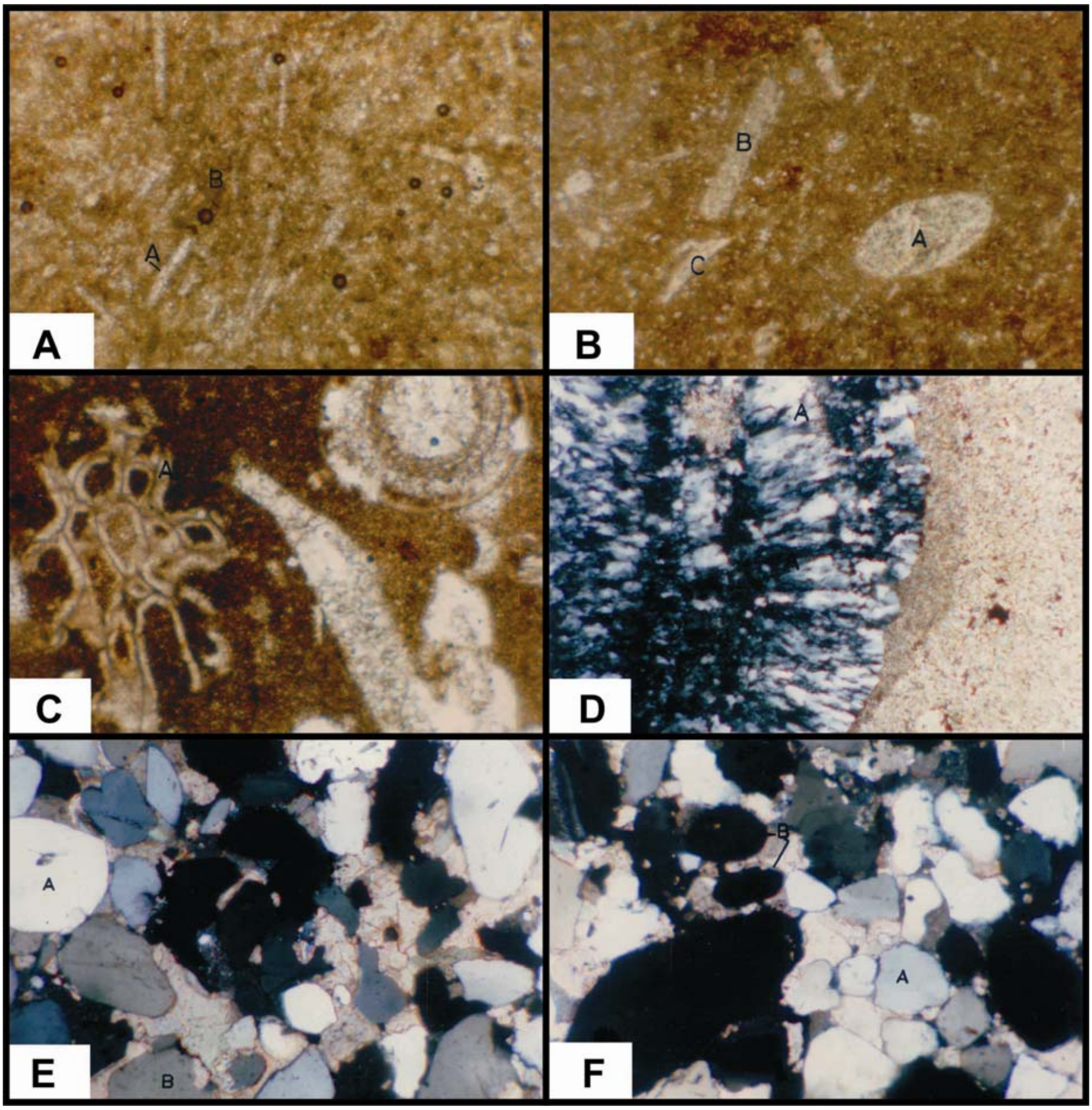

Fig. 8 Thin-section photomicrographs within the outcrop of Zgaimat Al-Hasah. **A** Wackstone microfacies shows micritized shell fragments (*A*) micrite (*B*) - magnification X10/ XPL. **B** Bioclastic wackstone with abundant fragments including ostracods (*A*), pelecypods (*B*) and echinoids (*C*) embedding in micrite - magnification X10/ XPL. **C** Typical sample of MF (KZH-9), showing effect of micritization on bryozoans (*A*) - magnification X10/XPL. **D** Mudstone shows fracture filled with silica (*A*) - magnification X10/XPL. **E** Calcareous phosphatic quartz arentic microfacies shows detrital quartz rounded (*A*) and corrosive quartz grain due to calcite cement (*B*) - magnification X10/XPL. **F** Calcareous phosphatic quartz arentic microfacies with common detrital quartz subrounded (*A*) and rounded and subrounded phosphate particles (*B*) - magnification X10/ XPL.

The mudstone microfacies is recognised at several horizons, and is represented by the following by MF (ZH-3, 6, 8, 11, 14 and 15), as shown schematically in Fig. 5. The mudstone microfacies comprises a range of sedimentary constituents in which carbonate mud is dominant. Microscopically, this microfacies is a pure mudstone locally, very fossiliferous in places; individual pellets are smeared or coalesced, giving rise to patches of apparently homogeneous micrite. That represented by this microfacies which consists on unfossiliferous mudstone partly of completely recrystallized phenomenon. Fossiliferous mudstone has usually less than 10% particles, with fossils constituting one of more of the following types: echinoids, pelecypod fragments, ostracods and small foraminifers.

Interpreted depositional environment: these sediments were deposited in a low-energy lagoonal environment (cf. Rohl et al., 1991). This microfacies is interpreted as indicating the presence of a restricted marine shelf lagoon environment similar to Wilson (1975) facies belt 8 or 9, SMF 23 (?) and Flugel (1982).

11. Calcareous Phosphatic Quartz Arenite Microfacies

The facies consists mainly of phosphatic sandstone, typically violet, medium hard to friable, always massive, with sandstone occurring locally. This facies is recognized only in the Wadi Es Sir Formation at Zgaimat Al-Hasah section.

