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THE PERMIAN -TRIASSIC BOUNDARY, DEAD SEA, JORDAN: TRANSITIONAL ALLUVIAL TO MARINE DEPOSITIONAL SEQUENCES AND BIOSTRATIGRAPHY

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Abstract. The Permian to Triassic transition in Jordan is characterised by a sequence boundary underlain by red-bed, alluvial lithofacies deposited in a humid-tropical climate by low-sinuosity rivers, and overlain by shallow marine siliciclastics with thin carbonates. The low-gradient alluvial floodplain was repeatedly subjected to the development of ferralitic and pisolitic paleosols on the interfluves. In contrast, dysaerobic environments in the fluvial channels and abandoned lakes resulted in the preservation of a prolific flora of macro-plants and palynomorphs that indicate a probable range from Mid- to Late Permian age, though the abundant presence of the distinctive pollen *Pretricolpipollenites bharadwajii* indicates the youngest part of that range. Above the sequence boundary, reddened shallow-marine beds characterised by ripple cross-laminated, siltstones/sandstone with desiccation cracks and sparse surface burrows mark the initial Triassic marine transgression in the region (Arabian Plate Tr 10). These are followed by two thin limestone (packstone) beds with shallow scours and bivalve shell lags, that have yielded a low diversity assemblage of conodonts (e.g. *Hadrodontina aequabilis*) and foraminifera ("*Cornuspira*" *mahajeri*) that are interpreted as euryhaline taxa characterising the early Induan (Early Triassic). Thus the absence of body fossils and vertical infaunal burrows in the lowest marine beds may reflect low-diversity ecosystems following the Permian-Triassic extinction event, or be a result of stressed shallow marine environments. A gradational upward increase in grey, green and yellow siltstones beds accompanied by a concomitant increase in bioturbation (and infaunal vertical burrows) and thin-shelled bivalves about 15 m above the boundary indicates colonisation of the substrate under more normal shallow marine conditions perhaps indicating recovery phase following the extinction event.

Introduction

The predominantly siliciclastic Permian to Triassic succession outcropping along the northern margins of the Dead Sea, Jordan (Figs 1 and 2) was first assigned a Triassic age by Cox (1924, 1932). The biostratigraphy of this succession was subsequently refined by Huckriede and Stoppel (in Bender 1968, 1974) who recognised Scythian conodonts from limestones within the middle part of the Triassic sequence. Middle Triassic (Anisian and Ladinian) conodonts were also described from the middle and upper parts of the succession near Amman (Bandel & Waksmundzki 1985) and from north Jordan (Sadeddin 1998), but conodonts and foraminifera have not been reported from the lower part of the Triassic succession in Jordan. The lower part of the Permian to Triassic succession was assigned a Late Permian age based on palynology (Bandel & Khoury 1981); they also formalised the lithostratigraphy and further refined the biostratigraphy. Diverse, well-preserved palynomorph assemblages and the paleoenvironmental setting of these fluvial, paralic and red-bed paleosol lithofacies, were described by Stephenson & Powell (2013, 2014) enabling better correlation with similar Permian successions across the Arabian Platform such as those of the Gharif and Unayzah formations in Oman and Saudi Arabia, respectively, where they represent important hydrocarbon plays (Osterloff et al. 2004).

Stephenson & Powell (2013) related the sedimentary sequences and alluvial architecture in the Umm Irna Formation to major sequence stratigraphical events (depositional sequences) during the Mid to Late Permian (Wordian to Wuchiapingian) across the Arabian Plate, which at that time

