The Cambrian sedimentary succession from the Wadi Zerqa Ma’in (northeastern Dead Sea area, Jordan): lithology and fossil content

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With 7 figures


Abstract: Results of a facies analysis (with a focus on carbonates) and a lithological revision of the sedimentary succession exposed at the classic Wadi Zerqa Ma’in locality on the northeastern shore of the Dead Sea are presented. Micropalaeontological investigations have been carried out here for the first time. Micro- and macrofossils are represented by echinoderms, hyoliths, brachiopods, trilobites, poriferans, calcimicrobes, and trace fossils. The hyolithellid Torellsia sp. is reported for the first time from this paleogeographic region. The common trilobite Kingscaspis campbelli (King, 1923) indicates a stratigraphically little younger position than the only other trilobite taxon known from the area, Palaedonura antiquus (Chernyshova, 1956). The outcrop represents a tidally influenced, marginal marine, regressive succession, deposited as the final act of a short-time transgression on the Arabian–Nubian Shield. Shallow-subtidal to intertidal, siliciclastic deposition has taken place probably under deltaic and/or estuary influence. Interbedded thin, open-marine, subtidal, and mostly high-energy carbonates point to some minor transgressive pulses during the generally regressive, but discontinuously deposited tendency.

Key words: Cambrian, Zerqa Ma’in, Burj Formation, Dead Sea.

1. Introduction

Cambrian deposits in the Jordan Rift Valley are widely exposed on the eastern side of the Dead Sea and of the middle and southern Wadi Araba (Jordanian side) and, locally, on the southwestern side of the graben (Israeli side), too. The first fossil finds in the SE Dead Sea area go back to 1884 and were made by E. HULL, but, were interpreted by him as Carboniferous (noted in BLANKENHORN 1910). Mainly based on some trilobite remains, a Cambrian age of the successions was firstly assumed by BLANKENHORN (1910) and later confirmed by DIENEMANN (1915), KING (1923), RICHTER & RICHTER (1941), and PICARD (1942). Later palaeontological work on trilobites, brachiopods, hyoliths, and trace fossils came from PARNE (1971), COOPER (1976), BANDEL (1986), SELACHER (1990), and RUSHTON & POWELL (1998).

Besides these palaeontological and stratigraphical investigations, petrographical, palaeogeographical, and facies aspects were highlighted by BENDER (1963, 1968, 1975), SELLEY (1972), SEGEV (1984), and SCHNEIDER et al. (1984). The most recent work on sedimentology, facies and depositional history came from AMIREH (1990), SHINAQ (1990), SHINAQ & BANDEL (1992), AMIREH et al. (1994), ELICKI & SHINAQ (2000), GEYER & LANDING (2000), and ELICKI et al. (2002).

All these investigations were mainly focused on the widespread exposures of the southern Dead Sea area.
because of the good outcrop and completeness of profiles. The only Cambrian surface outcrop north of this region, which is subject of this paper (Fig. 1), was discovered and sampled by Campbell at the beginning of the last century. At that time, the outcrop about 1 km north of the mouth of the Wadi Zerqa Ma’in was situated directly at the northeastern shore of the Dead Sea (sampling was done off a boat, 3 to 4 m above the water level). Today, the section is about 30 m above the water level and 80 m away from the shoreline, and directly next to the road, which runs from the northern edge of the Dead Sea up to the city of Aqaba on the Red Sea.

The Wadi Zerqa Ma’in outcrop represents the uppermost part of the Jordanian Cambrian succession and is in part highly fossiliferous. King (1923) has first investigated Campbell’s trilobite material ("Anomocare campbelli" – today Kingaspis campbelli) and mentioned the occurrence of "orthotheid hyoliths". Richter & Richter (1941) revised King’s taxonomic trilobite and hyolith determinations from the Wadi Zerqa Ma’in section to Pulaeolomes campbelli and Hyolithes kingi, and specified the biostratigraphic position as higher Lower Cambrian. There was no further investigation on that section until Bandel (1986), Shinaq (1990) and Shinaq & Bandel (1992), who have first published detailed lithological and facies descriptions of the lower parts of this succession. In the scope of the "Jordan National Geological Mapping Project" (Powell 1989), a first lithological description and environmental interpretation of the whole Wadi Zerqa Ma’in section is mentioned in a map sheet explanation by Shawabekeh (1998). In the same year, within the paper of Rushton & Powell (1998), a more detailed description and interpretation of the Wadi Zerqa Ma’in section was published. The stratigraphic determination of the Wadi Zerqa Ma’in section was

During own investigations on the Jordanian Cambrian within the last years, it was, however, not possible to fit all the beds observable in the “classical” Wadi Zerqa Ma’in outcrop into the published columns. So, the section was re-measured and extensively sampled with the main focus on palaeontology and carbonate facies. For the first time, micropalaeontological research on these carbonates was undertaken to help in interpretation of facies development and depositional conditions. That research led to the insight that hitherto published measurements and lithological descriptions differ significantly. So, based on new field and petrographic investigation, the aim of this paper is to redescribe that very important Cambrian section and to publish lithological and micropalaeontological data, and consequential interpretations.