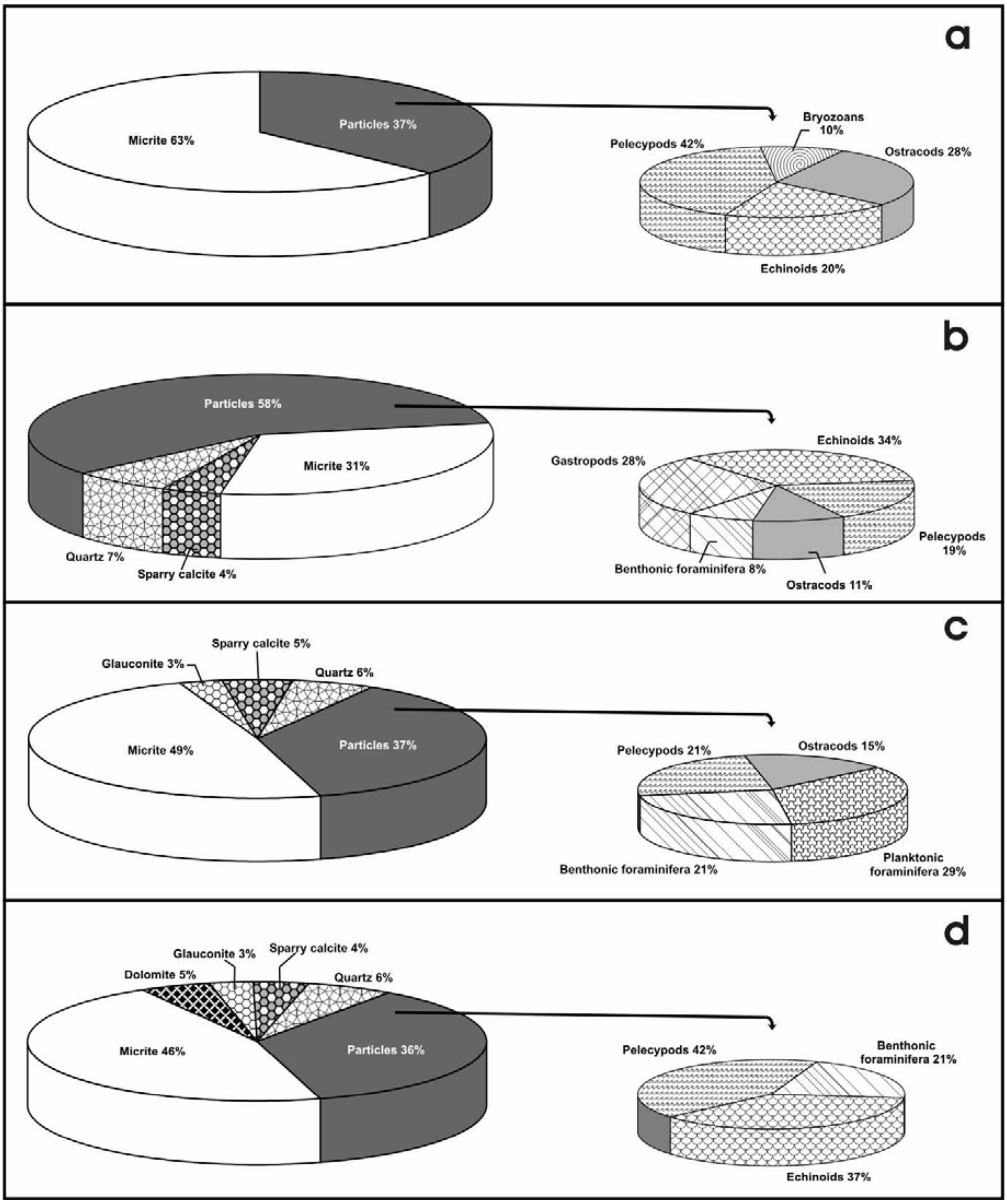

Fig. 9 Quantitative composition of the microfacies types within the outcrop of Zakimat Al-Hasah and Wadi Sirhan-2 Well. **A** MF (KZH-9): Bioclastic wackstone. **B** MF (KZH-13): Bioclastic wackstone. **C** MF (KWS-1): Foraminifera wackstone. **D** MF (KWS-4): Wackstone.

This microfacies consists of detrital quartz and rounded to subrounded phosphatic particles. It also, contains few glauconitic grains and is slightly dolomitic with the calcite cement. Microscopically, this section shows abundant detrital quartz and phosphatic particles including skeletal fragments (bones and teeth) and some intraclasts, and it is suggested that thin-sections MF (ZH-17, 18, 19 and 20) mostly represent calcareous phosphatic quartz arenite microfacies.

Interpreted depositional environment: the presence of phosphorite particles and glauconitic grains indicates that this sand is a marine sand with near-shore deposition for the supply of the abundant detrital quartz. The microfacies and sedimentological analysis suggest that this shallow near-shore marine depositional environment is restricted to the Wadi Es Sir Formation at the Zgaimat Al-Hasah section, and has only a relatively limited geographic distribution. It is probably equivalent to the depositional environment used as a similar facies by Wilson (1975); Southgate (1986).

12. Microfacies and Depositional Environments for the Wadi Sirhan-2 well

Thin-section studies show that the lower part of the Aljun Group in Wadi Sirhan-2 is represented by undifferentiated formations (Fig. 11). One core sample with a thickness of about 9 metres was cut in the undifferentiated Na'ur, Fuheis, Hummar and Shueib Formation from a depth of 643-790 metres. Four thin sections are made (Fig. 11). No core samples were cut in the Wadi Sir Formation in Wadi Sirhan-2. The summary of the undifferentiated formations as recognised in thin-sections is represented by the following WS-1, 2, 3, 4 and 5 (Table 4).

