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Lithostratigraphy of the Belqa Group (Late Cretaceous) in northern Jordan

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With 5 text-figures

Contents

Abstract

During deposition of the Wadi Sir Formation the shelf sea covering northern Jordan was fairly uniform and warm. Limestones and marls deposited, and when sea level dropped somewhat, land and lagoons, rudist banks and oyster flats formed. With begin of deposition of Um Ghudran- Ain Ghazal Formation at Coniacian time, colder and more nutrient-rich water resulted in the deposition of sediment composed mainly of planktic organisms. Oyster-rich beds at the basal Amman Formation indicate return of very shallow and coastal conditions during early Campanian time. Even more nutrient upwelling water of the Tethys Ocean resulted in a deposition of predominantly carbonate sediment rich with organic material. During early diagenesis phosphatic grains formed in it from fecal pellets and burried layers were transformed into chert. Rather variable thickness and lithological consistence within the represented sections reflect some structural unrest on the north Jordanian shelf during the time of deposition. When the sea regressed somewhat toward the top of the Amman Formation, and tidal flats were common, this resulted in much erosion and also formation of the characteristic phosphate rich sand beds of the Ruseifa Formation. During late Campanian time open marine conditions established again locally, before Muwaqqar Formation began to form predominantly at Maastrichtian time. Water chemistry changed again, so that within the sediment phosphatic grains no longer formed and biogene silica was more rare. Quite in contrast to the conditions at Coniacian time, the shelf area at Santonian and increasingly so at Campanian and Maastrichtian time developed a lot of topographical relief connected to structural unrest, which is clearly reflected in the here presented sections.

Zusammenfassung

Während der Ablagerung der Wadi Sir Formation bedeckte eine relativ einheitliche, flache Schelfsee das nördliche Jordanien, in der sich bei niedrigem Wasserstand Inseln und Lagunen, Rudistenbänke und Austernsiedlungen bildeten, ansonsten benthische Organismen die vornehmlichen Sedimentbildner

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darstellten. Wie die unterschiedlichen Mächtigkeiten und lithologischen Differenzen in den dargestellten Profilen belegen, sank mit Beginn der Um Ghudran- Ain Ghazal Formation im Coniac die Wassertemperatur, und es erhöhte sich der Nährstoffgehalt, so daß vornehmlich pelagische Organismenreste das Sediment bildeten. Mit Beginn der Amman Formation belegen Austerbänke wieder Flachwasserbedingungen und darauf folgend ein Überflutung noch Nährstoff-reicheren Aufstiegs-Wassers der Tethys. In der Folge entstanden vornehmlich kalkige, schlammige Sedimente mit hohem Anteil an organischen Stoffen, in denen frühdiagenetisch Phosphatisierung sowie Silifizierung stattfand. Zugleich bewirkte strukturelle Unruhe während des Campans eine stärkere Untergliederung des Meersbodens, als noch im Turon zu verzeichnen war. Eine Meeresverflachung führte zu Abtragung, Ablagerung im Gezeitenbereich und der Anreicherung von ausgewaschenem Phosphat in Sandbänken. Die dadurch sich bildenden Sedimente der Ruseifa Formation belegen eine anschließende, erneute weiterreichende Überflutung, ehe sich der Wasserchemismus erneut änderte. Mit Beginn der Muwaqqar Formation im Maastricht endete die frühdiagenetische Phosphatisierung, biogene Kieselsäure ist weniger vorhanden, und das Relief im Schelfbereich Jordaniens verstärkte sich noch.

I. Introduction

Depositional environment on the southern shelf formed by the African Continent and the Tethys Ocean changed during Coniacian time. At the Cenomanian and Turonian Jordan was largely covered by a shallow, warm sea. In it carbonate shells of benthic organisms contributed to a large extent to the sediment that was layed down. The coast of the sea lay far in the SE of the country and terrestrial particles with exception of some clay contributed very little to the sediments found in northern Jordan. Periodically the sea withdrew from much or part of the area during periods of low water level in the Tethys Ocean (Bandel & Geys, 1985). Such withdrawals have left indurated, dolomitized beds, intraformational conglomerates, and, rarely, clay beds and gypsum deposits, more commonly found in the south of Jordan. The margin of this shallow shelf sea to the more open ocean was characterized by a fauna containing rudistid bivalves and associated actaeonellid and nerineid gastropods (Mustafa & Bandel, 1992, Bandel & Mustafa, 1994), while the more restricted shelf had oysters (Aqrabawi, 1993) as characteristic representative of the most common macrofossils.

During Cenomanian and Turonian time the beds of the Ajlun Group (Naur-, Fuheis-, Hummar-, Shueib-, and Wadi Es Sir Formations according to the unpublished account of Masri (1963) adapted by Powell (1988) or Rumeimin, Salihi, Naur, Fuheis, Hummar, Shueib and Wadi Sir Formations according to Bandel & Geys (1985) were deposited. These sediments of a carbonate ramp environment have been set into relation with those of other areas in this region of the Tethys Ocean by Bachmann et al. (1996).

The Wadi Sir Formation composed largely of Turonian limestones are exposed from base to top in their type locality at Wadi Es Sir west of Amman. It is equivalent to the A7 unit of MacDonald, (1965), to the Judea limestone of (Wetzel & Morton, 1959) and to the Massive Limestone Unit of Bender (1968, 1974). Later the name was adopted by several authors (Parker, 1970; Abed 1982; Abed & El-Hiyari, 1985; Mustafa & Bandel, 1992). A Turonian age has been assigned to the Wadi Sir Formation on the presence of foraminifera (Basha, 1978). Ammonites and echinoderms confirmed that age determination (Bandel & Geys, 1985, Wiedmann pers. comm.) for most of the Formation, but also the transition into the Coniacian in the upper portion of it.

In Coniacian time the type of sedimentation switched from predominently benthic to predominantly pelagic with the deposition of the sediments of the Belqa Group (formations: Umm Ghudran = Ain Ghazal, Amman, Al Hasa Phosphorit = Ruseifa, and Muwaqqar) throughout Jordan. The bulk of the lithology of the Belqa Group of Quennell & Burdon (1959) consist mainly of chalk, limestones, chert, phosphorite and marl. Only close to shore environments in the SE of Jordan dolomite and sandstone are also present. The deposition of sediments dominated by pelagic organisms ranges in age from the Late Conician to Late Eocene. Deposits of the Belqa Group crop out in north and central Jordan, and along the eastern margins of the Jordan Rift. Its sediments cover much of the Jordanean plateau, extending from the Yarmouk River, in the north, to Ras En Naqab-Batn El Ghul escarpment in the south.

