Facies development during late Early–Middle Cambrian (Tayan Member, Burj Formation) transgression in the Dead Sea Rift valley

Olaf Elicki

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Olaf ELICKI [1]

Abstract: The transgressive Tayan Member of the upper Lower to Middle Cambrian Burj Formation (Jordan) has been investigated in several localities of the Dead Sea Rift valley, Jordan. The lower portion of this member consists of low-energy siliciclastics with indications of temporary, early pedogenetic processes, pointing to some stagnation during transgression. The upper portion of the member was deposited under higher energy conditions. Stromatolites, desiccation cracks, halite-pseudomorphs, laminated dolostones, and tepees, together with ripples, mud-clasts and scours point to a shallow intertidal to supratidal sabkha-related environment in a climate of tropical to subtropical aridity.

The fossil content of the Tayan Member consists exclusively of trace fossils. Simple endobentic, worm-like r-strategists are common in some horizons. For the first time, *Treptichnus pedum* has been reported from Jordan where it was found near the base of this member. The markedly reduced biodiversity together with sedimentological data led to the interpretation of a strongly stressed, paleoecologically unstable habitat.

Regional comparisons with high-energy transgressive environments laid down at the same time show that the main factors controlling facies development and the migration of facies belts are (1) the topography of the flooded surface and of the hinterland (mainly with only a local effect), (2) the configuration of the coast (local effect), (3) the rate of subsidence and transgression (local to regional effects), and (4) climate (large regional effects). The combination and overlap of these factors controlled facies gradients and may explain special differences between the facies of the Jordanian and those of the near-by Israeli transgressive deposits on the one hand, but, also the obvious general similarity of Lower to Middle Cambrian transgressive successions in the Middle East and the Mediterranean part of Gondwana on the other hand.

Key Words: Cambrian; Burj Formation; Middle East; paleoecology; facies

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Résumé : ***Variation de faciès au cours de la transgression s'étageant du Cambrien inférieur terminal au Cambrien moyen (Membre de Tayan de la Formation de Burj) dans le graben de la Mer Morte en Jordanie***.- Situé à la base de la Formation de Burj, le Membre de Tayan constitue une unité stratigraphique transgressive d'âge Cambrien inférieur terminal à Cambrien moyen. Cette unité lithostratigraphique a été étudiée dans plusieurs localités du graben de la Mer Morte, côté jordanien. Sa partie inférieure comprend des dépôts silicoclastiques de basse énergie présentant des traces de processus pédogénétiques précoces et de courte durée, soulignant des phases de stagnation au cours de la transgression. La partie supérieure de ce membre fut déposée dans des conditions d'énergie plus élevée. On y reconnaît des stromatolithes, des fentes de dessiccation, des pseudomorphoses de halite, des dolomies laminées, et des structures en tipi, associées à des rides, des galets mous et des traces d'affouillement typiques de milieux de type sebkha, intertidaux peu profonds à supratidaux en climat tropical ou subtropical aride.

Le contenu fossilifère du Membre de Tayan se limite à des ichnofossiles. Des organismes ressemblant à des vers fouisseurs, ayant probablement développé une stratégie de reproduction de type "r", sont fréquents dans certains horizons. À la base de cette unité lithostratigraphique, on note la présence de *Treptichnus pedum* qui est signalé pour la première fois en Jordanie. Couplée aux données de la sédimentologie, cette biodiversité extrêmement réduite est un élément qui conduit à imaginer des biotopes soumis à de fortes pressions environnementales et paléoécologiquement instables.

Des comparaisons interrégionales avec d'autres sites contemporains, présentant également des environnements de haute énergie en contexte transgressif, montrent que les principaux facteurs qui contrôlent le développement de certains faciès et les déplacements des bandes de faciès sont (1) la topographie de la surface ennoyée et de son arrière-pays (facteur exclusivement local), (2) la configuration de la côte (facteur local), (3) le taux de subsidence et la vitesse de transgression (facteurs locaux à régionaux), et (4) le climat (facteur supra-régional). Ce sont la combinaison et la superposition de ces facteurs qui peuvent expliquer les différences entre les séries étudiées en Jordanie et leurs équivalentes en Israël au même titre que les évidentes similitudes des séries transgressives du Cambrien inférieur-moyen du Moyen-Orient et de la partie méditerranéenne du Gondwana.

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Mots-Clefs : Cambrien ; Formation de Burj ; Moyen-Orient ; paléoécologie ; faciès

Kurzfassung: ***Faziesentwicklung während der spät-unter- bis mittelkambrischen Transgression im Toten-Meer-Rift (Tayan Member, Burj Formation).-*** Das transgressive Tayan Member der spät-unter bis mittelkambrischen Burj Formation Jordaniens wurde in zahlreichen Lokalitäten des Jordan-Grabens untersucht. Der untere Abschnitt des Members besteht aus niedrigenergetischen Siliziklastika und weist gelegentlich Merkmale einer initialen Pedogenese auf, was einen diskontinuierlichen Ablauf des Transgressionsgeschehens belegt. Der obere Abschnitt des Tayan Members wurde unter höher-energetischen Verhältnissen sedimentiert. Stromatolithen, Trockenrisse, Halit-Pseudomorphosen, laminierte Dolomite und Tepee-Strukturen sowie das Auftreten von Rippelmarken, Intraklasten und Kolken kennzeichnen ein flach-intertidales bis supratidales, Sabkha-artiges Environment unter einem tropischen bis subtropischen Klima.

Die Fossilführung des Tayan Members wird ausschließlich durch Ichnia repräsentiert. Diese sind simpel strukturiert, treten in bestimmten Horizonten massenhaft auf und wurden durch Wurm-artige, endobenthische r-Strategen angelegt. Erstmals wird aus dem jordanischen Kambrium das Ichnotaxon *Treptichnus pedum* gemeldet. Die auffällig reduzierte Biodiversität im Tayan Member charakterisiert zusammen mit sedimentologischen Daten den Bildungs- und Lebensraum als ein gestresstes, paläoökologisch instabiles Habitat.

Überregionale Vergleiche mit hochenergetischen transgressiven Abfolgen desselben Zeitfensters zeigen, dass die wesentlichen Steuerungsfaktoren der Faziesentwicklung und der Verlagerung von Faziesräumen folgende sind: (1) Topographie des transgredierten Untergrundes und des Hinterlandes (mit insbesondere lokalen Effekten), (2) Küstenkonfiguration (lokale Effekte), (3) Subsidenzrate und Transgressionsrate (lokale bis regionale Effekte) und (4) Klima (großregionale Effekte). Das Zusammenwirken dieser Faktoren kontrollierte entscheidend die Faziesgradienten und erklärt sowohl gewisse Unterschiede der transgressiven Abfolgen Jordaniens und des nahegelegenen südlichen Israels als auch die erstaunliche prinzipielle ähnlichkeit derartiger Profile im Unter-/Mittelkambrium des Mittleren Ostens zu denen benachbarter perigondwanischer Bereiche.

Schlüsselwörter: Kambrium; Burj Formation; Mittlerer Osten; Paläoökologie; Fazies

1. Introduction

Sedimentary rocks of Cambrian age have been known from Jordan since the beginning of the last century (BLANCKENHORN, 1910; DIENEMANN, 1915). Outcrops are located in the Dead Sea Rift valley and are exposed most spectacularly on its eastern side in the southern Dead Sea area and in the middle and southern part of Wadi Araba.

Following the first short reports by the authors listed above, paleontological and biostratigraphic studies were continued by KING (1923), RICHTER and RICHTER (1941), PICARD (1942), PARNES (1971), COOPER (1976), BANDEL (1986), SEILACHER (1990), and RUSHTON and POWELL (1998). Petrography, paleogeography and facies reconstructions were emphasized by BENDER (1963, 1968, 1975), SELLEY (1972), SEGEV (1984), and SCHNEIDER *et alii* (1984). Significant progress regarding in the knowledge of distribution and characteristics of Cambrian sediments in Jordan came from an extensive mapping program undertaken by the Natural Resources Authority of Jordan in cooperation with the British Geological Survey. This work resulted in 1 : 50000 scale geological maps published during the last two decades of the 20th century. Recent works on the sedimentology and depositional history of the Cambrian have been published by AMIREH (1990), SHINAQ (1990), MAKHLOUF and ABED (1991), SHINAQ and BANDEL (1992), AMIREH *et alii* (1994), ELICKI and SHINAQ (2000), GEYER and LANDING (2000), ELICKI *et alii* (2002), MAKHLOUF (2003), SHINAQ and ELICKI (2007), and SCHNEIDER *et alii* (2007).