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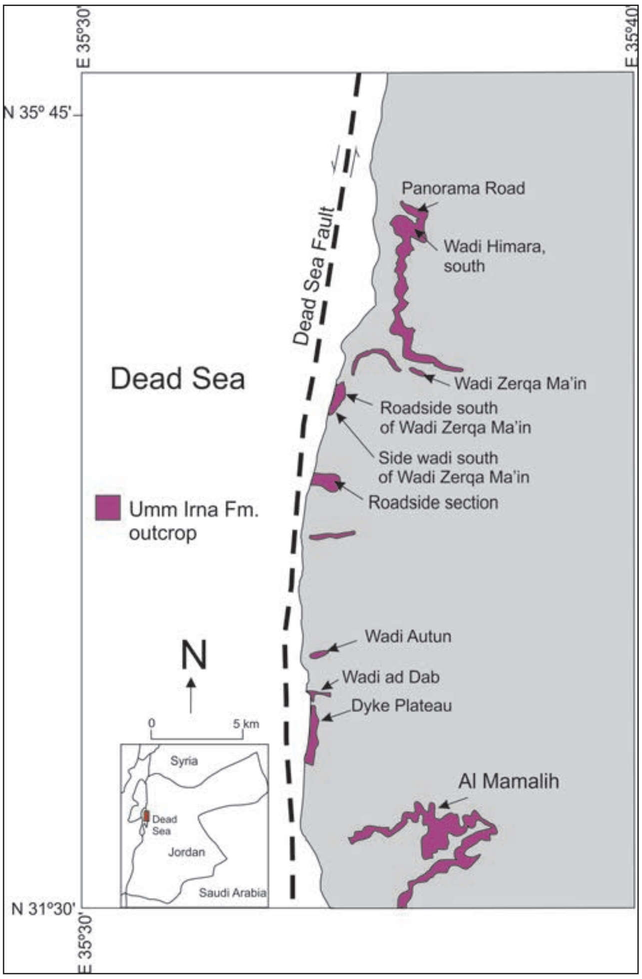

Fig. 1 - Location of the Permian to Triassic Umm Irna and Ma'in formations outcrops along the Dead Sea margins including the Dyke Plateau locality studied in this paper (based on Stephenson & Powell 2013).

was located in the equatorial zone at the southern margin of the Neo-Tethys Ocean (Stampfli & Borel 2002). The upper surface of the alluvial Umm Irna Formation is marked by a major sequence boundary (Stephenson & Powell 2013, fig. 7), overlain by shallow, red-bed marginal marine siliciclastics (Himara Member, Ma'in Formation) passing up to greenish-grey-yellow marine siliciclastics and thin carbonates (Nimra Member) (Stephenson et al. 2014).

A combination of macro-fossil data (Abu Hamad at al. 2008), palynological data (Stephenson & Powell 2013, 2014) and the new conodont and foraminifera faunas provide a better understanding of the sequence architecture and palaeoenvironmental setting of the Permian-Triassic boundary on the northern margin of the Arabian Plate and of the Lower Triassic marine faunas following the Permian-Triassic extinction event. This mass extinction is thought to have been the largest of the Phanerozoic with the loss of about 95% of marine species and 75% of terrestrial species (Shen & Bowring 2014 and references therein). A number of causative factors have been invoked ranging from Siberian flood basalt volcanism, asteroid impact, marine anoxia and euxinia, sea-level change, thermogenetic methane release and biogenetic methane release resulting from the rapid growth of a methanogenic microbe – or perhaps a combination of these scenarios. Consequently, the record and timing of this event and major environmental perturbation across the Arabian Plate is crucial to understanding both the causative mechanism and the impact on sedimentation in the region.

In this paper we describe, in detail, the transition from alluvial to marginal marine and fully marine sequences across the Permian-Triassic boundary from the southernmost outcrops adjacent to the Dead Sea shoreline. Newly discovered, thin limestones near the base of the marine Triassic succession have yielded, for the first time, a conodont and foraminiferal fauna from the lowermost Nimra Member that indicate an Induan age. We speculate on the nature of the Permian-Triassic sequence boundary and its significance in understanding the late Permian extinction and recovery of faunas during the Early Triassic transgression (Transgressive Systems Tract).