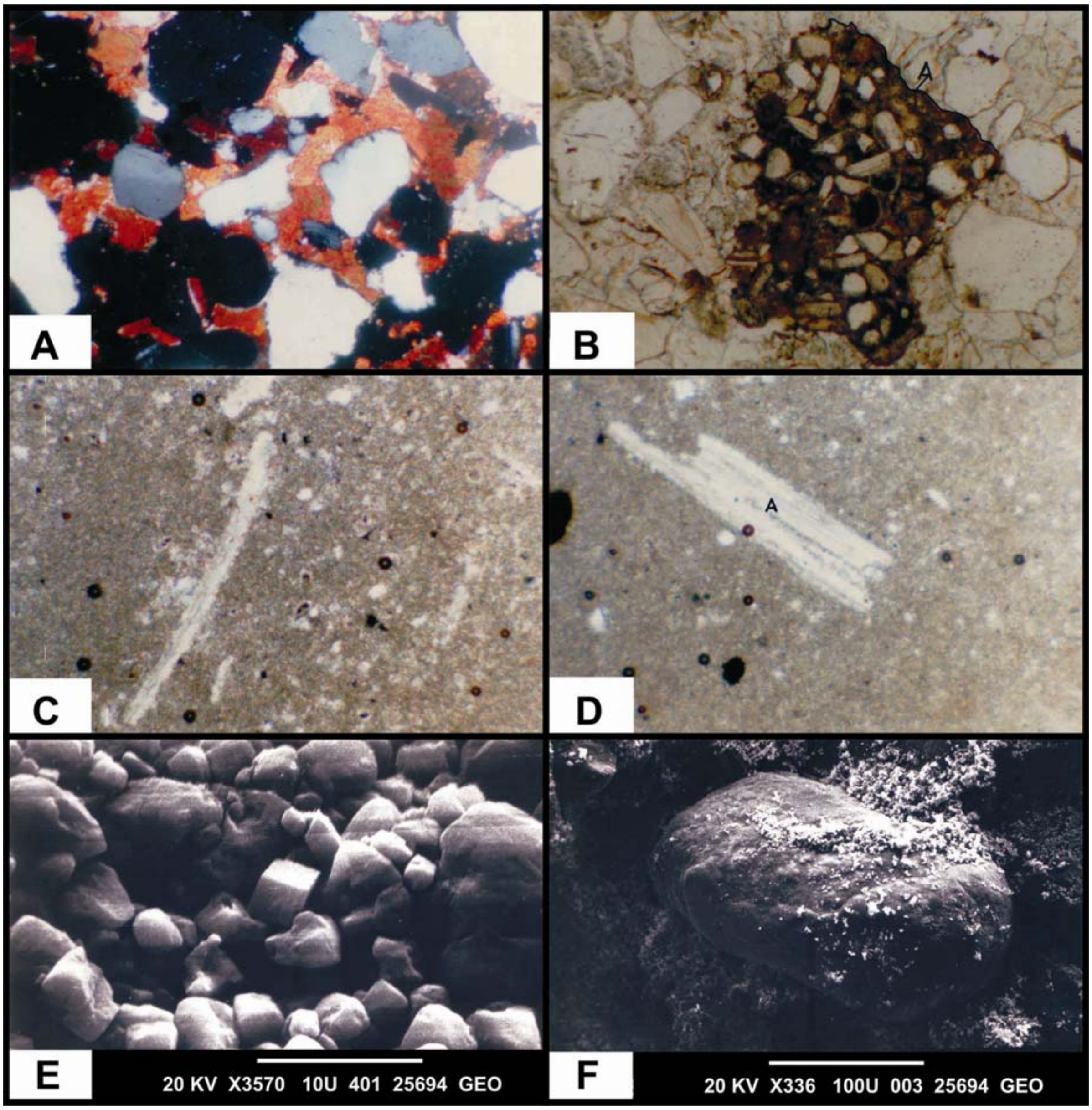

Fig. 10. Thin-section photomicrographs within the outcrop of Zgaimat Al-Hasah and Wadi Sirhan-2 Well. **A** Calcareous phosphatic quartz arentic microfacies shows calcite cements, phosphate particle brown-coloured pellets anisotropic fish debris - magnification X10/XPL. **B** Thin-section shows phosphate intraclasts (*A*) - magnification X10/ XPL. **C** Wackestone with numerous shell fragments embedding in micrite - magnification X10/ XPL. **D** Thin-section show pelecypod (shell fragment) - magnification X10/XPL. **E** SEM photomicrograph for MF (KZH-10) shows the crystal calcite. **F** SEM photomicrograph for Calcareous phosphatic quartz arentic microfacies show detrital phosphorite.