Thin-sections and palaeontological specimens figured in this paper are housed at the Geological Institute of Freiberg University (archive number FG 595).

2. Geological setting

Tectonostratigraphically, the region discussed in this paper belongs to the Arabian–Nubian Shield, which was consolidated during the Neoproterozoic (Cryogenian to Ediacaran) by an unknown number of terranes (Best et al. 1993). Near the end of the Proterozoic, an aborted triple junction developed east of the Sinai Peninsula, and one of its failed arms is represented by the Jordan Rift Valley. The Cambrian succession exposed in the southern Jordan Rift Valley (southern Wadi Araba near the Red Sea) rests nonconformably on the Precambrian magmatic and metamorphic basement (Aqaba Complex) of this craton (Fig. 2). Further north (middle of Wadi Araba), below the Lower Cambrian unconformity, Proterozoic sedimentary rocks of the Araba Complex (volcanoclastics, conglomerates) occur. The range of the stratigraphic gap between the youngest Proterozoic rocks and the oldest Cambrian rocks is hard to estimate because of problematic regional correlation with radiometric dated Proterozoic rocks and of lacking fossils in the oldest Cambrian strata (Bender 1968; Jarrar et al. 1991; Bandel & Shinaq 2003).

The thickness of the Cambrian succession increases from the south (on-lapping the Aqaba Complex base-
Fig. 3. Lithological columns according to the present work (1) and to hitherto publications (2-6). The columns are simplified for illustrating the position of carbonate intervals and the thickness of siliciclastic and carbonate portions. A correlation level is given by the top of the second carbonate unit which is clearly defined by all authors (except [6]). Note the discrepancies in the lower portion of the published columns and the lack of the third carbonate unit in the older documentation.

Cambrian Salib Formation (thickness up to more than 200 m), commonly interpreted as fluvial and alluvial plain deposits (possibly marginal marine influenced, SELLÉY 1972; POWELL 1989; AMIREH et al. 1994; MAKHLOUF 2003).

The transition to the overlying Burj Formation (Lower to Middle Cambrian) is sharp. This formation is characterized by marine carbonates and siliciclastics (thickness at the Dead Sea: 120 m [Safi area] to about 190 m [Zerqa Ma'in], POWELL 1989), and is commonly subdivided into three members (Fig. 2). The lowest is the transgressive Tayan Member, which consists of alternating probably intertidal to shallow subtidal silt- and sandstones with some marine trace fossils. This is followed by the fully marine, fossiliferous, shallow water carbonates and minor siliciclastics of the Numayri Member. The youngest unit of the Burj Formation is the regressive, marginal-marine Hannéh Member. The latter is similar to, but, coarser-grained than the underlaying Tayan Member below, and consists of siltstones and sandstones with marine trace fossils.

The youngest Cambrian is represented by fluvial sandstones, locally with some tidal influence, of the probably upper Middle to Upper Cambrian Umm Ishrin Formation and indicates the predominance of continental conditions (e.g., MAKHLOUF & ABED 1991; GEYER & LANDING 2000).

In summary, the Cambrian succession of the Jordan Rift Valley unconformably overlies the Precambrian basement of the northern Arabian–Nubian Shield, and is interpreted today as a progression from a con-
3. Lithological succession

The lithological succession of the Burj Formation at Wadi Zerqa Ma'in was published several times (Fig. 3). **Bandel** (1986), **Shinaq** (1990), and **Shinaq & Bandel** (1992) have measured and investigated the lowermost portion of this outcrop. **Powell** (1989) figured a long, simplified column of a drill core ("GTZ-2D-borehole Zerqa Ma' in" of **Marsawah** 1987). **Amireh et al.** (1994) published many Cambrian profiles from Jordan, but, for the Wadi Zerqa Ma'in section with different strata thicknesses and bed positions. **Shawabkeh's column** (1998) is much shorter, but, incorrect in the lithological succession. A more detailed profile published by **Rushton & Powell** (1998) is based on **Powell** (1989) and has the correct total thickness, but the thickness and the position of some beds (Rushton & Powell 1998: fig. 6, p. 136) are different from the outcrop (Fig. 3). Additionally, all of the published columns do not record a third and youngest bedstone population known higher upslope. As a consequence, we re-measured the section and sampled, investigated and characterized the carbonate intervals.

Generally, the exposed succession of the Burj Formation at Wadi Zerqa Ma'in can be subdivided into seven units (A–G, Fig. 4). Three of them represent carbonate intervals (units B, D, F), four are dominated by heterolithic siliciclastics (units A, C, E, G). At the top, the Cambrian succession is incomplete and ends with the sandstones of the Umm Ishrin Formation. Permo-Triassic siliciclastics unconformably overlie the Cambrian (Fig. 5.1).