Geological setting

The Permian to Triassic sequence, in Jordan, thins southward along the Dead Sea shore below the overstepping, unconformable Lower Cretaceous Kurnub Sandstone (Wetzel & Morton 1959; Bender 1974; Moh'd 1989; Powell & Moh'd 1993; Shawabakeh 1998), wedging out just south of the Al Mamalih area (Fig. 1). North of Wadi Mujib the Permian, Triassic and Jurassic sequence becomes more complete when traced northwards along the Dead Sea - Jordan Valley outcrop, below the Cretaceous unconformity. Bandel & Khoury (1981) and Powell & Moh'd (1993) suggested that relative completeness of the Early Permian to Jurassic succession in north Jordan, as compared to the Dead Sea area (this study), is the result of steplike, northerly extensional downfaulting of this succession in preCretaceous (Kurnub) times, probably during the late Jurassic.

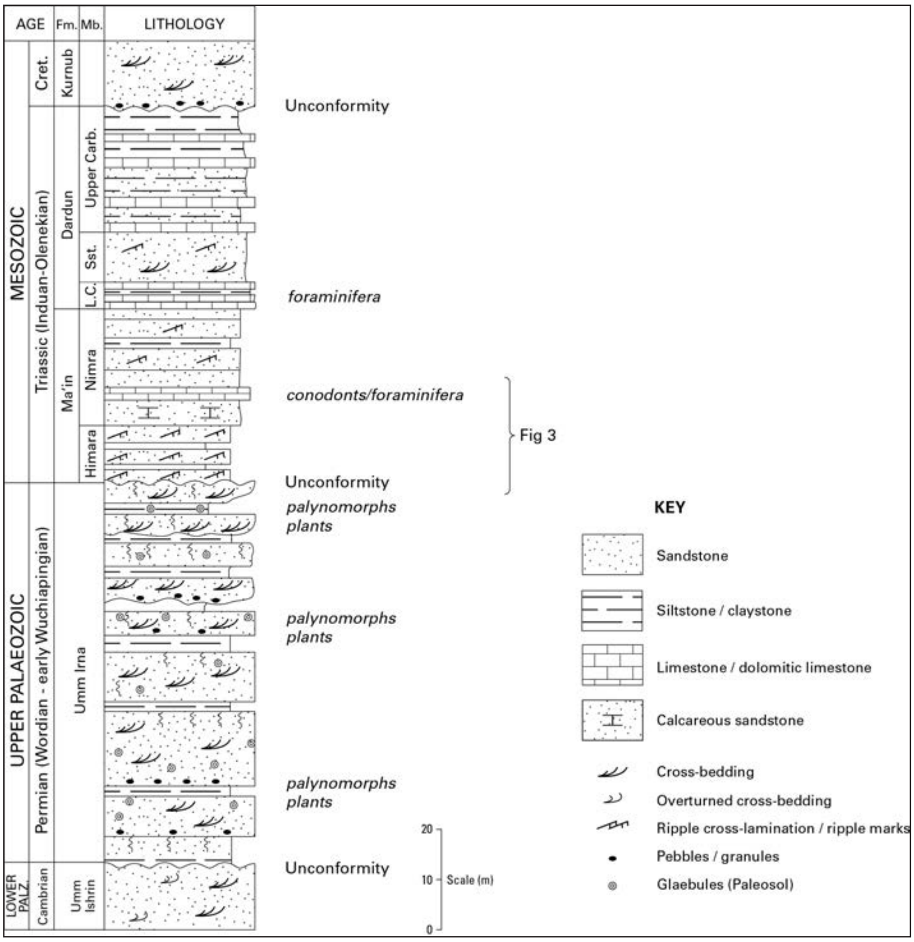

Fig. 2 - Generalised Permian to Lower Triassic succession in the study area (after Bandel & Khoury 1981). The studied section shown in Fig. 3 is shown.