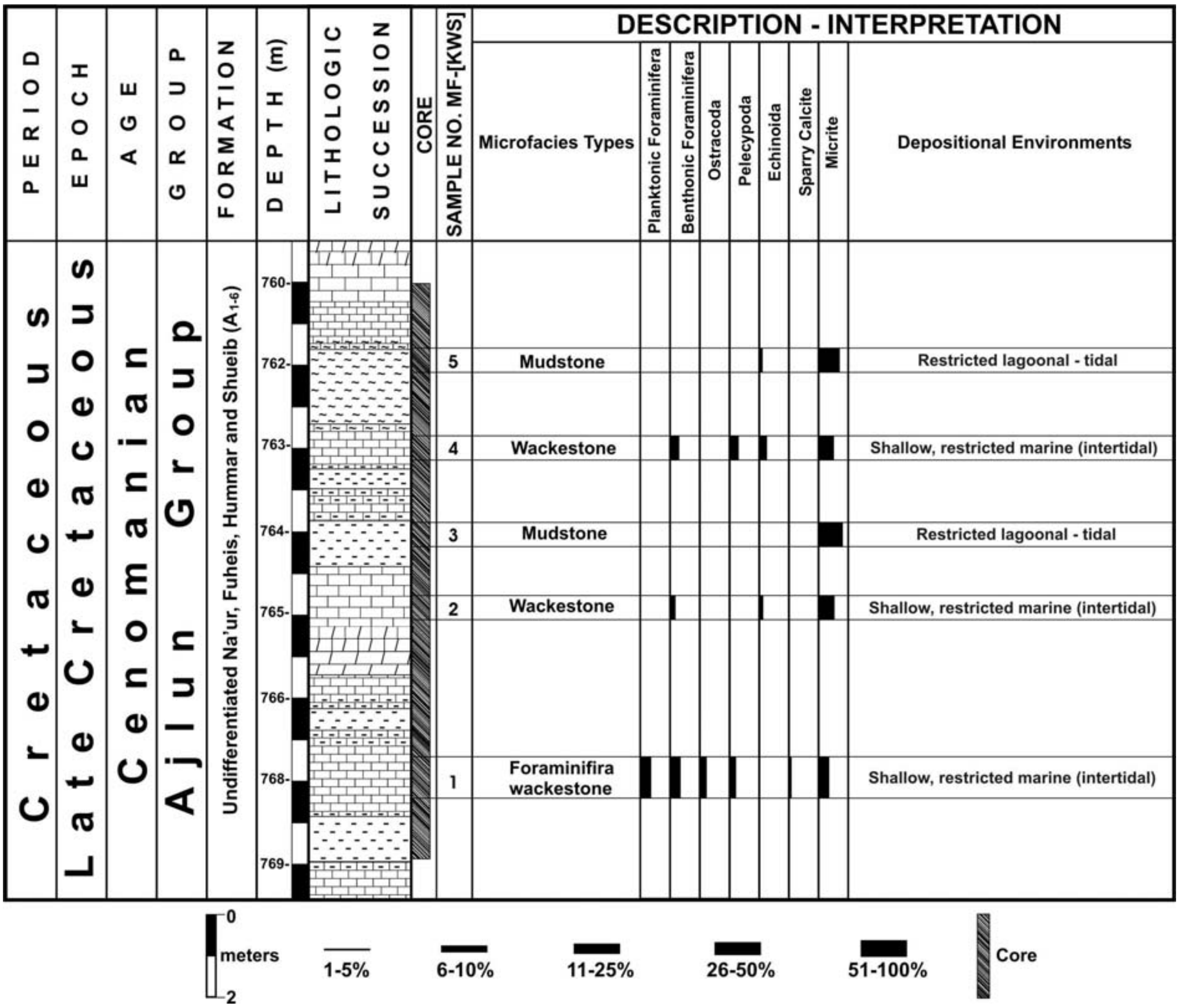

Fig. 11 Stratigraphic column of the undifferentiated Na'ur, Fuheis, Hummar and Shueib Formations in the Wadi Sirhan-2 well showing microfacies types, particles and depositional environment distribution.

Two microfacies analyses are recognized in this well. These microfacies belts and paleodepositional environments are discussed in ascending order below and the characteristics inherent to each facies are summarized in Fig. 4. They are subdivided into two major microfacies as follows: (1) foraminiferal wackestone/wackestone microfacies; and (2) mudstone microfacies.