The focus of past studies was on the paleontology of fossiliferous carbonates and on the depositional patterns of the clastic strata above and below the transgressive facies. Relatively little information is available on the sedimentologies of the transgressive facies themselves. So the characteristics of the flooding and their comparison with those of other regions are the subject of this contribution. To delimit and to define the character of the flooding event, eight sections from the southern Dead Sea area were studied and nine published descriptions from other areas were included in the analysis.

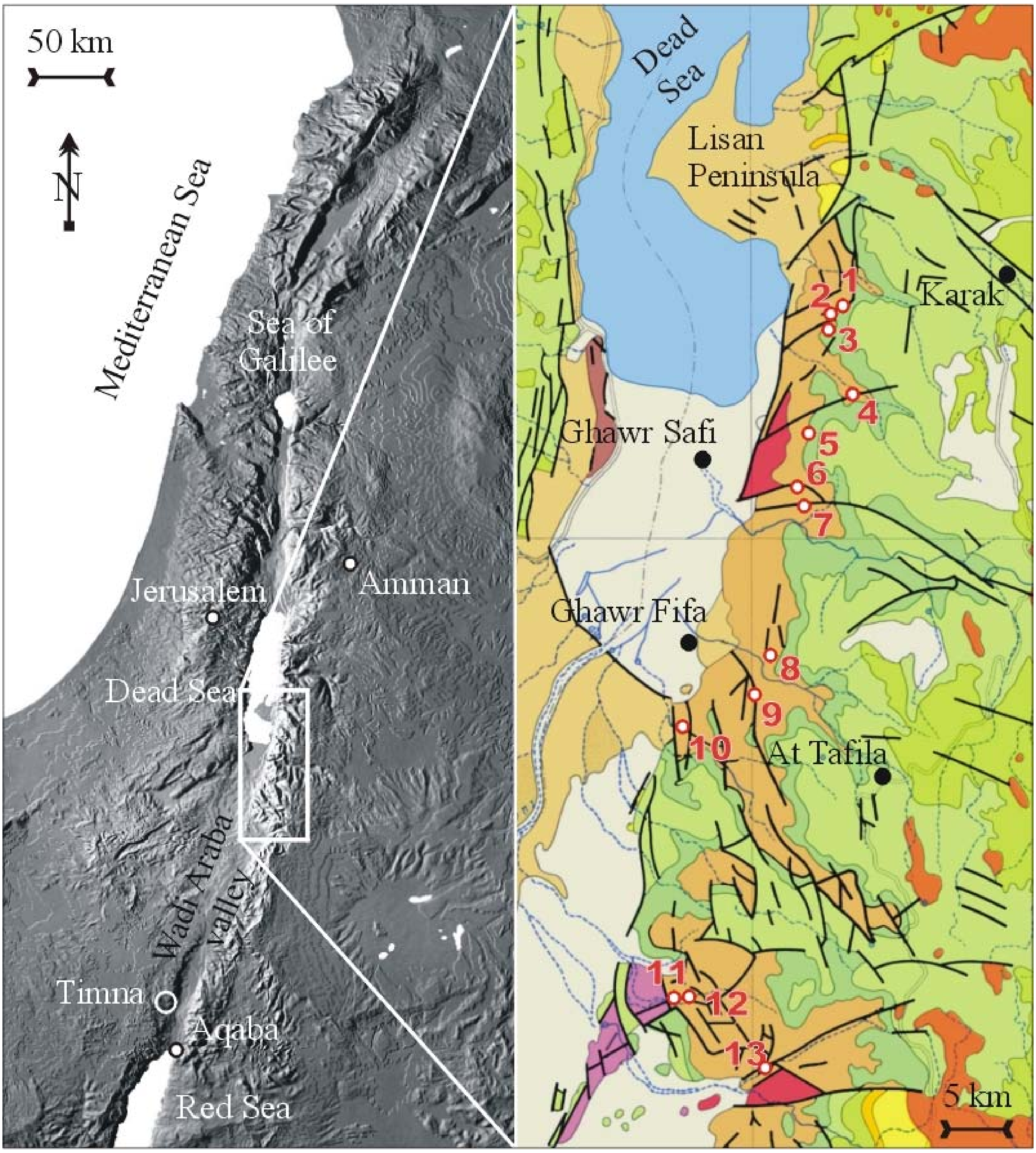


Figure 1: Regional and geological map of the study area with main locations for orientation and localities investigated or mentioned in the text (Dead Sea area: 1 – Wadi At Tayan/Wadi Uhaymir; 2 – south of Wadi At Tayan; 3 – Jabal Tabaq Hanneh; 4 – Wadi Numayri; 5 – Wadi Qunai; 6 – Wadi Saramuj; 7 – Wadi Al Hisa; Wadi Fifa area: 8 – Wadi Umm Jafna; 9 – Wadi Fifa; 10 – Wadi Khunayzira; Wadi Dana area: 11 – Jabal Al Jariya; 12 – Wadi Ghuwayb; 13 – Wadi Dana; deep red – Precambrian metasediments; magenta – Precambrian magmatic rocks; deep brown – Lower Paleozoic sediments; green – Cretaceous; light red – Tertiary basaltoids; yellow – Eocene sediments; light brown – Pleistocene sediments; light blue – recent alluvial sediments.

The Arabic geographic names used in this paper are from geological maps and their explanations. However, because of the lack of an official, generally accepted transliteration of the Arabic language, these names may be spelled differently on the several maps and explanations.

2. Geological background

The Cambrian strata of the southern "Jordan Rift Valley" (southern Wadi Araba) lie unconformably on the Aqaba Complex, a regional name for the Precambrian magmatic and metamorphic rocks of the Arabo–Nubian Shield. This craton was consolidated in Cryogenian to Ediacaran times (Neoproterozoic; BEST *et alii*, 1993). As reported by BENDER (1968), JARRAR *et alii* (1991), and BANDEL and SHINAQ (2003) farther north (middle of Wadi Araba), below the Lower Cambrian unconformity, Neoproterozoic volcanoclastics and conglomerates occur (Araba Complex).

As an onlap on the Arabo-Nubian shield the thickness of the Cambrian succession increases from south to north from 0 m at the northern shore of the Red Sea to nearly 700 m in the Dead Sea area, and exceeds 1000 m in the subsurface of northern Jordan and Syria (BENDER, 1968; POWELL, 1989; SHINAQ and BANDEL, 1992; BEST *et alii*, 1993).

The area studied (Fig. 1) follows the eastern margin of the Dead Sea Rift valley southward 60 km from the southern limit of the Lisan Peninsula to the Wadi Dana area. In this area, the Cambrian succession rests on an unconformable erosional surface. The sequence consists of continental conglomeratic siliciclastics (Salib Arkosic Sandstone Formation, ?Lower Cambrian) with maximum thicknesses of more than 200 m. They are interpreted as representing fluvial and alluvial plain deposits (SELLEY, 1972; POWELL, 1989; AMIREH *et alii*, 1994; MAKHLOUF, 2003). The Salib Formation is overlain by the marine Lower to Middle Cambrian Burj Dolomite-Shale Formation (up to 120 m in the working area; Fig. 2). Within this formation, marine carbonates (Numayri Dolomite Member) are bounded by siliciclastics both below (Tayan Siltstone Member) and above (Hanneh Siltstone Member). Whereas the Numayri Member is represented by open and restricted shallow marine limestones and dolostones with a locally abundant biota, but minor siliciclastics (SHINAQ and BANDEL, 1992; RUSHTON and POWELL, 1998; ELICKI *et alii*, 2002; SHINAQ and ELICKI, 2007), the underlying transgressive Tayan Member comprises only siltstones and sandstones with a few simple traces as its only fossils (POWELL, 1989; RUSHTON and POWELL, 1998). The Hanneh Member (mainly sandstones and minor siltstones) overlies the Numayri carbonates and represents a deltaic and/or estuary influenced marginal marine succession of the final phase of the short marine transgression in the Jordanian Cambrian (MAKHLOUF and ABED, 1991; AMIREH *et alii*, 1994; RUSHTON and POWELL, 1998; SHINAQ and ELICKI, 2007). The Hanneh Member contains rich trace fossil assemblages and rare trilobite hash layers (paleontological investigation in progress). The youngest Cambrian Umm Ishrin Sandstone Formation consists of fluvial siliciclastics with thin tidal intercalations of probable late Middle to Late Cambrian age, that indicate the return of continental conditions to this portion of the Arabo-Nubian Shield (MAKHLOUF and ABED, 1991; GEYER and LANDING, 2000).