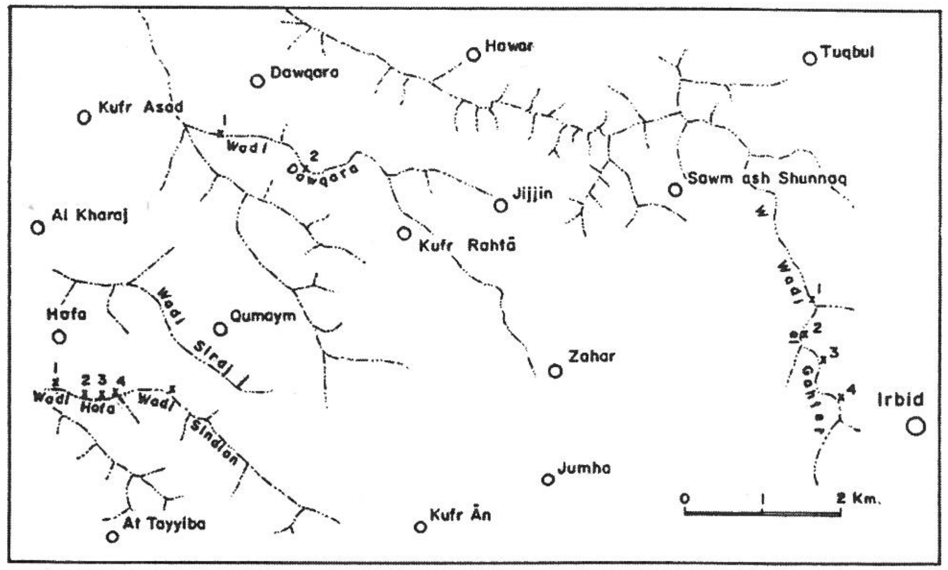

Fig. 1: Location map of the sections in figs. 2-5 from northern Jordan.

The type section is found in Wadi Umm Ghudran that lies 12 km WSW of Irbid. Ain Ghazal lies just to the southeast of central Amman within the city proper. The base of the Um Ghudran- Ain Ghazal Formations is in both cases well defined by the last hard, massive limestone bed of the Wadi Sir Formation. The top of the formation is recognized with the appearance of a thick chert bed of the base of the Amman Formation near Irbid and in case of the sections within Amman also by a more or less silicified bed of oyster coquina. The Umm Ghudran Formation was considerd to be Santonian in age (Wetzel & Morton, 1959; Quennell & Burdon, 1959; Parker, 1970; Bender, 1968, 1974) with the base in part of Coniacian age (Bandel & Geys, 1985).

Very similar sediments to those of the Jordanian Belqa Group have been described from Israel (Mount Scopus Group of Flexer, 1968). The Ain Ghazal- Umm Ghudran is comparable to the Menuha Formation as it occurs in the Negev. Here Lewy (1975), Reiss et al. (1985), Lewy & Honig (1985), and Lifshitz et al. (1985) recognized that the basal chalk of the Menuha Formation is of Late Coniacian age, while the middle part of that formation is Santonian in age. These biostratigraphic determinations are based on cephalopods, foraminifera, ostracods, and calcareous nannoplankton. The chalky Menuha Formation is succeeded by the chert and phosphat bearing Mishash Formation and the marly Ghareb Formation (Arkin & Hamoui, 1967; Kolodny et al, 1965; Kolodny, 1967,1980; Flexer, 1968; Bartov et al., 1972; Flexer & Honigstein, 1984; Fink & Reches, 1983; Reiss et al., 1985; here for additional references). These occurrences in Jordan and Israel can be compared with those of the Sinai and Egypt (Bartov & Steinitz, 1977; Flexer, 1971; Flexer & Starinsky, 1970; Freund & Raab, 1969; Bandel & Kuss, 1986; Bandel et al., 1987; see here for more literature).

The name of Amman Formation is taken from the capital city of Jordan, where it forms most of the bedrock (Masri, 1963; Bandel & Mikbel, 1985). It is equivalent to the middle cherty-horizon of the Calcaires a Silex de Qatrane, (Wetzel & Morton, 1959). Kolodny (1969) transferred this term into Quatrane Formation. In other context it is the middle cherty part of the Amman Formation as defined by Masri (1963), the lower part of the B2 Silicified Limestone by MacDonald (1965), the lower part of the Amman Formation (north Jordan) of Parker (1970). Bender (1968, 1974) had preferred the term Silicified Limestone Formation. Powell (1988) used the term Amman Silicified Limestone Formation, a name that was also utilized by Abu-Jaber et al. (1997) in their discussion on the formation of the silica beds. Bandel & Mikbel (1985) redefined these beds in the Amman area as Amman and Ruseifa Formations, elaborating an illustration presented by Bandel & Geys (1985), that represented the first published account of the term Amman Formation. The Amman Formation was determined to belong to the Campanian with ammonites (Nazzal & Mustafa, 1993) and thus agrees in age with the Mishash Formation (Reiss, 1955, 1988; Reiss et al., 1985; Parnes, 1956; Soudry et al., 1985; Moshkovitz et al., 1983; Gvirtzman et al., 1989; Lewy, 1990; see here for more literature).

The name of Ruseifa Formation was derived from Ruseifa near Amman. Ruseifa represented the main phosphate mining areas in Jordan, which has since shifted southwards. It is equivalent to the Phosphorite Member of Bender (1974), the upper part of Calcaires a Silex de Qatrane (Wetzel & Morton, 1959), the upper part of the Amman Formation (Masri, 1963), the upper part of the B2 Silicified Limestone Phosphorite Formation (MacDonald, 1965), and the upper part of the Amman Formation (Parker, 1970) in north Jordan. In the Negev it is equivalent to the phosphorite series member of the Mishash Formation (Soudry et al, 1985) and thus the upper, more phosphatic portion of the Mishash Formation. A distinction of lower chert rich deposits and overlying phosphatic deposits in Jordan had already been carried out by Krutsch (1911). Within the formation, there is the transition from the Campanian to the Maastrichtian (Bandel & Mikbel, 1985; Nazzal & Mustafa, 1993) with the possiblity that there was an interval of non deposition of some kind as interpreted to form the base of the Ghareb Formation (Reiss et al., 1985).

A more regional comparison is well possible, as for example with Egypt (Luger & Schrank, 1987). In the Western Desert of Egypt Garrison et al (1979) analysed phosphorite sand of Abu Tartur and noted that phosphatic grains had been winnowed from muddy substrates and concentrated into offshore tidal bars during an interval of sea level lowering. Bandel et al (1987) studied the Campanian phosphate shale cycle in Wadi Qena in the Eastern Desert of Egypt. In the Gebel Abu Had section of southern Wadi Qena synsedimentary structural unrest was evident. Here winnowed shale of the Quseir Member resulted in the deposition of sands of the Duwi Member, both Abu Had Formation. It is a shale-rich Campanian deposit that overlies the sediments of the Cenomanian Turonian cycle with a large hiatus and underlie chalk deposits. Sediments of the cycle of the Abu Had Formation in eastern Egypt formed in a shallow sea and close to its shore. The sea teamed with life and

was enriched with dissolved phosphate that resulted after their deposition on the sea floor due to biological activity in the early diagenetic formation of phosphorite pellets. These may have become enriched in phosphorite sands when the sediment was reworked and fine particles winnowed.