13. Foraminiferal Wackestone/ Wackestone Microfacies

This facies consists mainly of shale to shaly limestone with a few levels of limestone. The shale is greenish grey to dark grey, locally red-brown, and limestone is cream to dark brown. In some shale beds a few foraminifers, ostracods and pelecypods are present. This belt is composed mainly of wackestone to foraminiferal wackestone textures in the Wadi Sirhan-2 well (Fig. 11).

The criterion for this microfacies is the abundance of generally well preserved debris fragments of echinoids, ostracods, pelecypods and foraminifers. Throughout the thin-section other fossils are present in smaller numbers, such as brachiopod etc. and few detrital quartz that are embedded in a micritic matrix. The results of microscopic investigations of this microfacies were also in thin-sections MF (WS-1, 2 and 4), as shown schematically in Fig. 11.

Interpreted depositional environment: this microfacies is highly diverse and its distribution pattern indicates deposition in intertidal environments (Flugel, 1982). The suggested environment for this facies is a shallow, restricted marine environment.

14. Mudstone Microfacies

This belt is dominated by shales, which comprise 70% or more of the Wadi Sirhan-2 well (Fig. 11). The shale is dark grey grading to greenish grey locally shaly limestone.

Microscopically, the term "lime mudstone microfacies" is used here in the manner suggested by Dundam (1962) to indicate rocks made up of pure lime mud. Microscopically, this microfacies is pure mudstone, for the most part without fossils, sometimes a few shell fragments of pelecypod, echinoids and foraminifers are present. Unfossiliferous mudstone consists completely of micrite which often shows dolomitization processes; see thin-sections MF (WS-3 and 5).

Interpreted depositional environment: this microfacies is believed to have been deposited in restricted lagoonal to tidal environments (cf. Flugel, 1982).

15. Discussion

The Ajlun Group, Cenomanian-Tutonian, is present throughout Jordan in except the extreme south where it was eroded as a consequence of the recent uplift associated with formation of the Dead Sea Transform (DST) in the Middle Miocene (Bender, 1974; Powell, 1989). It crops out fully in many wadis throughout the western mountain range forming the eastern shoulder of the DST. It becomes subsurface in the Jordanian plateau further east except for certain "inliers" like the Zgaimat Al-Hasah (Fig.1).

Typically, the group is made of alternating limestone and marl horizons ranging in thickness from 50 to 150 meters. However, sand starts to invade the group from central Jordan southwards until it becomes almost completely a marine sandstone in the south. The southwards increase of sand is explained by the proximity to the Palaeozoic Nubian sandstone facies. The abundant sandstone brought to the southerly localities seems to have diluted the carbonate facies or interfered seriously with the carbonate factory.

On the other hand, the group thickness decreases in the same direction of sand increase; i.e. southwards. In a distance of 350 km along the western mountain range, the thickness varies from around 600 meters in NW Jordan, 400-500 meters central Jordan to in the south. Also, the thickness decreases in a W-E direction, but more rapidly to 25 meters at Zgaimat Al-Hasah in a distance of <150 kilometres. (Fig. 12). We believe that the reason for the drastic decrease in the group thickness at the Zgaimat Al-Hasah is the presence of a paleohigh or arch called the Bayer-Kilwa Arch. This high decrease seems responsible for the non-deposition of the whole Triassic and Jurassic periods (Powell, 1989). With the onset of the major Cenomanian transgression, the Bayer-Kilwa high was submerged, thus creating some accommodation for the deposition of the Ajlun Group.

Such a setting would allow the deposition of Ajlun Group within the inner shelf not far way from the shore lines of the Neotethys further south east. Small changes in relative sea level, partly associated with low rate of uplift of the Jordanian plateau, can explain the changes in the microfacies and depositional environments described above. Four shallowing cycles are shown in Fig. 4. They consist of the slightly restricted shelf lagoon represented by the bioclast wackestone – packestone at the base changing into the more restricted micrite facies. The fourth cycle, consisting of phosphatic quartz arenite, indicates that the Zgaimat Al-Hasah became more proximal to the sand source area; i.e. shallowest.