**Unit A:** First siliciclastic interval (thickness: >1 m):

The lowermost Cambrian beds exposed at the Wadi Zerqa Ma'in locality consists of an alternation of greenish sandstones and thin-bedded greenish claystones. Sandstone beds are slightly angular- to wavy bedded and yield rare claystone lithoclasts in their lower portion. The beds are dm-thick, medium-grained, and contain angular to well-rounded quartz grains. Rare peloids and echinoderm fragments occur. At the top, dolomitic cements can be observed.

**Unit B:** First carbonate interval (thickness: 4.5 m, Fig. 4):

A distinct carbonate interval develops continuously from the lower siliciclastic unit within a short vertical distance. The lowest limestone horizons are sandy, dolomitic, rich in rounded echinoderms (Figs. 5.2-5.3, 6.1), and yield small and flat claystone pebbles. Broken shelly remains and ooids also occur locally; some bioturbation is visible. A common feature is syntaxial cement around the echinoderm ossicles. In this echinoderm-dominated lithology, a peloidal limestone occurs. This limestone is laminated by variably sized fecal pellets and the small lithoclasts (Fig. 6.2). Locally, algal lumps can be observed. Quartz grains are rather rare and claystone clasts reach diameters of up to 1.5 cm. Echinoderm fragments occur in distinct layers. The bedding of this limestone is slightly wavy, and bioturbation is not observed. Here, a brownish fine-grained, clayey, and sparsely arenaceous to dolomitic limestone layer (mudstone) with a slightly wavy texture, and with few relictic pseudoclasts (solution remains) of micritic dolomite is intercalated. Up-section, a coated-grain grainstone follows for a few decimeters. This limestone shows distinct bioturbation that produces a nodular texture. Quartz grains are quite common and especially accumulated in burrows by bioturbation. The bioclasts are represented by trilobites and echinoderm remains. Isopachous and syntaxial cements are common.

After about a 20 cm intercalation of thinly laminated, greenish claystone/siltstone, the carbonate becomes oolitic and cross-bedded. Most of the ooids have only a few envelopes around the cryptocrystalline or (rarely) quartz cores. Isopachous blady cement is common. Fragmented trilobites, echinoderms, and unidentifiable shelly remains occur (Fig. 6.3). Up-section, a prominent bioturbation can be observed (Fig. 5.3-5.4). In the bioturbated portion, the trilobite *Palaeeolenus antiquus* was found (Fig. 7.2).

After a 20 cm intercalation of greenish claystone to siltstone, a bioclastic grainstone to rudstone bed occurs. At its base, a several centimeter-thick accumulation of hyoliths (*Hyolithes kingi*, Fig. 7.6-7.7) with common cone-in-cone nesting is very distinctive (*"Hyolithes kingi horizon"*, Fig. 6.4). This hyolith rudstone passes into a bioturbated grainstone to rudstone facies (Fig. 5.4) dominated by shelly bioclasts (trilo-
Fig. 4. Documentation of the lithological succession of the Wadi Zerqa Ma'in outcrop (middle) with detailed profiles of each carbonate unit.
bites, hyoliths, brachiopods) and echinoderms. At the

top, trilobites represent the majority of the bioclasts
(Fig. 6.5). Most conspicuous here are abundant
specimens of the trilobite Kingaspis campbelli
("Kingaspis campbelli horizon", Fig. 7.3-7.4).

Unit C: Second siliciclastic interval (thickness:
10.9 m) (Fig. 4):

This interval consists of sandstone-siltstone alter-

tations (Fig. 5.2-5.3). The sandstone is represented by
platy, up to several dm-thick, light-colored, massive
horizons. They are medium-grained and calcite
cemented. Intercalated between the sandstones is a
thinly laminated greenish siltstone to claystone. Oscil-
lation wave ripple marks are common. In the lower
part of this unit, trough-cross-bedding of the sand-
stone beds is quite common (Fig. 5.3), and is overlain
by a distinct heterolithic alternation of laminated silt-
stone and thin platy sandstone beds (Fig. 5.5) with a
large number of Cruziana salomonis ("Cruziana
level") on nearly every lower surface of the sandstones
(Figs. 5.6, 7.1).

Sandstone beds of the upper part of unit C are
dominated by equally spaced bodies separated by thin
clay laminae and showing distinct foresets (in some
levels bipolar cross-bedding), tidal bundles, and wave
ripples.

Unit D: Second carbonate interval (thickness: 3.6 m,
Fig. 4):

The limestones of this carbonate interval develop
from the underlying sandstone facies by a gradual
increase in the shelly content (mainly trilobites) and
in echinoderm fragments about one decimeter
below the first distinct limestone horizon of unit D.
The shelly fragments are strongly orientated and
horizontally accumulated in distinct levels. Just below
the lower boundary of the first limestone horizon
the shelly bioclasts decrease clearly, but, oolites and
calcareous grains, also focused first on distinct layers/
sheets, occur increasingly (calcareous sandstone).

The overlying limestone represents a dolomitized
oolitic grainstone. Biogenic remains as small trilo-
bites, echinoderm ossicles and some hyoliths are
identifiable. The quartz content (angular grains) is
very low. Near the middle of the second carbonate
interval, the dolomitization effect is much lower (Fig.
6.6). But, at the top, it is heavily pronounced, again.
Cements, ooids and other components are replaced by
cosmic dolomite crystals, so that detailed structures
are obliterated.