Models for the formation of bituminous, chert-bearing and phosphatic sediments as present in the Mishash Formation west of the Wadi Araba and equivalent to the Amman and Ruseifa Formations east of the Jordan Rift have been presented for example by Reiss, (1962), Bartov et al. (1972), Bartov & Steinitz (1977), Kolodny (1965, 1969, 1980), Birch (1980), Flexer (1968, 1971), Flexer & Starinsky (1970), Soudry & Champetier (1983), and in Jordan by Bandel & Mikbel (1985), Abu Jaber et al. (1997). The overall interpretation is that of a shallow shelf sea on which cold upwelling water from the deep Tethys Ocean influenced the type of sediments formed. These during Umm Ghudran - Menuha time were mainly chalky with some concentrations of silica in rare flint beds. During Amman - lower Mishash time phosphatic material in connection to a more organic rich calcareous muddy deposit resulted in the formation of phosphatic particles during early diagenesis (Kolodny, 1969, 1980; Bandel & Mikbel, 1985). Silicious sceletal elements of diatoms, silicoflagellates, radiolaria and sponges (Kolodny et al., 1965; Soudry et al., 1981; Moshkovitz et al., 1983; Haas et al. 1985) were common and mostly dissolved during early diagenesis and redeposited in chert beds. This process occurred early in diagenesis but after phosphatization had changed soft pellets into hard grains, as was analysed by Bandel & Mikbel (1985) in the area of Ruseifa. Some of the very delicate fossils of the Amman Formation have been especially well preserved during this process, as for example embryonic shell of ammonites (Bandel 1982, 1986) or the larval shells of gastropods (Bandel 1993, 1998).

During deposition of Amman Formation, there was some structural unrest that influenced sedimentation that produced thicker beds in depressions and thinner beds on high places. With begin of Ruseifa Formation this unrest increased to a degree that there was erosion and redeposition, especially connected to the depositional environment of phosphate bearing units. Bandel & Mikbel (1985) demonstrated that for the Ruseifa phosphate beds are the products of erosion of beds of the Amman Formation just a few kilometers to the south. Kolodny (1980) established by analysing the carbon isotopes that hypersaline evaporitic to fresh water may have influenced diagenesis of the chalks and cherts at that time. This idea became also adaptable to Jordanian diagenetic reconstruction since Bandel & Mikbel (1985) found clear indications for intertidal mud flat conditions during some portions of the depositional environment in the late Amman Formation and the Ruseifa Formation. Soudry & Champetier (1983) found microbial processes to be involved in formation of the phosphorits within tidal flats or extremely shallow water.

Faults running roughly from the NE to SW are connected to the phosphate beds also in other areas than that of Ruseifa. In the Al Hasa area Beerbaum (1977) noted the cooccurrence of horst and graben structures and phosphate enrichment. Shiloni (1981) correlated uplift and erosion of Mishash Formation with the redeposition and enrichment of phosphorite found in Beer Sheva valley. Movements during and after deposition of Mishash Formation were also described by Flexer et al. (1970) and Gilat & Honigstein (1981).

The Muwaqqar Formation crops out east of the Desert Highway, and in north Jordan. The name of the formation was taken from the town of Muwaqqar, 22 km SE of Amman, and was first introduced by Masri (1963). It is equivalent to the Marnes Grayenses de Ghareb together with the Marnes de Taqiye of Wetzel & Morton (1959), B3 Chalk and Marl Formation (MacDonald et al., 1965), Chalk-Marl Unit (Bender, 1968, 1974), and the Muwaqqar

Formation (PARKER, 1970). West of the Rift, it is equivalent to both the Ghareb and Taquiye Formations (SHAW, 1947; FLEXER, 1968; BARTOV et al., 1972). The base of the Muwaqqar Formation is sharp and is marked by the junction of tan, pink or yellow marl overlying heterogeneous lithologies (chert, limestone, phosphorite) of the Ruseifa Formation. With begin of Muwaqqar Formation phosphatization as well as chert bed formation ceased in northern Jordan. In the area of Azraq Cretaceous portions of Muwaqqar Formation are absent, similarly as described for the Abu Gosh area near Jerusalem by LEWY et al. (1994). Thus the Arabian shelf sea at Maastrichtian time in Jordan and Palestine/Israel consisted of rather deep and subsiding basins in which more or less bituminous marls and chalks were deposited in a more or less restricted but fully marine environment existing close to structural highs with low or no deposition at all.

The top of Muwaqqar Formation is defined at the base of a prominent bed of hard chalky limestone with limonitic pebbles (POWELL, 1988). The formation was found to be of Maastrichtian age by BENDER (1968), with the transition from Cretaceous to Tertiary within its deposits. Apparently the Cretaceous (Maastrichtian)-Tertiary (Paleocene) boundary is not marked by any abrupt lithological change in the wadis to the north of Irbid. In some areas (El-Lajun) the Muwaqqar Formation is very rich in bitumen (BENDER, 1968).

II. Description of the measured sections

II.1. Wadi Sir Formation

The Wadi Sir Formation is well exposed forming step-like, steep cliffs along the Rift escarpment from north to south Jordan. It represents a prominent mapping unit above the more marly Shueib Formation. It represents the topmost formation of the Ajlun Group and is unconformably overlain by the white chalk of the basal Belqa Group. The base of the formation is defined at the junction between the soft marls, mudstone or siltstone of the Shueib Formation and hard dolomicritic limestone or micritic limestone above.

The Wadi Sir Formation consist of well-bedded, hard massive fine to medium crystalline limestone, dolomitic limestone and dolomite. Sandy limestone and marls are locally present near the base, while thin layers and nodules of chert are common in the middle and upper parts. In north and central Jordan its top consists of hard, medium-bedded micrite, wackestones or packestone carbonates that form the base of the soft weathering chalk of the Umm Ghudran Formation. In north Jordan the formation is thickest in Irbid area (ca.296m), as indicated by subsurface data from Qumeim well (S18). At the Azraq area to the east in the Hamza 1-5 wells the formation measures 235-370 m and thins in the Amman-Madaba area and towards the south.

In the Wadi Es Sir section about 107 m of limestone characterize Wadi Sir Formation. It differs from underlying Shueib Formation by its more massive appearance and the onset of cliffs. Its upper limit is even more clearly reflected in a prominant ledge formed between the hard limestone on top of the Wadi Sir Formation and the soft marly chalk of the Ain Ghazal Formation (= Umm Ghudran Formation). The lower portion of the Wadi Sir Formation are well exposed to the west of Bakha while upper beds are also very well exposed in the quarries on the road from Ras El Ain in Amman towards the west and to Naur, but also in Wadi Es Sir. The whole sequence is exposed in the cliffs to the east of the road leading from Wadi Es Sir to Suweilih.