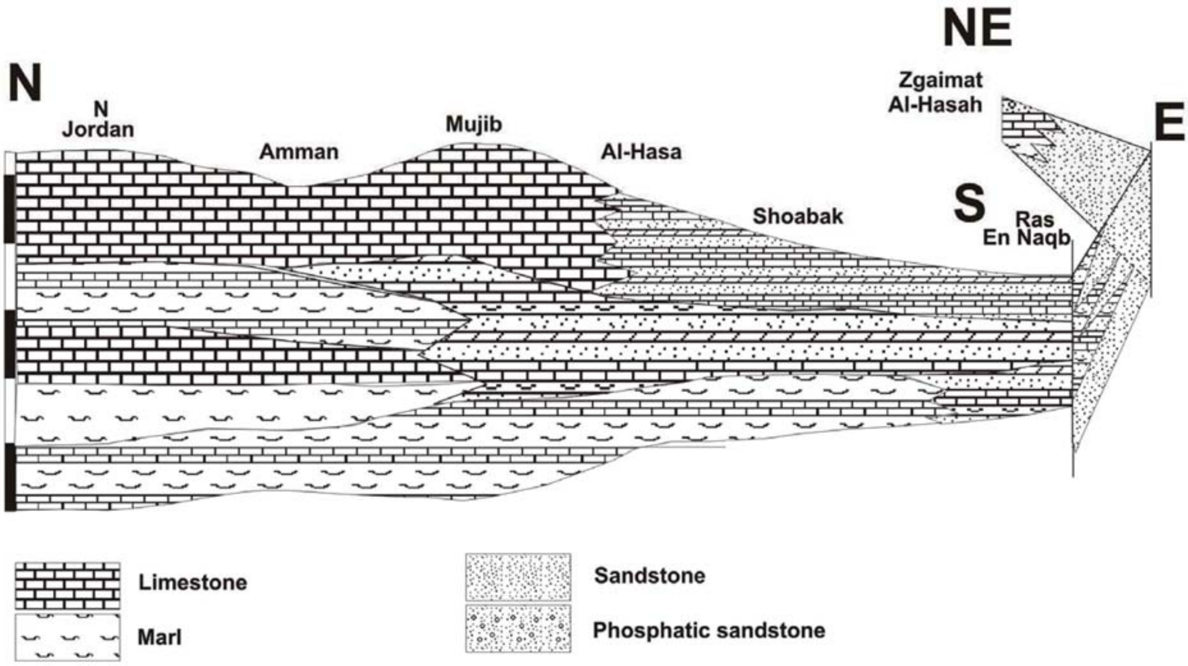

Fig. 12 A generalized fense diagram showing the lithological and thickness changes throughout Jordan.

16. Conclusions

1. Zgaimat Al-Hasah formed part of the Bayer-Kilwa paleohigh during most of the Mesozoic with the non-deposition of the Triassic and Jurassic periods.
2. Zgaimat Al-Hasah was submerged since the early Cenomanian as a consequence of a major global eustatic sea level rise, carbonate sedimentation commenced.
3. Changes in relative sea level associated with low rate of uplift in the Jordanian plateau did not allow much accommodation for sediments to accumulate, thus restricting them to 25 meters for the whole Ajlun Group compared with a 10-20 folds thickness in the western mountain range.
4. Microfacies analysis indicates near shore depositional environments of slightly restricted (wackestone/packstone) to more restricted shelf lagoon (micrite) arranged in 4 cycles of sea level changes. The 4th cycle contains phosphatic sandstone where accommodation is nearly closed.
5. The Sirhan Basin deepened northwards because the Bayer-Kilwa paleohigh is subdued in that direction or the basin is plunging in the same direction.

Acknowledgements

This work was supported principally by University of Jordan in collaboration with the Petroleum Geology Division of the Jordanian Natural Resources Authority as part of MSc thesis. I am grateful to Dr Grant-Mackie (The University of Auckland) for the review of the final version and his many suggestions and useful amendments.

References

Abed AM (1994) Shallow marine phosphorite-chert-palygorskite association, Late Cretaceous, Amman Formation, Jordan. In: Siliceous, pf the Tertiary and Mesozoic (Eds Jijima A, Abed AM, Garrison R), VSP, Zeist, Netherlands, pp. 205-324.

Abed A, Amireh BS (1999) Sedimentology, geochemistry, economic potential and palaeogeography of an upper Cretaceous phosphorite belt in the southeastern desert of Jordan. Cretaceous Research 20: 199-133.

Abed A, El Hiyari M (1986) Depositional environment and palaeogeography of the Cretaceous Gypsum Horizon in West-Central Jordan. Sed. Geol. 47: 109-123.