The Permian Umm Irna Formation, unconformably overlies Cambrian sandstones (Umm Ishrin Sandstone Formation; Powell 1989; Powell et al. 2014) and, in turn, is overlain by the lower Triassic succession comprising the Himara and Nimra members of the Ma'in Formation and the Dardun Formation (Lower Carbonate Member of Bandel & Khoury 1981) (Figs 1, 2 and 3). We focus, here, on the uppermost Umm Irna Formation and the Himara/Nimra members (Fig. 3) exposed in cliffs and road cuttings adjacent to the Dead Sea about 10 km north of the Wadi Mujib delta. The lower (Permian) part of this transition was described and figured in detail by Stephenson & Powell (2013, plates 6, 7, 8), with special emphasis on the so-called 'Dyke Plateau' section.

The type section of the Permian Umm Irna Formation was defined by Bandel & Khoury (1981) in Wadi Himara located about 2 km east of the Dead Sea [N 31 38' 24.2"; E 35 35'05.] where it is about 68 m thick. They subdivided the formation into 6 informal units (upward fining cycles) comprising pebbly, coarsegrained sandstone, siltstone and mudstone with irregularly developed ferruginous pisolitic horizons. Paleosols with ferruginous glaebules and pisoliths are developed in the middle and upper part of the formation (Makhlouf 1987; Makhlouf et al. 1991; Powell & Moh'd 1993). Organic-rich lenses and beds comprising both dispersed mega-flora and disseminated finely comminuted plant material, charcoalified wood and immature coals are present, especially in the upper part of the formation (Uhl et al. 2007; Abu Hamad et al. 2008; Dill et al. 2010; Stephenson & Powell 2013, 2014).

Permian rocks (Hudayb Group) have also been penetrated in hydrocarbon exploration wells (North Highlands-2 and Ajlun-1) in north and north-east Jordan (Andrews 1992) indicating an arc-shaped subcrop of potential hydrocarbon source/reservoir rock in north Jordan (Naylor et al. 2013). An Early to Late Permian age was assigned to these sub-surface rocks in north Jordan, constrained in some of the wells to Kungurian (late Early Permian) to Kazanian (= Wordian; Mid Permian; Keegan et al. 1987a, b). The lowermost unit (Anjara Formation) comprises paralic and alluvial sandstones and