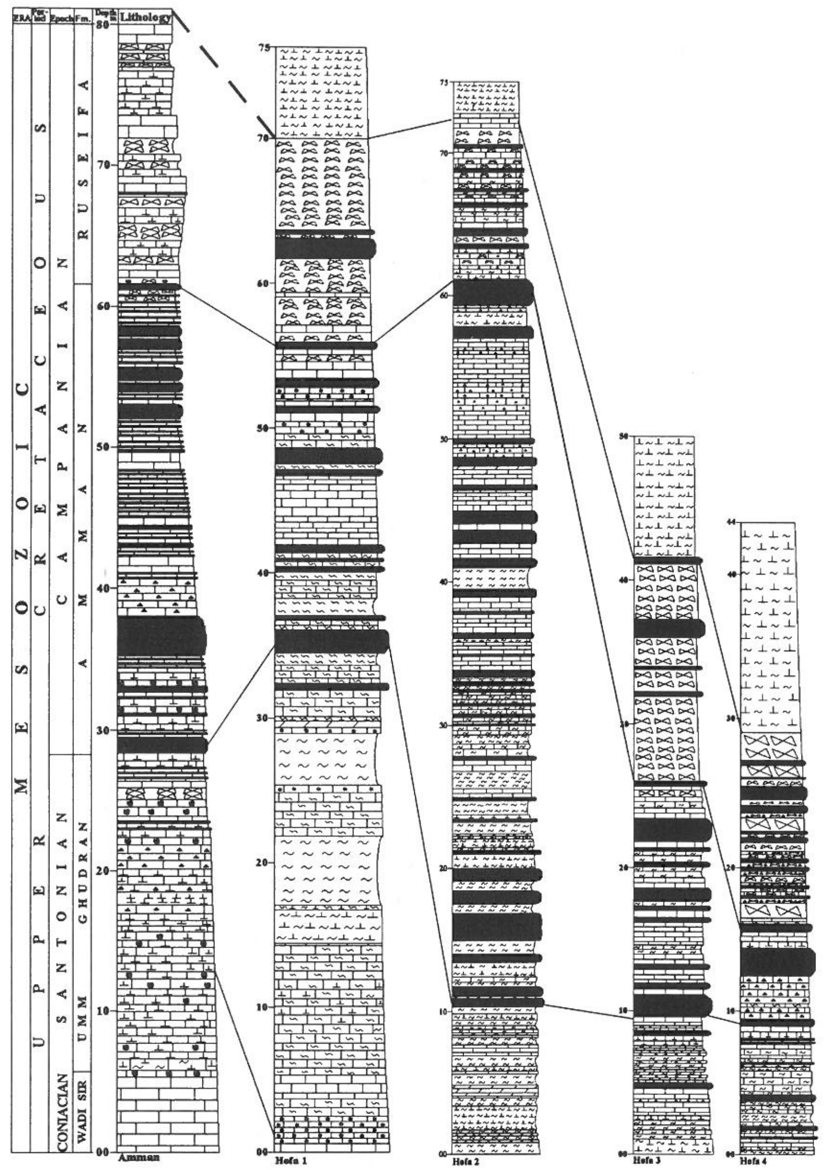

Fig. 2: Columnar sections of the Belqa Group in Amman and Wadi Hofa.

On the slope opposite the road toward Wadi Es Sir coming from Amman the Wadi Sir Formation is exposed in its full thickness (BANDEL & GEYS, 1985, fig.8). These authors recognized the members 34- 37 with the lower one consisting of a 30 m thick intercalation of nodular limestones and banked limestones. With exception of a few laminated beds in the upper central portion of this member all beds are bioturbated. A few bivalve shell beds are present commonly showing reversed grading. The following member 35 is 37 m thick and can be separated from the member below by beds of laminated limestone that contain 1-4 cm thick crusts and flat nodules of chert. Intercalated bioturbated nodular limestones with flint beds and laminated sandy limestones are intercalated with a few dolomitized bored hardgrounds that indicate terrestrial intervals of non-deposition and erosion. The top of the member 35 consists of nodular limestone with conglomeratic layers, intraclast beds and oolites and here some layers at Ras el- Ain contain a rich fauna of regular seaurchins (loc. 8; BANDEL & GEYS, 1985), probably of a near-beach environment.

The member 36 consists of 20 m of bioturbated limestones intercalated with marls, layers of chert concretions, oolites and laminated limestones especially well developed near Ras el-Ain in Amman. Bored hardgrounds, often associated with intraclast layers, are present thoughout indicating interuptions in deposition. Horizontal and vertical facies changes are common so that layers rich in fossils with signs of abundant benthic life change with others, showing no or little sign of the activity of endobenthos. The uppermost bed of the member contains a rich fauna and can be traced down-river Wadi Zarqa to Sukhna. Wherever exposed, this bed is rich in gryphaeid oysters and regular and irregular seaurchins (BANDEL & GEYS, 1985, loc. 9a and 9b, AQRABAWI, 1993). In the quarry at Ras el-Ain also ammonites were found. The next member is a 20 m thick massive limestone in which thick bivalve shells have commonly been bored by sponges. In the uppermost beds a rich fauna of gastropods, especially turritellids, and bivalves are represented in sometimes silicified shell beds. Here also some seaurchins are found (loc. 10a, BANDEL & GEYS, 1985).

Near Irbid the upper part of the Wadi Sir Formation is exposed in Wadi Gahfer (fig.3,1) and Wadi Hofa (fig.2,1) to the west consisting mainly of crystalline, hard massive limestone. In the uppermost part of the formation a rich fauna of gastropods, bivalves and rudist (hippuritid) bioclastic grainstone is present.

Environment of deposition

The Wadi Sir Formation was deposited on a wide, shallow marine carbonate platform. Rudist banks and associated lagoonal deposits are present in the north, indicating more open marine conditions, as they have also been noted in the Judean Hills to the west (LIVNAT, 1985). In the area of Amman oyster banks may be more common than such of rudists and even further to the south in the area of Wadi Mujib marls sometimes grade into gypsum bearing beds and algal micrites with monotypic ostracod and gastropod fauna indicating restricted conditions. In the Irbid area, the sequence is thicker than in the south and the basal portion is predominantly poorly fossiliferous micrite and dolomicrite, interpreated as quiet-water lagoonal sedimentation, overlying shallow-water molluscan packstone sediments. Rudist banks associated with floatstones and coarse grainstones and soil calcretes in the middle of the section indicate emergence of the platform in the area. The upper part of the unit consist of foraminiferal-, peloidal micrite and partialy molluscan wacke-packstone, indicating a return to shallow water and lagoonal conditions. Lithofacies, are similar at the base of the formation in the Amman area, indicating uniform conditions over the carbonate platform. MUSTAFA & BANDEL (1992) described from lagoonal limestones in Istefena just north of Ajlun some actaeonellids and nerineids. BANDEL & MUSTAFA (1994) determined the rudist limestone below these deposits to be of Cenomanian age, while the lagoonal limestones above these hold Turonian rudist. They also clearly demonstrate, that during deposition of the limestone units of the Wadi Sir Formation Jordan repeatedly was covered by extremely shallow sea with lagoons and even at times was dry land.

II.2. Umm Ghudran Formation (= Ain Ghazal Formation).

In the area of Amman the Ain Ghazal Formation according to BANDEL & MIKBEL (1985, figs.32, 33) consists of the members 38 to 39. 13 m of uniform unstratified marly chalk is

intensely churned by bioturbation resulting in a mottled appearance of the freshly exposed white rock. Bivalves, gastropods and ammonites may be found preserved as paper-thin brownish casts on bedding planes, sometimes in great abundance. Fish remains like scales and teeth are very common. In the uppermost portion of this member pygnodontid oysters (AQRABAWI, 1993) and worm tubes are preserved. Also uncompressed silicified gastropods may locally be encountered. 4 m of chalk contain some laminated beds with flat flint concretions and many fish remains. The member ends with a chalk bed rich in bivalves, especially a small gryphaeid oyster.