After few centimeters of greenish siltstone, the
uppermost about 1 m of the second carbonate interval
is represented by a cross-beded oolitic grainstone
(Fig. 5.7). The fossil content of this dolomitic and
sandy lithotype is the same as below. Additionally,
the occurrence of glauconite grains is very distinct.

Unit E: Third siliciclastic interval (thickness:
27 m) (Fig. 4):

The second carbonate interval (unit D) is overlain by
this siliciclastic interval which is very similar to the
upper part of the second siliciclastic interval (unit C)
below. It is characterized as well by thick bipolar
cross-bedded and trough-cross-bedded sandstones, as
of equally spaced sandstone bodies. Both lithotypes
are occasionally intercalated by some thinner silt-
stone-sandstone alternations. Interference and oscilla-
tion ripple marks, and (in the sandstones) calcite
cement and siltstone-claystone clasts can be observed.

Unit F: Third carbonate interval (thickness: 4.4 m,
Fig. 4):

In the upper portion of the Wadi Zerqa Ma’in section a
further carbonate unit was newly detected. This unit is
composed of alternating sandstone and limestone
beds.

In the lower part, there are oolitic grainstone
horizons (limestone, 0.7 m) interlayered by sandy
layers within cm-distances. Some small and broken
shelly remains occur. This is overlain by a mix of two
densely alternating rock types: (1) ooid-bearing bio-
clastic grainstone and (2) sandstone (Fig. 6.7). Bio-
clasts of the limestone (type 1) are palaeontologically
clearly dominated by trilobite fragments. These and
further unidentifiable broken shell remains show a
very distinct orientation. Few echinoderm sclerites
and sponge spicules occur, too. The boundaries be-
tween the bioclastic grainstone horizons and the sand
beds are always transitional and are interpreted as a
repeated interfinger ing of both facies. In the bioclastic
grainstone, cranidia of disarticulated Kingaspis camp-
belli were observed.

After a 1.8 m sandstone intercalation, the youngest
carbonate bed of the Wadi Zerqa Ma’in section occurs.
This lithotype has various amounts of sandy fraction,
so petrographically it represents a cm-beded, very
sandy limestone up to calcareous sandstone (Fig. 6.8).
The fossil content mainly consists of echinoderm
relics, but some shell remains occur, too. All fossils
are fragmentary preserved and strongly diagenetically
overprinted (until obliteration).
Unit G: Fourth siliciclastic interval (thickness: about 30 m) (Fig. 4):

The highest portion of the Wadi Zerqa Ma’in outcrop is represented by sandstone and siltstone. Because of the poor exposure of this interval, this portion cannot be described in detail. Nevertheless, the first 3-6 m is similar to units C and E and consists mainly of trough-cross-bedded sandstone beds as described below. This is overlain by about 23 m of typical Hanneh Member micaceous siltstone with intermediary micaceous fine-grained and partly trough-cross-bedded sandstone horizons. Typical sedimentary structures are load casts and very common wave ripple marks.

The transition of the Burj Formation into the overlying massive red-brown sandstones of the Umm Ishrin Formation is distinct.

4. Palaeontology

Although the Wadi Zerqa Ma’in locality has been investigated palaeontologically from nearly a century, only a few macrofossils are known. Additionally, microfossils have remained practically unknown. Some observation of calcimicrobes (Girvanella sp.), undefined poriferan spicules, and disarticulated echinoderm ossicles have been noted in the course of thin section facies analysis (Powell 1989; Shinao & Bandel 1992).

Trilobites represent the most common Cambrian fossils from the northeastern Dead Sea area. They occur as disarticulated and sometimes fragmented exuvial remains in nearly all carbonates of the Wadi Zerqa Ma’in section. Although a large number of more-or-less well preserved librigenae and craniidae can be found, the remains of only two ellipsocephalid (psychopariid) species from the first and third carbonate intervals (units B & F, Figs. 4, 5.2), have been recorded.

During our fieldwork, in the upper part of unit B, and just below the highest about 20 cm thick claystone/siltstone intercalation within the first carbonate interval (Fig. 4), several cranidia of Palaeolenum antiquus (Chernysheva, 1956) were found (Fig. 7.2). This taxon was first reported from the Wadi Zerqa Ma’in by Rushton (1988) as belonging to the genus Schistisophaerus, but was brought later to Palaeolenum antiquus (Chernysheva 1956) by Rushton & Powell (1989). The other taxon is Kingspis campbelli (King 1923), which always occurs disarticulated (Fig. 7.3-7.4), too. It was first described as Anomocare campbelli by King (1923), later as Kingspis campbelli by Kohayashii (1935), and brought to Palaeolenum campbelli by Richter & Richter (1941). Librigenae and cranidiae of this taxon are very common within a hash layer near the top of the first carbonate interval (unit B), about 1 m above the “Hyolithes kingi horizon” (Fig. 4). It has also been found in the third and youngest, hitherto unknown carbonate interval (unit F). Kingspis campbelli may indicate a stratigraphically little younger age than Palaeolenum antiquus (Chernysheva 1956).