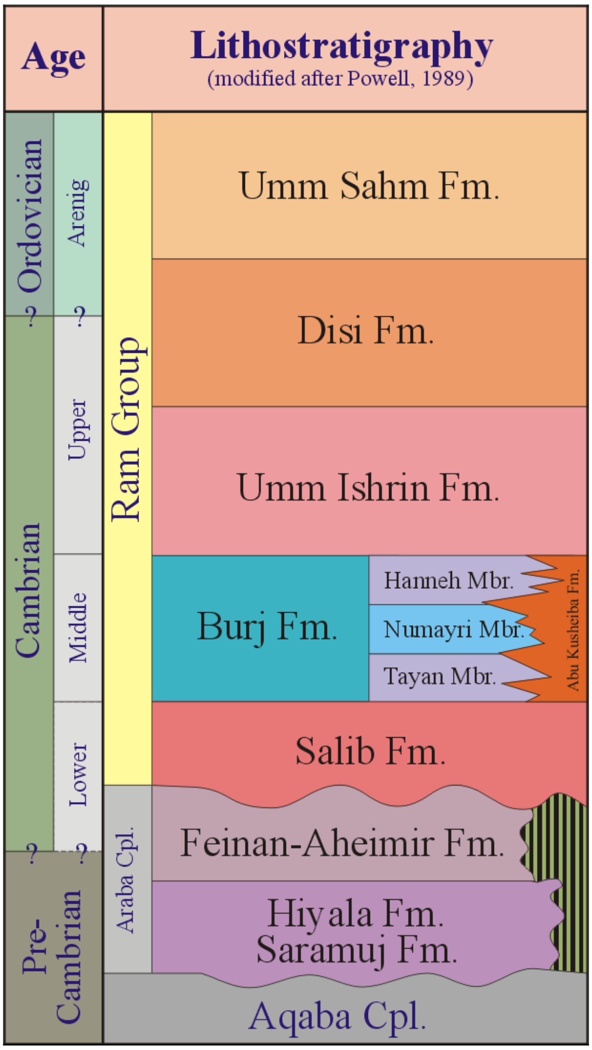


Figure 2: Simplified lithostratigraphy of the late Precambrian and early Paleozoic of Jordan.

3. Lithology and paleontology of the Tayan Member

A siliciclastic succession sandwiched between the continental Salib Formation below and the marine Numayri Member (carbonates, Burj Formation) above was originally called "lower siltstone unit" by BENDER (1968). The current formal litho-stratigraphic appellation comes from the Wadi At Tayan and Jabal At Tayan, named locations immediately south of the Lisan Peninsula (POWELL, 1988; Figs. 1 and 2).

3.1. Lithologic aspects

The Tayan Member was originally described as a succession of finely laminated, micaceous sandstone and siltstone showing wave ripples, and ripple cross- and parallel lamination (POWELL, 1988, 1989). The color of the rock varies from green to buff, mauve and red. Small-scale bimodal trough cross-bedding and claystone intraclasts are recorded from some of the thicker sandstone beds. In the middle of the member dolomite lenses may be present. The base of the member represents the base of the Burj Formation and is defined as being at the boundary between micaceous sandstones above and the underlying, significantly coarser and cross-bedded pebbly to conglomeratic sandstone of the Salib Formation. The top of the Tayan Member is set at the occurrence of the "first thick bed of limestone or dolomitic limestone" of the Numayri Member (POWELL, 1988). The total thickness of the Tayan Member is reported as 18 to 20 m in the type area.

Geographically, the Tayan Member has been described in outcrops from Wadi At Tayan in the north to the Wadi Dana region in the south, a distance of about 80 km (POWELL, 1988; TARAWNEH, 1988, 1992; RABB'A, 1994; Fig. 1). The sections investigated in the course of the present work and adopted from literature can be categorized from north to south by their lithofacies into three regional groups (Fig. 1) comprising:

(1) the southern Dead Sea area between Wadi At Tayan and Wadi Al Hisa,

(2) the Fifa area between Wadi Umm Jafna and Wadi Khunayzira, and

(3) the Wadi Dana area (near the Dana Wildlife Reserve) between Wadi Ghuwayb and Wadi Dana.

Here, the Tayan Member of the southern Dead Sea area (group 1) is investigated at several localities: a small valley immediately south of Wadi At Tayan (31°08'38.7"N, 35°32'36.6"E), and at Wadi Numayri (31°06'46.1"N, 35°34'16.3"E), Wadi Qunai (31°05'36.7"N, 35°33'13.5"E) and Wadi Al Hisa (31°00'53.6"N, 35°32'01.5"E). Published data from Jabal Tabaq Hanneh (TEIMEH *et alii*, 1990) and from the northern slope of Wadi Saramuj (POWELL, 1988) are included. From the Fifa area (group 2) the Tayan Member was studied at Wadi Umm Jafna (30°56'34.0"N, 35°30'08.2"E), Wadi Fifa (30°55'36.0"N, 35°29'38.8"E) and Wadi Khunayzira (30°52'23.3"N, 35°26'30.2"E). Further information for this region comes from the 1 : 50000 geological maps (TARAWNEH, 1988, 1992). The lithological data of the Wadi Dana area (group 3) are adopted from TEIMEH *et alii* (1990) and RABB'A (1994).

The Tayan Member in the southern Dead Sea area

From this area (Al Karak map sheet; POWELL, 1988) over a distance of about 16 km (Fig. 1), three complete and one incomplete section were measured and two other complete sections were adopted from the literature (Fig. 3.1). The base of Tayan Member is a very sharp, erosional contact with the underlying coarse-grained, pebbly and distinctly cross-bedded sandstone of the Salib Formation (Figs. 5.1-5.3). The lithology enjoins a division of the Tayan Member into lower and upper portions.

The lower portion ranges in thickness from 9 to 13 m and consists of red to mauve micaceous siltstone and claystone (Figs. 5.4-5.7). In one locality, the first two decimeters are dark-grey (Wadi Al Hisa section). A distinctive feature of this lower unit is the occurrence of irregular bleached horizons and occasional intense color-mottling (Fig. 5.6). Only a few thin levels of more sandy, slightly dolomitic beds are intercalated. The sediments are dominantly massive and occasionally lel-laminated. Indications of higher energy flow were not observed.