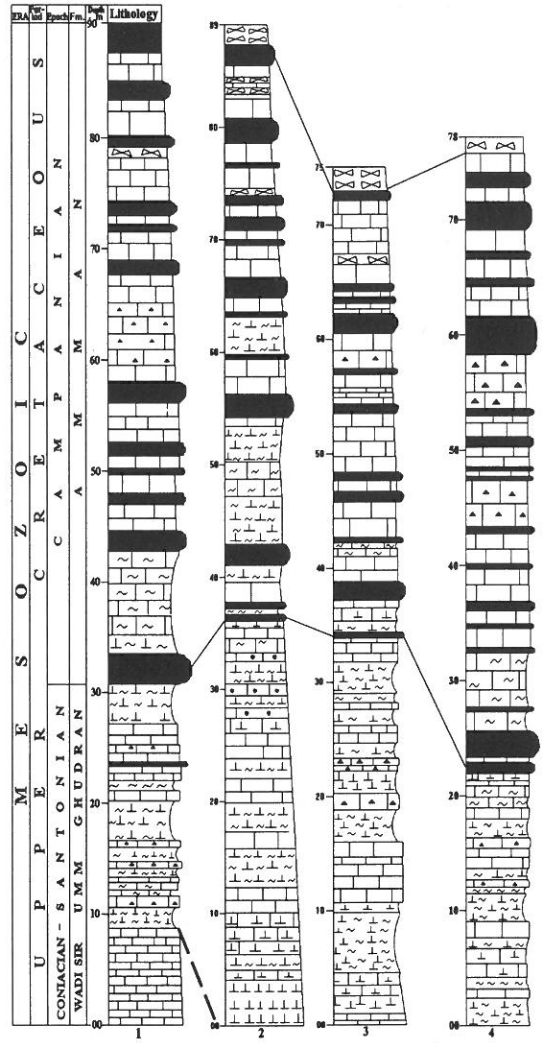

Fig. 3: Columnar sections of the Belqa Group in Wadi El Gahfer 1, 2, 3, 4.

In the Irbid area the Umm Ghudran Formation is 12-35 m thick. In Wadi Siraj (fig.4) it is about 10 m thick and consist predominantly of intercalations of white, fossiliferous, bioturbated marly chalk with thin layers of chert at the base. Above there is a 5 m thick uniform and fossilferous marly limestone and a final 2 m thick intercalation of hard, massive limestone with thin layers of chert. In Wadi Sindian the Umm Ghudran Formation is about 7 m thick and consist of white, fossiliferous, highly bioturbated marly chalk, and thin layers of fractured chert (fig.4).

In Wadi Dawqara (figs.5, 1) the formation is about 12 m thick. Its base consists of a layer of 1.5 m white, marly chalk, followed by 2 m of fossiliferous, highly bioturbated chalky marl, and 2 m of hard, massive finely crystalline limestone. Above this limestone there are about 4 m of intercalation of chalky marl and çhalky limestone present, succeeded by a 2.5 m thick, hard, massive limestone-bed. The uppermost part of the Umm Ghudran Formation consists here of about 0.8 m of chalky marl.

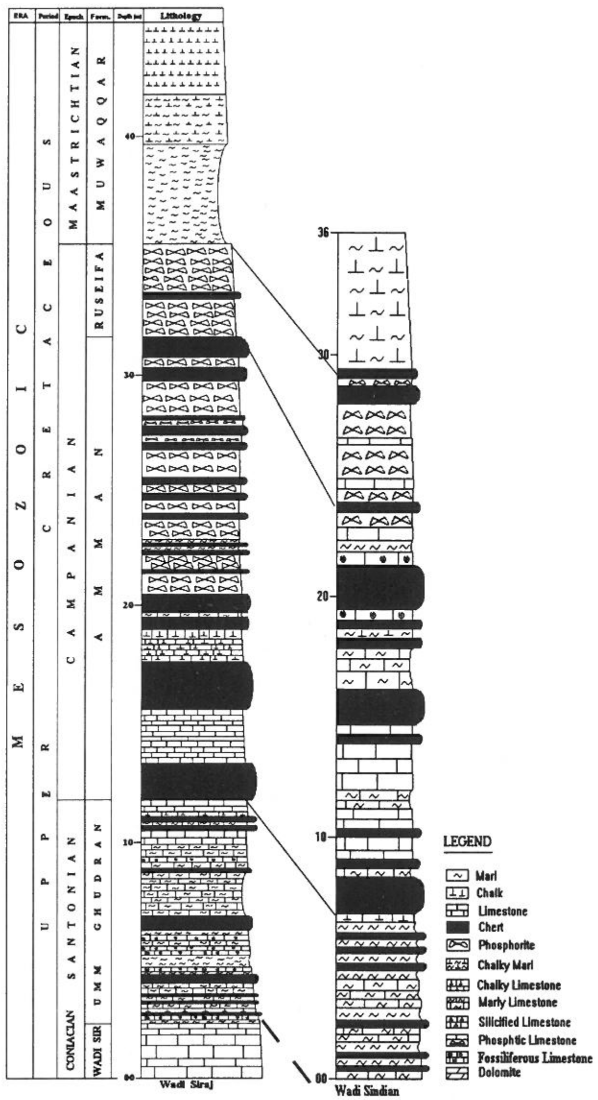

Fig. 4: Columnar sections of the Belqa Group in Wadi Siraj and Wadi Sindian.

In another section of Wadi Dawqara (figs.5, 2) the Umm Ghudran Formation consist of an intercalation of chalky marl, fossiliferous chalky limestone, and thin chert beds at the base.

In Wadi Ghafer (figs.3; 1, 2, 3, 4) the formation measures 22-37 m in thickness and consist predominantly of intercalations of white or pink, bioturbated marly chalk, fossiliferous, bioturbated, and highly fractured chalky limestone, and thin, hard, finely crystalline, and silicified limestone beds. The transition zone between the Umm Ghudran Formation and the Amman Formation consists of marly chalk or chalky marl.

In Wadi Hofa (fig. 2) the Umm Ghudran Formation varies in thickness between 8 and 35 m. Its base in section 1 consist of 1m thick, fossiliferous limestone, followed by 11 m uniform, white or pink, highly fractured, bioturbated, fossiliferous, marly limestone. Its upper part consist of an intercalation of marly chalk, and chalky, fossiliferous, bioturbated limestone. In sections 2, 3, and 4 the formation is about 8-10 m thick, and consist of intercalations of chalky marl, chalky limestone, silicifid limestone and thin layers of chert. Concretions of limestone and chert are present within the lower part of the Umm Ghudran Formation.

Environment of deposition of Umm Ghudran Formation

Following the local erosion of the carbonate platform of the Wadi Sir Formation, the Tethys Ocean transgressed again over the margin of the African Continent. In the Late Coniacian the margins of the Tethys Ocean had changed configuration form a broad carbonate platform with local highs to an extensive low gradient ramp (Flexer et al., 1986; Bachmann et al., 1996), over which the sea extended eastwards into Saudi Arabia and southwards to Egypt. The sediment type changed in response to a change in oceanic circulation. Water was colder and deposition dominated by pelagic organismic remains. Of these only the calcitic ones like coccoliths remained undissolved after diagenesis, while silicious as well as aragonitic shells were dissolved during this process. The pelagic sediments usually consisted of soft mud and provided a suitable environment for a rich benthic fauna, but quite a different one to that which had settled on the coquinas and sandy bottom of the sea at Wadi Sir time. The lithologic change from detrital carbonate sand of upper Wadi Sir Formation to carbonte muds of Ain Ghazal and Umm Ghudran Formation thus reflects a change in temperature and chemistry of the water that entered the shelf sea from the Tethys Ocean while depth probably was not much different to the times before in Turonian and Cenomanian periods.