Hyoliths are common elements especially in the upper part of the first carbonate interval (unit B). At the base of the highest limestone bed of this unit, at the top of the ca. 20 cm claystone/siltstone intercalation noted above (Fig. 4), these fossils compose a rudstone. The hyoliths are all brought to Hyolithes kingi Richter & Richter (1941) (Fig. 7.6-7.7). The remains are often orientated and show cone-in-cone nesting (Fig. 6.4), but there are no signs of remarkable abrasion. The Wadi Zerqa Ma’in hyoliths were first reported by King (1923) as “Hyolithus”, Richter & Richter (1941) revised and assigned them to the newly erected taxon Hyolithes kingi. Bandel (1986) discussed their palaeobiology and systematic position. He equated Hyolithes kingi systematically with Salterella and Volbortella, and this suggests an annelid affinity. Further, Bandel (1986) compared the palaeoecological and taphonomic conditions with those of the recent tube-worms Pectinaria of the

Fig. 5. 1 – Cambrian outcrop of the higher Burj Formation about 1 km north of the mouth of Wadi Zerqa Ma’in, composite picture, vertical extent of pictured succession: about 23 m; 2 – lower part of the Wadi Zerqa Ma’in section, lower units are indicated, note the distinct heterolithic nature in unit C, car for scale; 3 – lower part of the Wadi Zerqa Ma’in section, note the distinctive bioturbated (nodular) carbonate beds of unit B and the trough-cross-bedding in the overlying siliciclastic unit C; 4 – detail of unit B pictured in (3), note the cross-bedded oolitic part (above hammer) sandwiched by the two strongly bioturbated levels, hammer for scale; 5 – detail of lower part of the siliciclastic unit C, note the trough-cross-bedded sandstone beds at the bottom overlain by thinly bedded heterolithics, man for scale; 6 – detail of (5) with numerous specimens of Cruziana salomonis at nearly every lower surfaces of thin sandstone-layers within the heterolithic part of unit C, scale bar: 0.2 m; 7 – distinctly cross bedded oolitic grainstone, upper unit D, hammer for scale.
Fig. 6 (Legend see p. 265)
North Sea, and concluded that *Hyalolithes kingi* represented an animal that lived within the lower intertidal to upper subtidal zone and was accumulated (mainly post-mortally) by such unusual currents as storms or tides. The shell of *Hyalithes kingi* is preserved as coarse calcite pseudomorphs (Fig. 6.5). The size of the observed specimens ranges from a few millimeters up to about 30 mm, the diameter is up to 4 mm.

Trace fossils (ichnofossils) were observed only in silicilastic intervals. Although an investigation of the silicilastic units and of the trace fossil content is in progress and is not in the focus of this report, the massive occurrence of trilobite traces in the heterolithic alternation of laminated siltstone and thin platy sandstone beds of unit C is remarkable. Here, large tracks of *Cruziana salomonis* Seilacher (1990) occur in large numbers, and occur on the lower surface of nearly every sandstone bed (Fig. 5.6). This ichnospecies (Fig. 7.1) was erected by Seilacher (1990) from the Wadi Zerqa Ma’in outcrop as the type locality.

Picard (1942), who first reported *Cruziana* traces from the Wadi Zerqa Ma’in locality, also mentioned the occurrence of *Protichnites* in upper parts of the section. However, Parans (1971) doubted this observation and assumed a confusion with unformable overlying, younger sandstone strata.

Echinoderms are quite common in all carbonate intervals, generally as disarticulated ossicles. As well crystallized as silicofossil preservation occurs (sometimes within the same sample, Fig. 7.14). The abundance can be very large, as in the lowest part of the first carbonate interval (unit B), so that an echinoderm grainstone originated. However, mostly the ossicles occur as more or less frequent components within the bioclast spectrum. Whereas recrystallized and poorly preserved ossicles with dimly margins can be observed in thin-sections (e.g., in the upper part of the youngest carbonate level, unit F), the acid digestion produced as well abraded as very detailed preserved selerites, too. The selerites are represented by three "morphological types" of thecal plates: (1) flat irregular shaped or round plates (Fig. 7.8), (2) ossicles similar to (1), but, with distinct sutureal pore (epispines, Fig. 7.11-7.13), and (3) irregular, three-dimensional brick-like wall elements (Fig. 7.9-7.10). Incomplete annulate-segmented selerites may represent brachial or ambulacral parts. Epispines (typical for eocrinoids, cincta and some edrioasteroids) and the dominance of thecal plates and of small probable brachial/ambulacral elements, as well as, on the other hand, the lack of stem segments, of stylocone segments, and of typical cincter marginal plates as well as of axis channels may point to an affiliation to eocrinoids.