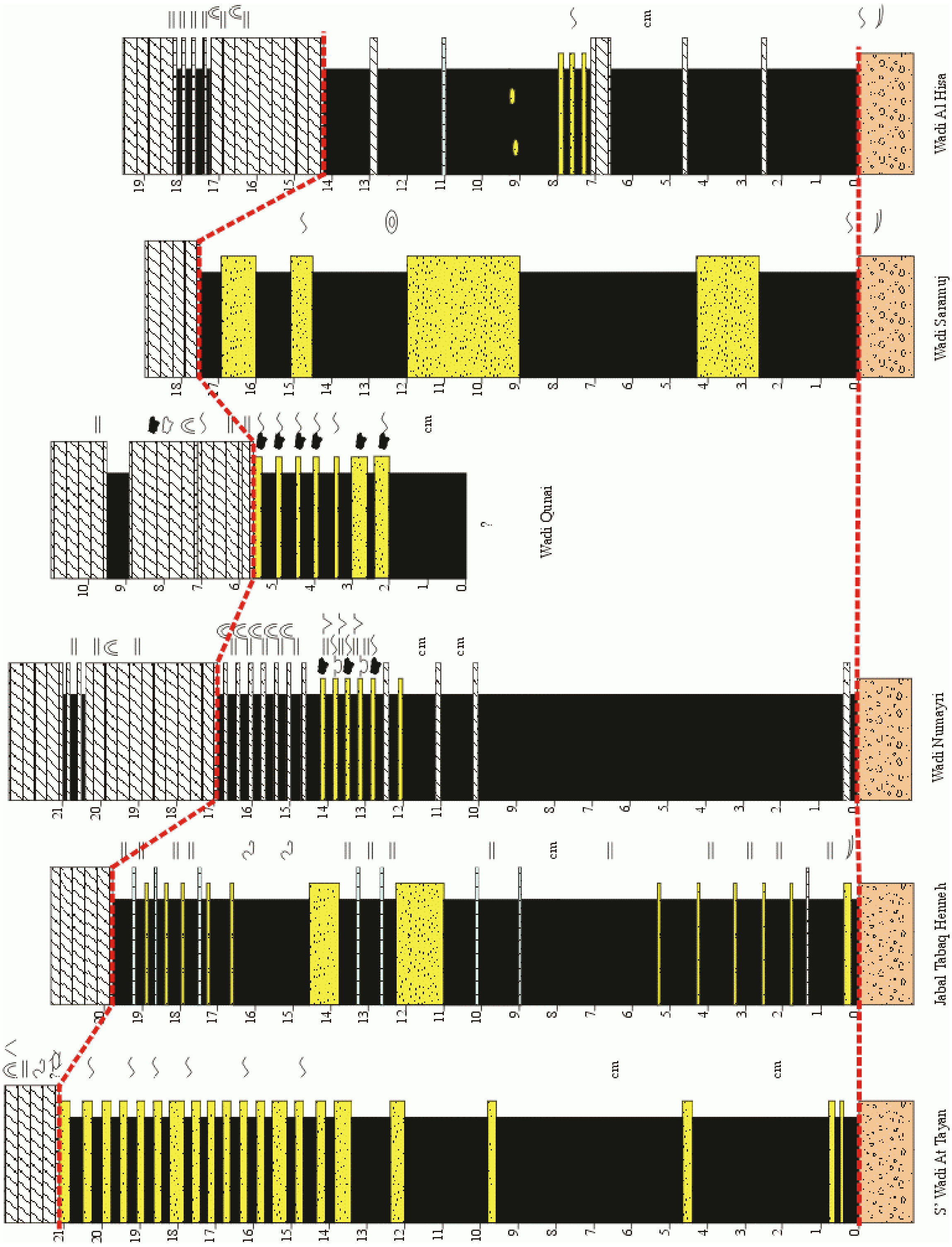


Figure 3.1: Lithological successions (weathering profiles) of the Tayan Member in the southern Dead Sea area from North (left) to the South (right). The column for the Wadi Saramuj is adopted from POWELL (**1988**). The red lines encompass the lithostratigraphically defined range of the Tayan Member.

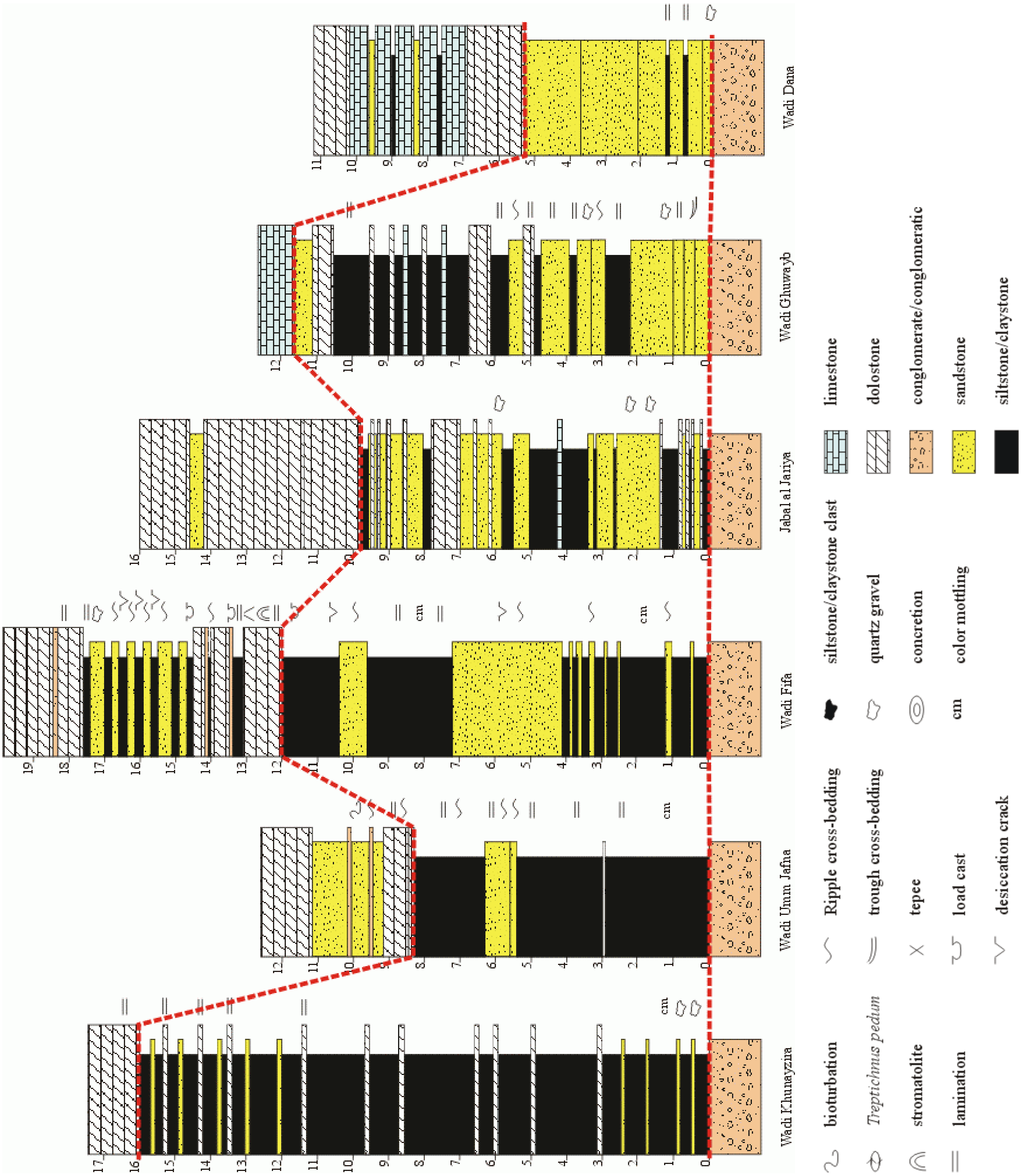


Figure 3.2: Lithological successions (weathering profiles) of the Tayan Member in the Fifa area (Wadis Khunayzira, Umm Jafna and Fifa) and in the Dana area (Jabal al Jariya, Wadis Whuwayb and Dana). The data for the Dana area are adopted from TEIMEH *et alii* (**1990**) and RABB'A (**1994**). The red lines encompass the lithostratigraphically defined range of the Tayan Member.

Over a vertical distance of a few centimeters the lithology clearly changes and marks the base of the upper portion of the Tayan member (Fig. 5.7). This upper portion is 5 to 10 m thick and characterized by the occurrence of many sandstone beds, typically as an alternation of light-colored sandstone and greenish siltstone (Fig. 5.3). The sandstone beds are commonly dolomitic and range in thickness from a few centimeters up to a few that attain several decimeters. Thinner sandstone beds show ripple cross-lamination (Fig. 6.3). In the Wadi Numayri section the lower part of the upper Tayan portion includes several of these beds with load casts, desiccation cracks and claystone clasts (Figs. 6.1-6.3), but in its upper part thin dolostone beds and stromatolites are more common. Sometimes these dolostones have no internal structure, but are sandy and show lithological gradations into dolomitic sandstone. In the Wadi Qunai section (Fig. 3.1) green claystone clasts are common in the sandstone beds of the highest part of the Tayan Member. TEIMEH *et alii* (1990; Fig. 3.1) report indeterminate trace fossils from these levels in the Jabal Tabaq section. POWELL (1988) mentions the occurrence of some sandstone lenses in the claystone/siltstone succession of a section on the northern slope of Wadi Saramuj (Fig. 3.1).

In all of the sections, the Tayan Member is overlain by a thick bed of laminated, somewhat sandy dolostone (Figs. 3.1 and 6.1) with stromatolitic levels and in few cases with tepee structures (south of Wadi At Tayan). Often, this first thick carbonate horizon is followed by a final siltstone intercalation, similar petrographically to the Tayan siliciclastics below (Fig. 3.1).

The thickness of the complete Tayan Member in the area ranges between 17 and 21 m, with the exception of the Wadi Al Hisa section where it is about 14 m.