II.3. Amman Formation (Lower Qatrana Formation)

Amman Formation occurs widespread in Jordan in its typical lithology. Only in the southeast of the country it wedges out and is replaced by continental varicolores sandstone (Bender, 1975). Amman Formation is of variable thickness in different locations of Jordan. In north Jordan it measures 15-59 m and in the Amman area 0-80 m in thickness. Amman Formation is distinguished by hard, massive chert beds which form a steep cliff above the pale weathering chalks of Umm Ghudran Formation in central and north Jordan. The top of Amman Formation is usually distinguished by the first appearance of thick phosphorite sand beds, and thus the begin of Ruseifa Formation.

Amman Formation can be traced from north to south Jordan due to its distinctive lithology. Here medium- to thick-bedded grey, brown or white chert, and grey microcrystalline limestone (both as beds and concretions) are intercalated with thin layers of chalky marl and chalk and medium-bedded, locally cross-stratified oyster-coquinal grainstones. Phosphate granules and peloides are sometimes common at the top of individual chert or limestone beds in the uppermost part of the formation.

In the Amman-Ruseifa area the top of the chalk unit of the Ain Ghazal Formation is indicated by the presence of massive chert beds and the occurrence of phosphatized particles in the sediment. Bandel & Mikbel (1985, figs.33-36) distinguished the members 40 to 43 in the area between Ruseifa and Wadi Es Sir, near Amman. The up to 3 m thick lowest member consists of an intercalation of laminated marly chalk and chert at the base and massive limestone with silicified oysters, many of which show that their valves are still connected. This member is well developed south of Ruseifa, while further to the east the characteristic oyster-rich massive limestone grades into banked limestone of which only the upper beds contain oysters while the lower beds hold other bivalves near Sukhna, while at Wadi Duleil no oyster bed is present. At Irjan esh Shariqiya near Palace Hotel (Sport City, Amman) member 40 cannot be differentiated from member 41, and at the Wadi Sir section east of the town of Wadi Es Sir only a thin oyster coquina may represent an equivalent to the oyster limestone in the type section defined by Bandel & Mikbel (1985) at Ain Ghazal.

The intercalation of marly chalk, chert and phosphorite sand is to about 19 m thick. The chert beds commonly show intraclast layers and bioturbation. Sometimes pholadid bivalves are still found within their burrow, and networks of crab burrows filled with phosphatic sand are common. The laminated chalky marls and limestone beds usually show many fish remains, sometimes with bones still connected. Limestone concretions, present in some of these beds, show that a rich benthic fauna was present, but disappeared due to solution during diagenesis in chalky beds.

At member 42,7 m of intercalated thin beds of chert and chalk are present. At the contact from chert to chalk a thin layer of phosphoritic sand is commonly present documenting that winnowing caused the intercalation. Chert represents the original mud, and chalk the redeposited fine sand and silt-sized redeposited fraction of the mud. This member can also be recognized in the sections east of Wadi Es Sir and south of Ruseifa. The fauna preserved in some beds is like that of member 41 and represents benthic molluscs of soft substrate. About 10 m of intercalated thick beds of chert, intraclast layers of chert, phosphorite sand, and chalky limestones with calcareous concretions follow in Wadi Qattar, east of the waste dumps of Amman and south of Ruseifa. This member is laterally very variable and has been eroded prior to the deposition of Ruseifa Formation. Crab-burrow systems are common, and baculitid ammonites as well as molluscs belonging to a soft-bottom fauna are preserved on top of many chert beds.

The Amman Formation near Irbid in Wadi Hofa (fig.2) is quite variable in thickness ranging from 7 to 50 m.

In Wadi Hofa 1 Amman Formation is about 20 m thick. Its base consists of 1.5 m thick bed of brown chert, followed by 4 m of intercalation of marl, marly limestone and thin layers of chert. The middle part is about 4 m thick and consist of finely crystalline, hard, massive silicified limestone. The upper part measures about 7 m and is made of grey and brown chert beds at the bottom, followed by thin layers of marly limestone, thin-medium layers of fossiliferous and phosphoritc limestones, with thin layers of chert on top.

In Wadi Hofa 2 Amman Formation measures about 50 m in thickness and consist of about 9 m of intercalation of medium-thick, bedded, grey and brown chert and thin-medium

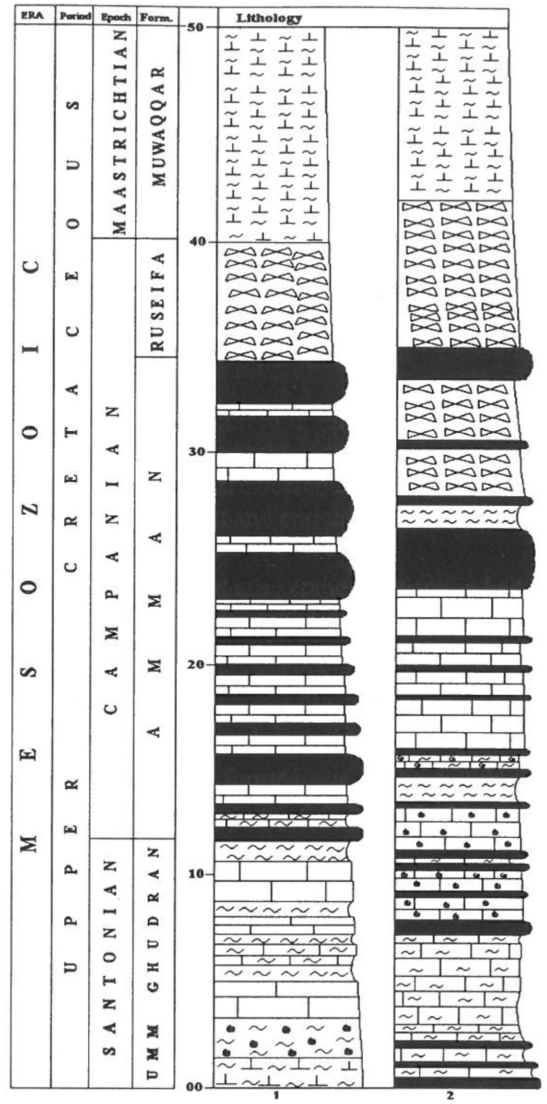

Fig. 5: Columnar sections of the Belqa Group in Wadi Dawqara 1 and 2.

layers of marl and chalky marl at the base, followed by about 21 m of intercalations of bedded chalky marl, marl, marly and chalky limestone, finely crystalline, hard and massive limestones. The following beds are about 8 m thick and consist mainly of bedded cherts and microcrystalline limestone. The upper part is about 12 m thick and consists of 8.5 m thick grey, microcrystalline, and occasionally fossiliferous or silicified limestone. It is succeeded by a 1 m thick chert bed and 1.5 m chalky marl. The top of the formation consist of a 1.5 m thick bed of chert.

In Wadi Hofa 3 (fig.2) the Amman Formation is about 14 m thick and consist predominantly of intercalated, bedded chert, massive hard limestone with microcrystalline structure and occasionaly marly limestones.

In Wadi Hofa 4 Amman Formation is about 7 m thick. The base is formed by about 1 m thick bed of finely crystalline limestone, followed by a medium bed of chert, and about 3.5 m of hard, massive, silicified limestone beds. The upper part is about 3 m thick and consists of a thick bed of chert at the base, followed by thin layers of chalky marl, fine crystalline limestones and chert.