Brachiopods are present in the carbonate beds as broken valves, and may represent a portion of the often not clearly identifiable shelly remains. Chemical digestion during laboratory work provided some very small, juvenile, not closer to define lingulid specimens (Fig. 7.5). The size of these double-shelled preserved specimens is between 0.4 and 1.2 mm. The material of the shell is pseudomorphic replaced by silica. For further studies the material was sent to Michael Bassett (Cardiff) to contribute to the revision of the whole Cambrian brachiopod fauna from the Middle East, which is in progress by him and colleagues.

Poriferans are extremely rare in the Zerqa Ma’in lithotypes. Bandel (1986) reported, but did not illustrate "fairly large spicules of sponges" from thin section analysis of the hyolith layer near the top of the first carbonate interval ("*Hyalolithes kingi horizon" of unit B, Fig. 4). During own investigation, a few microscleres were obtained by laboratory acid digestion from the lower portion of the new reported youngest carbonate level (unit F). They are mostly represented by tetraxones, but triaxones occur, too (Fig. 7.15-7.22). The size of the microfossils is between 0.5 and 1 mm. Palaeobiologically, the siliceous spicules are of hexactinellid affinity.

In the carbonates of the uppermost unit B and of the lower part of unit F, single phosphatic tubes were

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Fig. 6. 1 – dolomitic sandstone/limestone mixed lithotype with rounded echinoderm fragments, lower part of unit B, scale bar: 0.2 mm; 2 – microthiolithoelastic peloidal limestone, lower part of unit B, scale bar: 0.2 mm; 3 – oolitic grainstone with trilobite and echinoderm fragments, middle part of unit B, scale bar: 1 mm; 4 – hyolithid rudstone ("Hyalolithes kingi horizon"), note the cone-in-cone nesting of the hyolith tubes, upper part of unit B, scale bar: 3 mm; 5 – bielastic grainstone to rudstone with some cone-in-cone nesting of hyolith tubes ("Kingsgait campbelli horizon"), uppermost part of unit B, scale bar: 2 mm; 6 – dolomitized bielastic oolitic grainstone, lower part of unit D, scale bar: 1 mm; 7 – ooid-bearing bielastic grainstone/sandstone alternation of lower part of unit F, scale bar: 2 mm; 8 – echinoderm bearing sandy limestone to limy sandstone, upper part of unit F, scale bar: 1 mm.
Fig. 7 (Legend see p. 267)
found. One of them (from unit F) is very fragmentary and poorly preserved (Fig. 7.25), but, the specimen from unit B shows some interesting details. So, the small conical tube has an elliptical cross section and is irregularly curved (Fig. 7.23). In assumed growing direction, the angle of divergence is not constant and widened to the distal part of the tube. The outer surface is ornamented by well pronounced transverse rings which are sometimes regular, but, some other time rather not. The occurrence of perpendicular fine corrugations between the rings is very distinct (Fig. 7.24). Whereas nearly all the mentioned features (material, size, shape, and cross-section) are characteristic for the hyolithelinthid genus Torellella, the perpendicular corrugations are not yet described by the knowledge of the authors. Unfortunately, the diagnostic definition of torellellids and hyolithellids (the only two families of the hyolithelinthides) is very imprecise on family level and is highly controversial on lower levels (see discussions in Landig 1988, and Brasier in Cowie & Brasier 1989: 127 f), so that this confusion makes a detailed taxonomic decision problematic. Because of this and of the limited material, the specimens from Wadi Zerqa Ma'in are preliminary assigned here in open nomenclature to Torellella sp.

5. Interpretation and discussion

The main characteristic of the Cambrian succession at the northeastern Dead Sea is the well developed alternation of carbonate lithotypes and silicilastics within the Numayri Member – Hanneh Member transitional interval of the Burj Formation (Figs. 3-5), which is in distinct contrast to all other sections further south (e.g., Bender 1968; Powell 1989; Teimur et al. 1990; Ellick et al. 2002). This means that a decision on the affiliation of the exposed Wadi Zerqa Ma’in succession to one of the two members is problematic. The base of the Hanneh Member is lithostratigraphically defined in the southern Dead Sea area by the “sharp contact” of the youngest carbonate bank of the Numayri Member to the overlaying “green, red or grey micaceous siltstone or fine-grained sandstone...” of the Hanneh Member (Powell 1989; Geyer & Landig 2000). Following Powell (1989), the “second carbonate unit” at Wadi Zerqa Ma’in – corresponding to unit D described herein – is “overlain by about 50 m of marine silicilastics equivalent to the Hanneh siltstone of the Safi area” of the southern Dead Sea region. Accepting this lithostratigraphic concept, the recognition of the newly discovered third carbonate interval published here (unit F) would lead to a shift of the Numayri-Hanneh boundary more than 30 m upstream. Alternatively, one could follow Powell’s idea to accept the base of the Hanneh Member at Wadi Zerqa Ma’in at the top of unit D (= second carbonate interval). This would mean that open-marine fossiliferous carbonates are still present within the Hanneh Member, too. But, in this case, the position of the base of the Hanneh Member would be rather random, because if this member may contain carbonate beds, too, than as well the whole Wadi Zerqa Ma’in surface succession as only parts of it could, in turn, could be regarded as belonging to the Hanneh Member.