The Tayan Member in the Fifa area

In the Fifa area (At Tafila and Fifa map sheets; TARAWNEH, 1988, 1992), the Tayan Member was investigated at three localities over a straight line distance of about 10 km (Figs. 1 and 3.2). The lithologic divisions of the member are the same as those in the southern Dead Sea area: a reddish, massive to parallel laminated lower portion and a greenish, ripple cross-laminated upper portion. Also the occurrence of bleaching spots and color-mottled beds in the lower portion and of load casts and desiccation cracks in the upper part is repeated. From the Tayan Member of Wadi Khunayzira (Fig. 3.2), BENDER (1968) figured halite-pseudomorphs (for which the exact lithostratigraphic level is not given). In the Fifa area the main difference from the southern Dead Sea sections is a greater abundance of sand in the lower portions of the Wadi Fifa and the Wadi Khunayzira sections (Fig. 3.2). Occasionally, the lowermost part of the Wadi Khunayzira section contains quartz pebbles up to a cm in diameter of the same type as those in the underlying Salib Formation. At the upper limit of the member, the first carbonate intercalation (which marks the lithostratigraphic boundary of the overlying Numayri Member) is not as thick (about 1 m) as it is in the southern Dead Sea area. This intercalation is mainly laminated dolostone showing tepee structures (Wadi Fifa) and is followed by a prominent coarse-grained siliciclastic unit, which is either a thick sandstone (Wadi Umm Jafna) or an alternating sandstone-siltstone (Wadi Fifa), both with two mature micro-conglomeratic horizons in the lower half (Fig. 3.2). These conglomerates have variable thicknesses of up to 25 cm and consist almost entirely of slightly altered, rounded, quartz pebbles with diameters up to 5 mm in a dolomitic matrix (Fig. 5.8). Near the top of the sandstone-dominated unit quartz pebbles reappear, but they do not form a conglomerate. Ripple cross-lamination and bioturbation, and in the Wadi Fifa section desiccation cracks and trace fossils too, are present in this uppermost sandy portion of the Tayan Member.

The total thickness of the Tayan Member is 12 m at Wadi Fifa and 16 m at Wadi Khunayzira; the Wadi Umm Jafna section is incomplete. If the characteristic upper sandstone-siltstone alternation described above (Fig. 3.2) is regarded as a unit of the Tayan Member, the thickness of the Tayan is on the order of 16–17 m. Graphic columns of the explanations from the 1 : 50000 geological maps give the thicknesses of the Tayan Member as 20 m (TARAWNEH, 1992, for the Fifa map sheet) and as nearly 30 m (TARAWNEH, 1988, for At Tafila map sheet). These measurements are not in accord with those of this author.

The Tayan Member in the Wadi Dana area

Geological documentation of the Cambrian of this area that includes the Tayan Member was published by TEIMEH *et alii* (1990) and RABB'A (1994). Three sections were measured by these authors at Jabal Al Jariya, at Wadi Ghuwayb, and at Wadi Dana (Fig. 3.2). The distance between the two northern sections is about 4 km; the Wadi Dana section is located about 13 km south-southeast (Fig. 1).

The published data show that the siltstones, sandstones and dolostones of Wadi Dana are correlative with the lithologies of the areas farther north, but the sand content of the Tayan Member is clearly enriched. Several levels contain quartz-pebbles, but no true conglomerate occurs. Generally, the siltstones are laminated, whereas the (dolomitic) sandstone beds often show small-scale trough cross-bedding. In the lowermost portion of the Wadi Ghuwayb section TEIMEH *et alii* (1990) report granitic clasts in cross-bedded sandstone. The same authors mention limestone clasts in a breccia at the base of the Tayan Member at Wadi Dana. In all three sections the boundary between the Tayan and the overlying Numayri Member is marked by a thick, sandy dolostone immediately above the clastic succession (Fig. 3.2). In complete sections in the area (e.g. at Jabal Al Jariya and Wadi Ghuwayb) the Tayan Member is noticeably thinner (10 to 11.5 m) than it is farther north (the Wadi Dana section is incomplete).

3.2. Paleontological aspects

Body fossils are unknown from the Tayan Member. Extensive investigation of this member at all localities described here have not been successful in finding any. Interestingly, KING (1923; cited by BENDER, 1968, 1974, and by TARAWNEH, 1988) reported trilobite fragments from "green micaceous mudstone" (siltstone) at Wadi "Rimeileh" (= Wadi At Tayan after RUSHTON and POWELL, 1998). For some of these remains KING proposed an asaphid character. PARNES (1971) suggested a taxonomic affiliation to ?*Myopsolenus*. ÖPIK (1975) revised this affiliation to *Myoposolenites* and RUSHTON and POWELL (1998) interpreted the fragments as *Onaraspis*. Subsequently, GEYER and LANDING (2004) discussed their taxonomy in detail reassigning them to *Myopsolenites*. During the course of this study disarticulated trilobite remains of precisely the same character were seen in similar green micaceous siltstones and sandstones of the Hanneh Member in the Wadi Issal outcrops which are close to KING's locality (publication in progress). In the Numayri carbonates at the Wadi At Tayan/Wadi Uhaymir section such trilobite remains occur too, but in marly carbonate, not siltstone. Thus, KING's trilobite-bearing mudstone cannot be from the Tayan Member but is probably correlatable with the stratigraphically younger Hanneh Member. Indications of biotic activity within the Tayan Member exist in its upper portion and include: (1) trace fossils and bioturbation, (2) stromatolitic layers and (3) cloud-shaped bleached levels (color-mottling).

The occurrence of indeterminate trace fossils in the Tayan Member was reported from the southern Dead Sea area by TEIMEH *et alii* (1990, Jabal Tabaq Hanneh section). With regard to the siliciclastic lithologies of both the Tayan and the Hanneh members, POWELL (1989) stated that "Trace fossils, including circular, horizontal to sub-vertical burrows and *Rusophycus* (...), are common on some of the bedding planes in the Tayan and Hanneh members". For these two members RUSHTON and POWELL (1998) reported "an ichnofauna characteristic of shallow-water environments, including the arthropod resting and crawling traces *Rusophycus* and *Cruziana*". Our extensive observations from about 15 sections including all members of the Burj Formation indicate that *Rusophycus* and *Cruziana* are found only in the Numayri and Hanneh Members, not in the Tayan Member.

Near the base of the Tayan Member at Wadi Qunai (at some distance from the measured section) is a fine-grained sandstone bed with simple trace fossils and the ichnotaxon *Treptichnus pedum* (Figs. 4 and 6.8). The traces are on the bedding plane. They consist of tubes about 2 mm in diameter. These string-like traces show a clear separation of the tube into distinct segments. *Treptichnus pedum* chains follow a variable, but more-or-less curved to circular course.

Indeterminate surface burrows and bioturbation have been reported on some bedding planes in the Tayan Member. TEIMEH *et alii* (1990) recorded these structures from the upper portion of the member in the southern Dead Sea area (Jabal Tabaq Hanneh). Immediately above the first significant carbonate intercalation (a laminated, sometimes somewhat sandy dolostone, see chapter 3.1), distinctly bioturbated horizons occur in the sections south of Wadi At Tayan and at Wadi Qunai (southern Dead Sea area) as well as in the Fifa area (Fig. 6.7). Most of these simple traces (hyporeliefs), which may be very abundant on bedding planes, are single tubes parallel to the bedding plane with no surface structures (Fig. 6.6), but in some, short probes branch from the tube (?*Treptichnus*). Commonly, discrete generations of tubes cross each other. The diameter of the burrows is up to 3 mm.

Stromatolite carpets are well-developed in the uppermost Tayan Member of the Wadi Numayri section (southern Dead Sea area). The mats occur in grey laminated dolostones that alternate with grey, parallel-laminated siltstones (Fig. 3.1). The thicknesses of these bioconstructions are but a few centimeters. In all the sections from the southern Dead Sea area (Fig. 6.5) other stromatolite beds with thicknesses up to about one decimeter occur in the first carbonate intercalation (laminated dolostone, see chapter 3.1) immediately above the Tayan Member (Fig. 6.5). At this lithostratigraphic level low dome-shaped stromatolite heads and carpets occur. Farther south, only in the Wadi Fifa section do rare stromatolitic structures exist at a comparable level.