In the Wadi Gahfer area (fig.3) the Amman Formation is 42 to 59 m thick. 59 m are present in Wadi Gahfer 1. Here the base consists of a 3 m thick, brown chert bed, followed by 10 m of uniform, grey and occasionally pinkish marly limestone and about 15 m of intercalation of brown or grey chert and finely crystalline, hard, massive limestone. The upper 25 m of the formation consist of an intercalation of medium-thick beds of chert and microcrystalline, hard, massive, locally fossiliferous, and phosphatic limestone.

In Wadi Gahfer 2 Amman Formation is about 51m thick. It consist of intercalations of thin beds of chert and marl, followed by an about 2 m thick bed of hard, massive, microcrystalline limestone and 1 m of chalky marl. A thick bed of brown chert rest above these. The middle part is about 20 m thick, and consist predominantly of chalky marl and marly limestone, followed by thick beds of chert, microcrystalline, hard, massive limestone, and chalky marl. The top of the formation is formed by 23 m of intercalated, medium-thick chert beds and microcrystalline, hard, massive, locally fossiliferous, and phosphatic limestones. The amount of phosphate increased towards the top of the formation. In Wadi Gahfer 3 the Amman Formation measures about 42 m and in Wadi Gahfer 4 it is about 53 m thick. The lithology in both sections is similar to that of Wadi Gahfer 1.

In Wadi Siraj (fig.4) Amman Formation is about 23 m thick. It is predominantly composed of about 2-3 m thick beds of brown or grey chert with microcrystalline, hard, massive limestone at their base. Above follow about 2 m of grey, chalky limestone and about 2 m of chert. 13 m thick of intercalations of thin, medium and thick beds of granules phosphate (fish and reptile skeletal fragments) and chert follows concluding the formation whith a thick bed..

In Wadi Sindian (fig.4) Amman Formation is about 14 m thick and consist mainly of intercalation of medium-thick layers of grey or brown chert, microcrystalline, and occasionally fossiliferous and bioturbated limestone and marly limestone.

In Wadi Dawqara 1 (fig.5) the Amman Formation is about 23 m thick. The lower part measures 12 m and is composed of medium beds of brown or grey chert and microcrystalline, hard, massive limestone. The upper part is about 11m thick and consist mainly of thick beds of chert and medium beds of microcrystalline, hard, massive limestone. In Wadi Dawqara 2 the sequence is about 17 m thick and consist of intercalations of thin-medium beds of chert, fossiliferous, hard, compact limestone, marly limestone and marl at the base, followed by about 8 m of microcrystalline, hard, massive limestone with thin layers of chert, especially in the middle part. The top of the formation is made of a 2.5 m thick bed of chert.

Environment of deposition

During deposition of Amman Formation in Campanian times, the shore lay in the far south of Jordan. Near the top of Umm Ghudran- Ain Ghazal Formation first layers with phosphatic fecal pellets are found representing the onset of a phosphorite diagenesis that characterizes the following Amman and Ruseifa Formation ceasing only with the onset of Muwaqqar Formation. Water of the shallow open sea was rich in dissolved mineral carbonate, phosphate and silica. This water came from the Tethys Ocean and probably was recharged in mineral content by upwelling currents that came from the depth of that ocean. When

currents spread the nutrient rich, cold water over the shallow, broad shelf of the northern Gondwana Continent water rapidly warmed up, and a rich fauna and flora of planktic and nectic organisms developed. Their skeletal hard parts as well as fecal pellets rained to the sea floor forming carbonate muds rich in organic matter. Productivity of this fertile water of the shelf was so high that organic deposits were not totally decomposed by rich benthic, soft bottom fauna comprising among others molluscs and crustaceans. While the former left their shells to be preserved in abundance in the sediment, the latter excavated their burrow systems now found in profusion within trace fossils and bioturbation of the rock. Fecal pellets and larger organic and phosphatic skeletal hardparts were transferred into solid phosphate particles after only shallow and short burial in the soft mud. This transition and early diagenesis occurred before sediment was indurated and before aragonitic shells became dissolved.

Phosphatisation of fecal pellets occurred in the soft mud due to interstitial solutions rich in phosphate ions and fixation of these to the organic matter and mucus. When periodical currents washed across the muddy bottom calcareous shells as well as phosphatized pellets and sceletal particles were winnowed out and enriched in sands, now intercalated with the fine-grained beds.

Silicification of some beds occurred after some compaction had occurred, but before the minute aragonitic shell remains had dissolved. Even minute and thin shells as those of planktic foraminifera, larval gastropods, minute bivalves and scaphopods, and just hatched ammonites remained unchanged (Bandel 1982, 1993, 1998, Bandel et al., 1982). Transformation of fine-grained beds into chert occurred when beds were covered by several meters of sediment. Muds were formed due to increased deposition of carbonate skeletal remains of planktonic organisms, while chert was formed due to the solution and redeposition of siliceous skeletal elements (sponge spicules, diatom and radiolarian sceletons) in the sediment.

Structural unrest had already left traces in the deposits of Amman Formation around Amman and to about the area of Qatrana in the south of it. Small scale fold-like synsedimentary structures with an amplitude of few meters to wave length of about 5-25 m do not continue into the underlying and overlying beds. Most diapiric folds and domes are found in the lower beds of Amman Formation that overlie the chalky Ain Ghazal- Umm Ghudran Formation directly. South of Qatrana, where Ain Ghazal Formation is not developed, synsedimentary folds are absent or rare. Water released during diagenesis of the marly chalks pushed up the well bedded mud-sand intercalations of the deposits of the Amman Formation into diapiric mounds. Also at later stages of deposition of Amman and Ruseifa Formation diapiric folds of smaller size formed. Probably fold formation is connected with faults that follow the margins of the Arabian-Nubian Continent and cross the rift lineament. Bandel & Mikbel (1985) noted that at places where sliding and synsedimentary folding occurred, and also where beds came to the surface of the sea bottom due to current erosion that had lain in several metres depth, no chertization was present. Thus silicification of beds in the Amman and Ruseifa Formation occurred deep within the sediment, but at shallower depth than aragonite dissolution and compaction flattening delicate shells.

II.4. Ruseifa Formation (Upper Qatrana Formation)

The Ruseifa Formation represents late Campanian to possibly early Maastrichtian deposits. It is distinguished from the Amman Formation at its base by the occurrence of first thick phosphate beds, and the Muwaqqar Formation above by the disappearance of phosphate beds and chert, as well as the appearance of massive marl and chalky marl instead. Ruseifa Formation consists of a heterogenous lithology of medium-thick beds of phosphorite, which are intercalated with thin-medium-bedded chert, marl, chalky marl, microcrystalline limestone and oyster-coquinal grainstones. The formation discussed herein is described from the Ruseifa-Wadi Es Sir area around Amman and area around Irbid.