Fig. 7. 1 – big specimen of *Cruziina salomonis* from the heteroliths of unit C (“Cruziana” level), scale bar: 5 cm; 2 – *Palaeodiscus antiquus*, cranium, upper part of unit B, scale bar: 5 mm; 3 – *Kingsii campbelli*, juvenile cranium, upper part of unit B, scale bar: 0.5 mm; 4 – *Kingsii campbelli*, adult cranium, upper part of unit B (“*Kingsii campbelli* horizon”), scale bar: 3 mm; 5 – undefined juvenile brachipod, lower part of unit D, scale bar: 0.1 mm; 6 – *Hyolithes kingi*, steinkern fragment, note the distinct septum in the apical part, which often acts as a post-mortem break line, lower part of unit D, scale bar: 0.1 mm; 7 – *Hyolithes kingi*, side view of a steinkern fragment of the most apical part typically broken along the break line as mentioned in (6), lower part of unit D, scale bar: 0.1 mm; 8 – platy echinoderm ossicle, note the stereom structure and the nodes on the distal surface, upper part of unit B, scale bar: 0.1 mm; 9 – brick-shaped echinoderm ossicle with central wall-like rise, lower part of unit D, scale bar: 0.1 mm; 10 – brick-shaped echinoderm ossicle with a central node, lower part of unit D, scale bar: 0.2 mm; 11-13 – platy echinoderm ossicles with distinct marginal sutures (epispires), all from lower part of unit D, scale bars: 0.2 mm; 14 – internal structure of a broken platy echinoderm ossicle, outer side of the plate is at the right, note the larvalistic meshwork stereom in the proximal part and the galleried structure in the distal part, upper part of unit B, scale bar: 0.05 mm; 15-22 – siliceous sponge spicules, all from lower part of unit F, attached neomorphic crystals are K-feldspars, scale bars: 0.05 mm; 23 – phosphatic tube of *Torellella* sp., upper part of unit B, scale bar: 0.3 mm; 24 – detail of (23), note the fine corrugations perpendicular between the transverse ring-like ornamentation of the outer surface, scale bar: 0.1 mm; 25 – poorly preserved *Torellella* sp. fragment, lower part of unit F, scale bar: 0.1 mm.
Here, we follow Rushton & Powell’s (1998) terminology that the incomplete Wadi Zerqa Ma’in succession “belongs to the uppermost part of the Numayri Member and/or the Hanneh Member”.

Whereas the sedimentary features of the siliciclastic portions of the Wadi Zerqa Ma’in section are quite similar for the higher three units (C, E, G), unit A is different. Only 1 m of this lowermost unit is exposed, so that an interpretation is difficult because of limited data. Nevertheless, for unit A, the horizontally laminated to slightly wavy bedded sandstone described above, the interlayered laminated claystone horizons and the erosional features (clay-clasts within the sandstone) point to a low-energy siliciclastic, subtidal environment occasionally reworked by stronger currents.

The onset of the first carbonate interval (unit B) at its lower part (evolution from sandy dolomitic to echinoderm and peloid-supported laminated textures, see above) suggests a rather quiet marginal-marine environment, occasionally affected by erosional high-energy processes (occurrence of intraclasts). To the top, rather open-marine conditions of a well-populated shallow depositional area are indicated (trilobites and other shelly fossils, local pellets, some bioturbation, etc.). A good indication of high-energy shallow subtidal conditions is the occurrence of the overlying cross-bedded oolite. Further, the overlying, above described mass accumulation of cone-in-cone nested Hyolithes kingi shells near the top of the first carbonate interval, can be interpreted as originated by tidal currents or storms as already proposed by Bandel (1986). The intense bioturbation of the uppermost carbonates of unit B (bioclastic grain- to rudstone) points to a reduced sedimentation rate following temporary depositional episodes.

Tidal influence can be observed in the overlying siliciclastic portions (units C, E, G), which are interbedded with further carbonate units (D, F). The most conspicuous feature of the siliciclastics consists in the alternation of thick sandstone beds and sandstone-siltstone interbeds (Fig. 5.2, 5.5). The described features (bipolar cross-bedding, bundling etc.) of the sandstone beds (see above) support an interpretation of tidal influence. The occurrence of both trough-cross-bedding and planar cross-stratification (Fig. 5.3) may point to alternating deposition of subaqueous sandbars (3D-dunes) and of tabular sandwaves (2D-dunes) depending on the water-flow energy. The associated, thinly interbedded heterolithics (Fig. 5.5-5.6) are interpreted as deposition on tidal flats or in interbar areas periodically colonized by marine fauna (Crustana salomonis, see above).

Between the siliciclastic units C and E, the second carbonate interval (unit D) occurs. The oolitic fossiliferous, glauconitic grainstone develops gradual from underlying sandstone and is distinctly cross-bedded in its upper part (Fig. 5.7). This unit, we interpret as an open-marine oolite shoal evolving in the front of the tidally influenced area.

The overlying thick siliciclastic portion (unit E) is very well comparable to unit C (Fig. 5.2) and may represent a tidal depositional area, too. That means, the oolitic shoal environment of unit D is an open-marine carbonate interplay within a generally tidally influenced siliciclastic environment.