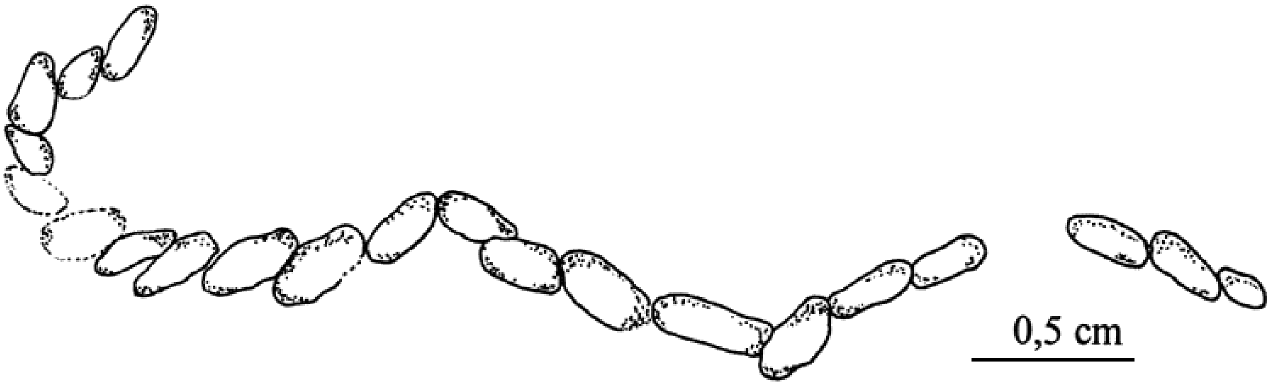


Figure 4: Line drawing of the ichnotaxon *Treptichnus pedum* from the lower portion of the Tayan Member at Wadi Qunai. The drawing is of the hand specimen shown in **Fig. 6.8**.

Color-mottling is a common phenomenon in the Tayan Member of all the sections studied. (Figs. 3.1 – 3.2). Because it may be related to microbial activity (see discussion below) these phenomena are mentioned here. Color-mottling consists mainly of light greenish- to ochre-colored, cloud-shaped, irregular bleached horizons and spots within mauve to red siltstones (Fig. 5.6). The transition into underlying and overlying red to mauve lithologies is gradational and irregular, although the lower transition looks more frayed than the upper and the density of the bleached areas increases upward. Color-mottling is restricted to the lower portion of the Tayan Member. The few color-mottled horizons attain a maximum thickness of about 25 centimeters, but most are narrower.

4. Discussion

4.1. Paleoecological interpretation

An interpretation of the paleoecological conditions that existed during deposition of the Tayan Member requires consideration not only of its paleontology and sedimentology, but also of the character of the surface on which the transgression occurred. Useful information comes from regional variation in the facies of the higher Tayan Member and the changes exhibited during the transition to the overlaying Numayri Member including the first Numayri carbonates. Depending on the geographical location of sections, changes in the lithology and thickness of the Tayan Member are more or less conspicuous. In the three regions investigated here (southern Dead Sea, Fifa, Wadi Dana; Fig. 1) the successions thin southward (Figs. 3.1 – 3.2). As reported by BENDER (1968) the southernmost occurrence of the Burj

Formation is at Wadi Moghata, several kilometers south of the Wadi Dana area. Farther south the Precambrian basement was higher paleotopographically and the Burj Formation thins in this direction (POWELL, 1989; AMIREH *et alii*, 1994; GEYER and LANDING, 2000; BANDEL and SHINAQ, 2003). Facies equivalent siliciclastic sediments of continental, fluvial and intermittently of marginal-marine origin occur southward as far as southern Jordan.

In the southern Dead Sea area, there is a notable differentiation in the Tayan Member between a lower, reddish, rather fine-grained unit and a contrasting upper, greenish and coarser-grained portion. To the south this differentiation is not as apparent (Fifa area) and is absent in the Wadi Dana area. Siliciclastics are generally coarser-grained in the same direction. In the Fifa and Wadi Dana areas, quartz gravels in the siltstones and thin, mature quartz conglomerate beds indicate a rather proximal position during their deposition. Such a facies differentiation is also apparent in the underlying, mostly braided fluviatile Salib Formation (MAKHLOUF, 2003). The transition of the youngest, distinctly cross-bedded strata of the Salib Formation into the overlying parallel-laminated lower Tayan Member is always sharp and the contact is erosional (Fig. 5.3). The absence of a transgressive conglomerate suggests a rapid marine flooding on an unconsolidated surface. Nevertheless, as reported by POWELL (1989) and MAKHLOUF (2003), the occurrence of a few marine trace fossils at several levels in the Salib Formation indicates some minor marine ingression before this clearly defined transgression. So, the flooding can be characterized as initially oscillatory, but subsequently rapid in the main phase.

During investigation of the sections of the lower Tayan Member determinable fossils were found only in the Wadi Qunai section: the trace fossil *Treptichnus pedum* occurs there accompanied by indeterminate simple surface traces (see above). Although JENSEN (1997) interpreted this ichnotaxon as the shelter construction of a surface deposit-feeder, most authors assume that it is the fodinichnid feeding burrow of a worm-like, probably undermat miner (SEILACHER, 1955; BANKS, 1970; CRIMES *et alii*, 1977; GEYER and UCHMAN, 1995; DZIK, 2005; SEILACHER, 2007). The sedimentary environment where the *T. pedum* animal created its traces is commonly interpreted to have been intertidal or shallow subtidal (BRYANT and PICKERILL, 1990; GEYER and UCHMAN, 1995; HAMDI, 1995).

The color-mottling at some levels of the lower Tayan Member may be another indication of early biotic activity as well as of low energy. In the geological literature there are many references that interpret color-mottling as an early stage of soil formation and/or early groundwater diagenesis. Paleosols are usually identified by a combination of textural, organic, and stratigraphic features (WRIGHT, 1986; GERRARD, 1992; READING, 1996; MEYER, 1997). For pre-Devonian successions, however, such indications are problematic because of the primitive level of plant evolution (e.g. absence of the roots of vascular plants). If the sediments are red as they are in the Tayan Member, any content of organic carbon is lost due to subsequent oxidation. The typical patchy bleaching concentrated in discrete horizons of the clay-enriched lower Tayan lithology along with their gradational transition downward to the red state may indicate pedogenesis and so to episodic non-deposition in exposed areas.

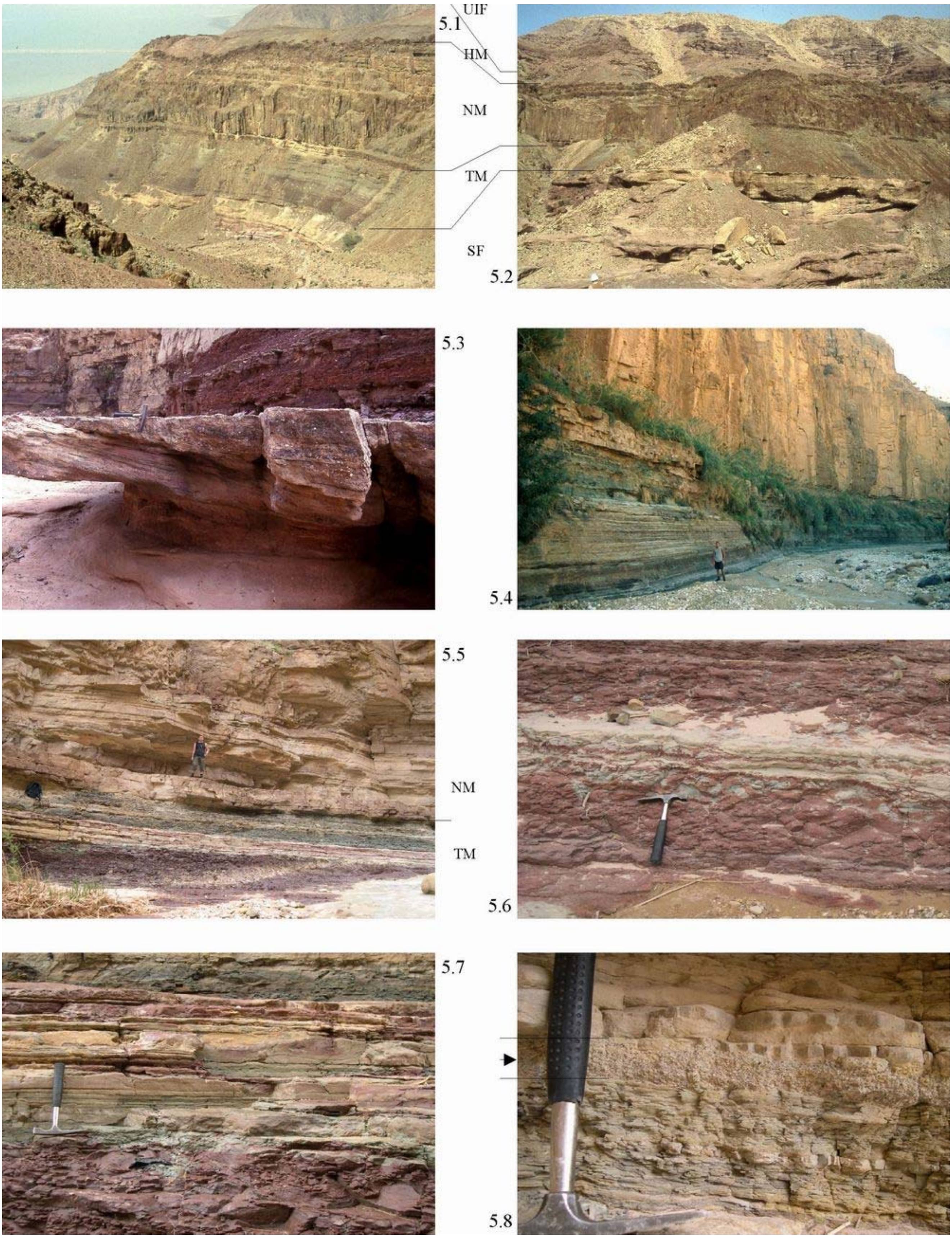
The fossil content and sedimentary features of the upper portion of the Tayan Member indicate quite different environmental conditions for these strata. Larger quantities of sand and a greater number of sandstone beds, the occurrence of pebbles of claystone and siltstone in some of the sandstones along with common ripple cross-lamination, and occasional scour structures indicate a higher depositional energy than that of the lower portion of the Tayan Member. Load casts in some horizons indicate rapid sedimentation (OELE, 1964). The upper Tayan Member can be interpreted as having been deposited in a very shallow and intermittently exposed environment. This explication is supported by multiple levels of desiccation-cracks (Fig. 6.1). Bioturbation (Figs. 6.6-6.8) indicates the environment as a suitable habitat for endobentic, probably worm-like organisms, when flooded. Intercalations of beds of dolostone are more common in the almost always dolomitic sandstones of the upper Tayan Member. In the higher portion at Wadi Numayri layers of stromatolites occur in rhythmically intercalated dolostone beds. All these features, together with reported halite-pseudomorphs (BENDER, 1968: plate-figure 54) indicate a tropical to subtropical aridity and a sabkha-related environment. This interpretation is consistent with the palaeogeographic reconstructions of SHARLAND *et alii* (2001) that place Jordan at less than 30° south in palaeo-latitude. Stromatolitic dolostones with occasional tepee-structures cap the Tayan Member. These basal Numayri carbonates indicate the persistence of these climatic conditions until the stage of maximum flooding.