Abed AM, Schneider W (1982) The Cenomanian Nodular Limestone Member of Jordan, from subtidal to supratidal environment N. JB. Geol. Palaeontol Monatsh 9: 513-522.

Amireh BS (1997) Sedimentology and palaeogeography of the regressive-transgressive Kurnub Group (Early Cretaceous) of Jordan. Sed. Geol. 112: 69-88.

Barjous MO (1986) The Geology of Siwaqa, Map Sheet No. 3252 IV. Geological Mapping Project Bull. 4. Natural Resources Authority of Jordan, Amman.

Basha SH (1978) Foraminifera from the Ajlun Group of east Jordan. Jour. Geol. Soc. Iraq 11: 67-91.

Bender F (1974) Geology of Jordan. Borntraeger, Berlin, pp 196.

Bowen R, Jux U (1987) Afro-Arabian Geology. Chapman and Hall, London.

Dilley FC (1985) Cretaceous correlations in the Hamza Wells No. 1 to 5. Palaeontology Report No. 6. Natural Resources Authority of Jordan, Amman.

Dunham RJ (1962) Classification of carbonate rocks according to depositional texture. In: Classification of Carbonate Rocks. A Symposium (Ed. Ham WE), AAPG Mem. 1: 108-121.

Flugel E (2004) Microfacies Analysis of Limestone. Springer Verlag, Berlin, pp 1-975.

Haq BU, Qahtani AM (2005) Phanerozoic cycles of sea-level changes on the Arabian Platform. GeoArabia, 10: 27-160.

Holmes MJ, Harland WB, Suleiman AL (1989) The geology and seismic interpretation for Wadi Sirhan Area ‘A’. Natural Resources Authority of Jordan, Amman.

Krenkel E (1924) Der Syriasche Bogen. Zentralbulletin fur Mineralogie Geologies and Palaontologies, 9: 274-281; 10: 301-313.

Masri M (1963) The geology of the Amman-Zerqa Area. The Central Water Authority of Jordan, Amman.

MacDonald, SM, Partners (1965a) East Bank Water Resources. The Central Water Authority of Jordan, Amman, volume 6.

MacDonald SM, Partners (1965b) Bank Water Resources. Hydrogeological Survey of the Madaba-Maan area. The Central Water Authority of Jordan, Amman, volume 3.

Parker DH (1969) The hydrogeology of the Mesozoic-Cainozoic aquifers of the Western Pighlands and Plateau of East Jordan. UNDP/FAO 212.

Pettijohn EJ, Potter PE, Siever R (1973) Sand and sandstone. Springer, Berlin.

Powell J (1989) Stratigraphy and sedimentation of the Phanerozoic rocks in central and south Jordan, part B: Kurnub, Ajlun and Belqa Groups. Bulliten, vol. 11. Geology Directorate, Natural Resources Authority of Jordan, Amman, pp 130.

Qteishat A (1987) Wadi Sirhan Basin evaluation. Natural Resources Authority of Jordan, Amman.

Quennell AM (1951) The Geology and Mineral Resources of (former) Transjordan. Colonial Geology and Mineral Resources 2: 85-115.

Rabadi NR (1986) Final geological report on Wadi Sirhan-2 (WS-2). Natural Resources Authority of Jordan, Amman.

Rohl U, Dumont T, Von Rad, U, Martini R, Zaninete L (1991) Upper Triassic Tethyan carbonates off Northwest Australia (Wombat Plateau, ODP Leg 122). Facies 25: 211-252.

Selley RC (1988) Applied Sedimentology. Academic Press.

Southgate PN (1986) Cambrian phoscrete profiles, coated grains and microbial processes in phosphogenesis, Georgina Basin, Australia. J. Sed. Petrol. 56: 429-441.

Wetzel R, Morton DM (1959) Contribution a la geologie de la Transjordanie. Notes et Memoirs sur le Moyen Orient 7: 95-191.

Wilson JL (1975) Carbonate Facies in Geologic History, Springer, Berlin, pp 471.

Wolfart R (1959) Geology and hydrogeology of the Irbid District (Hshemite Kingdom of Jordan). Bundesanstalt fur Bodenforschung. Hannover.