In some vertical distance, the hitherto unknown third carbonate interval (unit F) is a combined unit of two carbonate horizons with sandstone intercalations. In the lower part, a bioclast-bearing oolite to oolite-bearing bioclast grainstone-sandstone alternation represents an interfingering of both lithotypes within a transitional environment. Above, a thick sandstone intercalation occurs, overlain by the youngest limestone which has a large sandy proportion. The bioclasts of all carbonates of this unit show very distinct orientation, so that a deposition under stronger currents is striking, what is supported by their fragmentary preservation, too.

Siliciclastic unit G is the uppermost part of the Cambrian succession in the Wadi Zerqa Ma’in outcrop. As described above, the lower few meters correspond to the lithological development known from the siliciclastic units below. Also for this portion a tidally influenced marginal-marine deposition is interpreted. Because of the poor outcrop conditions, the transition into the siltstone-sandstone dominated Hanneh Member facies can not be observed directly, but concluded by some punctual insights. The distinctly larger amount of fine elastics, the generally thinner bedded layers, and the practically omnipresent ripple marks point to a further shallowing of the sea. In fact, desiccation cracks and marine trace fossils were not yet observed from the Hanneh Member at the Wadi Zerqa Ma’in locality, but, both are known from better preserved Hanneh Member outcrops further south (e.g., Wadi Issal area at the southern edge of the Lissan peninsula).

This youngest unit of the Burj Formation is overlain by massive red-brown channel sandstones of the Umm Ishrin Formation which is interpreted as predominantly fluvial, braided river deposition (Selley 1972;
POWELL 1989; MAKHLOUF & ABED 1991; RUSHTON & POWELL 1998; SHAWABEKH 1998). This formation is incomplete because of erosion due to late Palaeozoic uplift and it is unconformable superimposed by Permo-Triassic sediments (BANDEL & KHOURY 1981; SHAWABEKH 1998).

Concluding, based on lithological, petrographical and palaeontological data of the Wadi Zerqa Ma'in section presented here, a principle development from marginal-marine shallow subtidal to intertidal and subsequently to predominantly fluvial conditions can be confirmed. Whereas the lowermost part (unit A) may indicate somewhat lagoonal conditions (SHAW & SCHREIBER 1991; READING 1996), the siliciclastic portions of units C, E, and lower G point to tidally influenced deposition (CLIFTON 1982; WEIMER et al. 1982, DALRYMPLE et al. 1992). The three short carbonate intercalations (units B, D, and F) suggest brief transgressive pulses during the discontinuous shallowing process.

Because of the described sedimentary textures, of the geometry and distribution of sand bodies and silt/clay beds (see above), a tidally and maybe deltaic to estuary influenced environment can be concluded (NICHOLS et al. 1990; SIMPSON 1991; READING 1996; COLEMAN & PRIOR 1982; MIDDLETON 1991; DALRYMPLE et al. 1992; SCHRODER-ADAMS 2006). The described massive sandstone beds of the Wadi Zerqa Ma'in section which represent the upper Numayri Member and/or parts of Hanneh Member could be interpreted as elongate sand bars and broad sand flats of a bay mouth zone. The heterolithic to muddy facies within the siliciclastic units and within the typical Hanneh Member have a characteristic lithology, typical, e.g., for a low energy central zone of an estuary funnel. Finally, the fluvial sandstones of the overlying Umm Ishrin Formation can be attributed to the braided zone of a proximal area of an estuary.

Because of the low dimension of the observed cross-bedding, of the thickness of the siliciclastics beds, and of lacking deep flanks of troughs, a meso-to microtidal regime is probable for the upper Burj Formation at Wadi Zerqa Ma'in. The fluvial transport of the sandy material was from South (Arabian–Nubian Shield) to North into the marine realm (BENDER 1968; SELLEY 1972; SCHNEIDER et al. 1984; SEGEL 1984; MAKHLOUF & ABED 1991; AMIREH et al. 1994). These siliciclastics were redeposited and distributed by tidal currents and coastal transport in opposite direction and were periodically populated by marine fauna (see trace fossil content). When seaward sediment transport was temporarily reduced, some periods of an open-coast with tidal flats may have also existed as a comfortable marine habitat indicated by the rich Creticiana ichnofauna in some levels.

Nevertheless, the direction of material transport and the occurrence and frequency of traces of marine organisms, obviously, is not always of the same kind, what we interpret as repeated changing deltic/estuary conditions, depending on fluctuating fluvial sediment supply and on changing rates of small-scale sea-level rises and falls (DALRYMPLE et al. 1992) within a general, but discontinuous regressive trend intermitted by some transgressive pulses. The occurrences of some larger scaled sea-level changes are demonstrated by the intercalation of the three carbonate units. The more the regression proceeds, the more the open-marine character of the environment decreases.

Detailed investigations on surface sections and drilling cores from further areas are in progress to clarify the depositional and the palaeoecological conditions of the Cambrian Burj Formation in detail.

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