Paleoecologically, in Tayan times in Jordan the environment can be interpreted as having been supratidal to intertidal and rather unstable, with episodes of flooding and drying and of fluctuating salinity. This is concomitant with the mass-occurrence of rather simple infaunal pioneers in discrete horizons (bioturbation by r-strategists) as well as the absence of the higher taxa usually found in marginal-marine habitats at this time (e.g. arthropods).

4.2. Regional comparisons

The Cambrian Burj Formation of Jordan is comparable in origin and aspect with approximately coeval strata in eastern and southern Israel. The existing north-south alignment of the deposits on the west and east sides of Wadi Araba extends about 100 km (Fig. 1). They are so distributed as the result of dislocation by the "Dead Sea Transform". Correlation of the stratigraphy and facies of the two areas has already been discussed by SEGEV (1984), SOUDRY and WEISBROD (1995), RUSHTON and POWELL (1998), GEYER and LANDING (2000, 2004), and LIÑAN *et alii* (2003). All agree that both regions are in the same paleogeographic sector of the Arabo-Nubian Shield. The relatively short marine incursion in Jordan is recorded by the Burj Formation, and in Israel is represented by the Timna Formation. The Tayan Member, indicative of the main transgression, finds its lithostratigraphic equivalent in the Hakhlil Member of the lower Timna Formation of Israel (SOUDRY and WEISBROD, 1995). Although parts of the Hakhlil Member show a low energy lithofacies (siltstones, thin sandstone beds, halite-pseudomorphs, *etc*.; Fig. 6.4), like those of the Burj Formation, well marked differences exist in other portions of the Timna Fm: channel-filled sandstones and grits indicate a high erosional energy. In contrast to its Jordanian facies equivalent, the youngest strata of the Hakhlil Member contain body fossils (e.g., *Myopsolenites palmeri*) and related arthropod tracks (GEYER and LANDING, 2000). *M. palmeri* is reported by RUSHTON and POWELL (1998: as "*Onaraspis*") from the Wadi At Tayan region of the Jordanian southern Dead Sea area (the "asaphid" trilobite of KING, 1923, see above).

▶ **Figures 5:** Outcrops and sedimentary characteristics of the Tayan Member. **5.1** – complete section of the Burj Formation north of Wadi Numayri (Jabal Tabaq Hanneh, southern Dead Sea area; SF – Salib Formation, TM – Tayan Member, NM – Numayri Member, HM – Hanneh Member, UIF – Umm Ishrin Formation). **5.2** – complete section of the Burj Formation at Wadi Qunai (southern Dead Sea area), note the intensive trough cross-bedding in the uppermost Salib Formation (abbreviations as for 5.1; man bottom left for scale). **5.3** – erosional lower boundary of the Tayan Member on top of cross-bedded conglomeratic Salib Formation at Wadi Al Hisa (southern Dead Sea area; hammer for scale). **5.4** – upper portion of the Tayan Member (sandstone-siltstone alternation) and upper boundary to the Numayri Member (massive carbonates) at Wadi Numayri (southern Dead Sea area; man for scale). **5.5** – transition Tayan Member / Numayri Member at Wadi Fifa (Fifa area), note the characteristic change of color within the upper portion of the Tayan Member (man in the center for scale). **5.6** – massive siltstone to claystone of the lower portion of Tayan Member at Wadi Fifa (Fifa area) with characteristic color mottling (hammer for scale). **5.7** – transition from lower (massive siltstone to claystone) to upper portion (rippled sandstone dominated) of the Tayan Member at Wadi Fifa (Fifa area; hammer for scale). **5.8** – intercalation of a mature quartz-conglomerate in the transition interval Tayan Member / Numayri Member at Wadi Fifa (Fifa area; hammer for scale).


UIF
5.1
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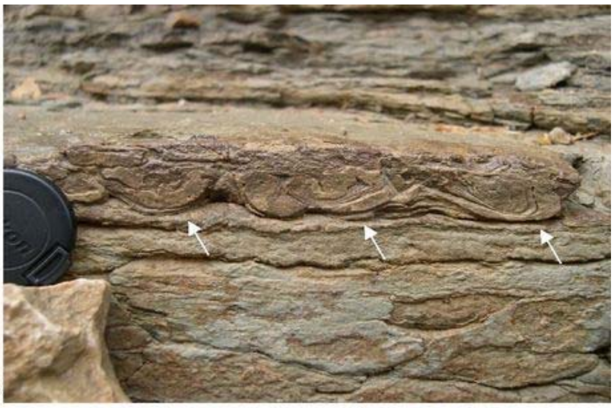
During recent investigations the formerly imprecisely reported localities and the lithostratigraphic levels of *Myopsolenites* were firmly established in the Wadi At Tayan/Wadi Uhaymir and Wadi Issal sections. At the first-mentioned site the fossil locality is in the upper part of the Numayri Member; the second is in the much younger Numayri-Hanneh transition interval. It cannot definitely determined if the occurrences of *M. palmeri* at discrete, widely separated lithostratigraphic levels – in Israel below the carbonate member and in Jordan above the carbonate member - reflect a facies relationship to an open marine, well agitated, siliciclastic environment, or merely that this taxon rather has a relatively long biostratigraphic range. Considering the thickness of the carbonate suite in the southern Dead Sea – Timna area (50 m to 80 m), the preferred interpretation is that the occurrence of this trilobite is related to a sedimentary facies of which the occurrences are diachronous.