In the area of Amman BANDEL & MIKBEL (1985, figs.36-37) distinguished members 44-45 of the sequence of the Upper Cretacous rock column belonging to the Ruseifa Formation. The basal member near Tel Es Sur to the south of Ruseifa consists of 9 m of intercalation of thick beds of phosphoritic sands intercalated with laminated chalky limestones. The sands represent off-shore dunes in which crabs excavated their burrow systems from above. Limestone pebbles in basal portions of the sands may hold a rich fauna of benthic soft-bottom molluscs as well as of cephalopods. The chalky limestones contain phosphoritic grains and numerous vertebrate bones and teeth. Concretions are common. Correlation to the about 20 m thick sequence at the type section of Ruseifa Formation in Ruseifa is possible. Here more muddy layers had been deposited and, thus, more chert beds are present. In the area south and west of Tel Es Sur sea bottom was raised above sea level so that a chain of islands formed. From these sediments of the Amman Formation were eroded and redeposited in shoal sands forming the now largely mined phosphate beds in the north.

About 7 m of limestone with phosphatic pellets and many fish remains compose this member at Wadi Es Sir. Its top is eroded. The central oolitic bed in Wadi Es Sir correlates to limestones separating the fourth phosphate bed of Ruseifa from the lower ones, and the large concretions above the fourth phosphate bed (in the lower member 45) is present in both sections. At the type section in Ruseifa the large concretions also characterize the same depositional level. This sand consists of oyster-shell debris and is connected to widespread growth of oyster reefs and banks nearby.

In the Irbid area the Ruseifa Formation is between 12 and 16 m thick. In in Wadi Hofa 1, about 15 km west of Irbid (fig.2), it consist mainly of thick beds of phosphatic sands, which are intercalated with thin layers of chalky limestones, rich in vertebrate teeths and bones in the lower part of the formation, followed by a thick bed of chert. The upper portion consist mainly of thick beds of phosphorite, which are intercalated with thin layers of chalky- and marly limestones. In Wadi Hofa 2, the Ruseifa Formation consist of intercalations of thin to medium bedded, phosphorite, cherts, and chalky-and marly limestones. The top of the formation is made of a finely crystalline, hard limestone bank.

In Wadi Hofa 3, Ruseifa Formation is mainly composed of thick beds of phosphatic sands, which are intercalated with thin layers of chert at the base and succeeded by a thick bed of chert. The upper part started with a thick bed of phosphorite, followed by a thin layer of chert.

In Wadi Hofa 4, Ruseifa Formation consists of intercalations of thin-medium bedded, phosphorite, cherts, and chalky limestones. In Wadi Gahfer (fig.3) the Ruseifa Formation is about 2-3 m thick or it is absent. It consists mainly of thick beds of poorly sorted, irregular phosphorite grains comprising fish and reptile fragments, phosphatized shells, and fecal pellets. In Wadi Siraj (fig.4) the Ruseifa Formation is about 4 m thick and consist mainly of phosphorite. A thin bed of chert is found in the middle part of the section.

In Wadi Sindian (fig.4) that formation is about 5 m thick and consist mainly of thick beds of phosphatic sands, which are intercalated with thin layers of chalky limestones, rich

in vertebrate teeth and bones in the lower part of the formation, followed by beds of chert at the top.

In Wadi Dawqara 1 and 2 (fig.5) the Ruseifa Formation is about 5-7 m thick, and consist mainly of thick beds of granular phosphorite with fish and reptile fragments, phosphatized shells, and fecal peloids.

Environment of Deposition

The Ruseifa Formation was deposited on a broad shelf in a sea that produced a sediment rich in organic matter derived mainly from nektic and planktic fauna and phytoplankton. The concentration of phosphate in this unit reflects the high organic productivity in waters derived from the depth of the Tethys Ocean, due to the upwelling of nutrient-rich water close to the shelf-break. Further concentration of phosphatic elements was by winnowing on the shelf (BANDEL & MIKBEL, 1985; POWELL, 1988). Here contemporaneous as well as earlier sediments containing phosphate particles that had formed to a large portion by early diagenesis in soft and fine grained marine muds were eroded. Such erosion of former sea bottom occurred in areas that fell dry due to structural unrest and regressive cycles. But coarser particles were also washed from the bottom muds during their erosion due to currents within the shallow sea.

Chalky laminites and microcrystalline limestone lacking bioclasts derived from benthic life also suggest quiet water conditions existing between phosphate sand dunes. But the presence of crab burrows in intercalated beds, and concentration of bivalves and gastropods in some beds indicate that periodic oxygenation of the basal water mass did occur. Mud cracked layers as well as intraclast beds indicate the environment of intertidal flats as well. Abundant ammonites at the top of the formation point to a return to full oceanic circulation prior to the higher sea-level stands (deeper-water pelagic marls) marked by the overlying Muwaqqar marly chalk.

II.5. Muwaqqar Formation

The Muwaqqar Formation consists of soft, thick-bedded chalky-marl, marl, and chalky limestone, with harder beds and nodules of microcrystalline limestone and chert. The lower part of the formation is yellow-pink-tan in colour followed by typically white-pale and grey colours. Adjacent to the Rift clayey grey-green, beds are common in the upper part of the formation and in areas of high bitumen content the rock is dark grey. The basal yellow-pink-tan marl overlie conformably the Ruseifa Formation with rapid disappearance of phosphat grains. But thin lenses of coarse, granular phosphate are occasionally present; ammonites are common at some localities. The succeeding grey-white chalky marls contain microcrystalline limestone concretions. Beds of chalky limestone are more common in the upper part of the formation, while the uppermost part is composed of thinly laminated, bituminous marl and chalky limestone.

The Muwaqqar Formation crops in in the studied area in Wadi Hofa, Wadi Dawqara, Wadi Sindian and Wadi Siraj. The extend of the formation has not been established. In Wadi Gahfer it is absent due to erosion. It consists mainly of intercalations of chalk, marl, chalky marl with thin layers of chalky-and microcrystalline limestone in the lower portion. Later it forms a uniform marly chalk that is dark when fresh and becomes of lighter colour when oxidized. The beds are intensively churned by bioturbation, with crab burrows usually well preserved (*Thalassioides* type) and sometimes *Chondrites* -like burrow systems common.

Environment of deposition

Large variations in thickness over short distances indicate differentiation into small locally subsiding basins and heights. The thickest successions are in the Jafr, Azraq and Hamza basins, and in the Yarmouk and Uneiza areas (Powell, 1988).

The presence of a high bitumen content in the Muwaqqar Formation in local fault-controlled basins such as El-Lajjun and the Yarmouk River area may be due to the formation of deeper-water basins with a stagnant anoxic basal water-mass, which preserved settling planktic and necktic organic matter. Such high bitumen marls are generally termed oilshale in Jordan, and are of commercial interest.

Following deposition of the Ruseifa Formation on a shallow water shelf during the Campanian, the sea-level rose and a transgression resulted in deeper water pelagic sedimentation over much the shelf during Muwaqqar time. Marine sedimentation spread over a large area, to southern Egypt and Saudi Arabia, but there were also areas not far away in Judea of today (Lewy et al., 1994) and east of the Azraq area that probably were above sea level during much or all of Muwaqqar time. Still it marked a major transgressive sea level rise during the late Cretaceous time. In subsiding, deeper-water basins, chert and microcrystalline limestone are rare or absent. Chalks and marls, containing abundant planktic and benthic foraminifera and calcareous nannoplankton, were deposited at these sites. Anoxic, reducing bottom conditions are indicated by the higher bitumen content in these areas. These basins were probably defined by normal faults and uplifted blocks may have produced bars that restricted basal water circulation. The bitumen is primary in origin, and accumulated at the base of a stratified watermass in anoxic basins perhaps characterised by intense algal activity.

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