As indicated above, the character of both sedimentary and bio- facies indicate that the marine transgression in Jordan was a low energy event with at least one probable minor earlier ingression. The Tayan Member was laid down on an unaccidented surface on which braided rivers had infilled a pre-existing paleorelief (Salib Formation; AMIREH *et alii*, 1994; GEYER and LANDING, 2000; MAKHLOUF, 2003). This type of low-energy sedimentation and the mode of its eventual flooding differs greatly from another more prevalent type of transgression: this one reflects a high energy environment, that is typical in the upper Lower–Middle Cambrian of this paleogeographic segment of Gondwana. Examples are the successions of the Cantabrian Mountain ranges (northwestern Spain) and the central Taurids (Anatolia, Turkey). Rather high energy and commonly channel-dominated siliciclastic successions pass upward under arid sub-equatorial conditions into shallow-marine carbonates. In the Cantabrian Mountains several kinds of channel-associated environments are reported in the Herrería Formation (tidally influenced bar and channel deposits, fluvial channels, *etc*., locally with some pedogenesis; OELE, 1964; BOSCH, 1969; LIÑAN *et alii*, 2002; ÁLVARO *et alii*, 2003; personal observations). In the central Taurids the continental-to-marine transition is represented by the gradation of the Hüdai Formation into the Cal Tepe Formation (BRINKMANN, 1976; GÖNCÜOĞLU and KOZLU, 2000; GÜRSU *et alii*, 2004). The Hüdai Formation includes high energy siliciclastic beach deposits in the upper levels and well-marked conglomeratic fluvial channels in the lower portion (DEAN and ÖZGÜL, 1994; GÜRSU pers. comm., 2006; ELICKI *et alii*, 2007a and b). The high-energy facies of the lower Hakhlil Formation in Israel resembles these examples (whereas the Hakhlil low-energy facies is similar to the Jordanian Tayan Member). Paleoecologically, the high energy, marginal-marine transgressive tracts usually contain trilobite body fossils and related traces. It is unlikely this difference in biofacies from that of the low energy Tayan siliciclastics is taphonomic, for at least in the upper Tayan Member some rapid deposition is indicated (see above) so biotic remains would have been buried rapidly. In those beds typical arthropod trace fossils should have survived diagenesis. In addition to the strongly limited diversity in trace fossils of the Tayan Member, its other depositional features suggest restricted and unsuitable habitats (no "fossils" other than stromatolites, halite-pseudomorphs, *etc*.).

▶ **Figures 6:** Outcrop conditions and sedimentary characteristics of the Tayan Member. **6.1** – desiccation cracks in several horizons (arrows) of the upper Tayan Member (Wadi Numayri, southern Dead Sea area; hammer for scale). **6.2** – load casts (arrows) in the upper Tayan Member at Wadi Fifa (Fifa area; lens cap: 4 cm). **6.3** – ripple cross-lamination in the upper Tayan Member at Wadi Numayri (southern Dead Sea area; lens cap: 4 cm). **6.4** – halite-pseudomorphs from Hakhlil Formation (Timna, Israeli side of Wadi Araba) which is equivalent to the Tayan Member from where BENDER (**1968**) has reported them (lens cap: 4 cm). **6.5** – stromatolites at the transition Tayan Member / Numayri member (Wadi Qunai; hammer for scale). **6.6** – indeterminate simple trace fossils from the transition Tayan Member / Numayri member (south of Wadi At Tayan; lens cap: 4 cm). **6.7** – intensive bioturbated beds of the upper Tayan Member at Wadi Fifa (Fifa area; lens cap: 4 cm). **6.8** – trace fossil *Treptichnus pedum* from the lower Tayan Member at Wadi Qunai (southern Dead Sea area; length of the pictured segment of lens cap: 3 cm).


6.1


6.2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6.8

The two principle types of land-sea transitions during the late Early to Middle Cambrian transgression of the Middle East and the Mediterranean are best related to the topography of the flooded ground and that of the continental hinterland along with the type of climate. These factors triggered and continued to exert a strong influence on the development and location of facies belts and paleoecological conditions in the areas of deposition. During the Cambrian transgression on the northwestern edge of the Arabo-Nubian shield the interplay of local morphology and regional climate led to steep facies gradients and to unstable ecological conditions (salinity, food, sediment supply, *etc*.). In contrast to the high-energy transitional environments elsewhere, the Jordanian low-energy milieu appears to have been paleoecologically more stressful as indicated by the low biotic diversity and by the occurrence of rather simply organized r-strategists.

4.3. Positioning of Jordan in the tectonic setting and sequence models of the Arabian Plate

According to SHARLAND *et alii* (2001) the Cambrian processes discussed in this paper are in the second of eleven tectono-stratigraphic megasequences in the evolution of the Arabian plate that are grouped into five tectonic phases. The pertinent tectonic phase encompasses the late Precambrian to Late Devonian interval and is characterized by a largely passive marginal setting in low to moderate southern latitudes after the assembly of an Arabian plate and the initiation of a triple-junction regime that includes the Dead Sea Rift valley. Within this tectonic phase, from Early Cambrian up to Late Ordovician times the megasequence was characterized by extension, subsidence and mild uplift. Both the lower and upper boundaries are marked by strong erosional unconformities not only in Jordan, but in the whole circum-Arabian realm. SHARLAND *et alii* (2001) state that this megasequence consists of two second order transgressive-regressive depositional sequences. One spans the interval of time from about the Middle Cambrian to the Arenigian; the other from the Llanvirnian to the Ashgillian. SCHNEIDER *et alii* (2007) conclude from extensive field work mainly in southern and southwestern Jordan that the Lower Cambrian Salib Formation represents deposition in a lowstand system (Panafrican molasse) followed by marine sandstones and carbonates of a transgressive system tract (early and middle Burj Formation). They consider maximum flooding to have occurred during the deposition of clastics above Lower Cambrian strata followed by the highstand system deposits of the Umm Ishrin Formation. This general pattern of deposition can be followed from Jordan into Syria and Iraq. The Middle to Late Cambrian successions of Saudi Arabia, Bahrain, and Qatar are exclusively clastic, but resemble somewhat that of the Dead Sea Rift valley (SHARLAND *et alii*, 2001). Consequently, the factors of controlling the overall evolution of the shelf must, on the largest scale, be considered as eustatic changes in sea-level. Nevertheless, the lithological and paleoecological differences between the areas mentioned are interpreted here as having been caused by local and regional factors as discussed above. The earlier mentioned wave and tidal factors influenced significantly the sedimentary structures as well as the succession of facies. The sediments and biota of the Tayan Member of the lower Burj Formation demonstrate that the Tayan Member is part of a wide-ranging transgressive system tract that began at the change in facies coincident with the Lower to Middle Cambrian boundary interval in the circum Arabo-Nubian shield.

5. Conclusions

The transgressive Tayan Member of the upper Lower to Middle Cambrian Burj Formation was investigated at several sites in the Dead Sea Rift valley (Wadi Araba and southern Dead Sea area). In the southern Dead Sea area the member can be divided into a lower and an upper portion. The lower one consists of massive and parallel-laminated siltstones with few and thin sandstone intercalations, both mainly red in color. There are indications of intermittent early pedogenetic processes, indicative of some stagnation during a transgression. The lithologies of the upper Tayan Member are dominated by light-colored and green sands and sandstones with dolomite beds in the upper part. Sedimentary features as ripple cross-lamination, indications of intrastratal ero-sion, and claystone/siltstone clasts denote that energy was higher than it had been below. The occurrence of stromatolite lamination, of desiccation cracks, of halite-pseudomorphs, and of tepees, together with the sedimentary structures led to an interpretation of the environment of deposition as having been shallow intertidal to supratidal and sabkha-related in a climate of tropical to subtropical aridity.

Regional trends in the lithology and thickness of the sedimentary succession indicate a transgression from the northwest. The Tayan Member rests on an erosional surface, but no basal transgressive conglomerate exists. Its absence is taken to have been due to a rather rapid flooding of an unconsolidated, nearly plane surface without significant topography.

Paleoecologically, the Tayan Member represents deposition under restricted conditions. The only fossil content is trace fossils of simple, endobentic, worm-like r-strategists more abundant in some horizons. *Treptichnus pedum* is recognized for the first time near the base of the member. No other traces or body fossils have been found. This markedly reduced biodiversity, together with sedimentological data indicate a strongly stressed, unstable habitat, unsuitable for the biota that are the common denizens of Cambrian marginal-marine sediments.

In addition to this type of transgressive facies, another existed in this paleogeographic segment of Gondwana at that time: high-energy siliciclastics with extensive channel deposits and a rather diverse fauna. Examples from Anatolia and Cantabria, when compared with the successions in Jordan and Israel lead to the conclusion that the main factors controlling the type of facies that developed are (1) the topography of the flooded surface and that of its hinterland, (2) the configuration of the coastline and its bathymetry, (3) the rate of subsidence and the rapidity of the transgression, and (4) climate. Whereas (1) and (2) are factors of rather local influence that cause marked changes in facies within short distances, (3) has - in addition to its local importance - a regional impact and (4) affects the whole of a climatic province. An interaction of these factors may explain the differences between the facies of the Lower Cambrian transgressive deposits of Jordan and those nearby in Israel, but also account for the general similarity of geographically distant Lower to Middle Cambrian transgressive successions of this segment of Gondwana.

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