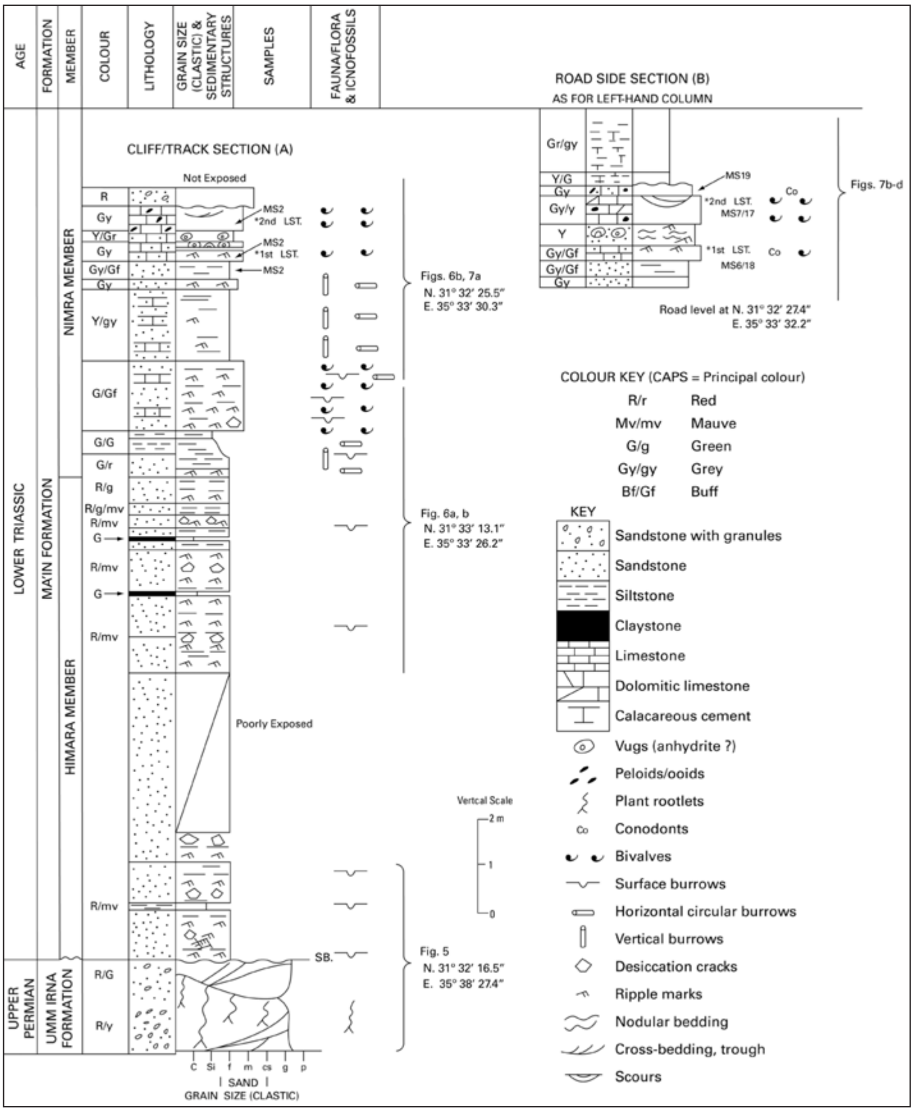

Fig. 3 - Graphic log of the Upper Permian to Lower Triassic succession in the studied Dyke Plateau section. Roadside section B is located 200 m east of the Cliff/track section A. SB is the sequence boundary between the Umm Irna and Ma'in formations. The approximate positions of Figs 5 to 7 are shown. MS indicates level of limestone samples.

mudstones with plant fossils, a similar lithofacies to the Umm Irna Formation of the Dead Sea outcrops.

West of the Dead Sea, but offset by a ca. 110 km left lateral shear on the Neogene Dead Sea Transform (Freund et al. 1970), Permian sediments were deposited in a shallow marine environment with inter-fingering fluvial siliciclastics representing the paleoshoreline in the Negev area (Eshet & Cousminer 1986; Eshet 1990).

Paleogeographic reconstructions for the Permian-Triassic interval indicate that the region lay about 15 to 20 degrees south of the paleo-equator at the northern margin of the Arabian Platform in a continental to marginal marine setting with the Neo-Tethys Ocean located to the north (Stampfli & Borel 2002) (Fig. 4). During high relative sea-level stands, marine transgressions advanced to the south and south east (Alsharhan & Nairn 1997) across the regional Hail-Rutbah Arch in the subsurface of eastern Jordan and Saudi Arabia (Sharland et al. 2001, 2004). The paleogeographical location, together with diverse and prolific macro- and micro-floras from the uppermost Umm Irna Formation, and evolved ferralitic palaeosols, indicate a humid-tropical climate (Makhlouf 1987; Makhlouf et al. 1991; Kerp et al. 2006; Stephenson & Powell 2013).

Materials and methods

Measured sections were logged at 4 localities to produce a composite section through the Umm Irna to Ma'in formations transition (Fig. 3) adjacent to the Dead Sea (Fig. 1), in order to focus on the southernmost Nimra Member where thin, laterally impersistent limestone beds are exposed. Additional sections were logged over this interval farther north at Wadi Himara, the type section of the Umm Irna Formation. Localities were recorded with a high resolution digital camera and GPS. Limestone samples for conodont and foraminiferal analysis were collected from the limestones and sandy limestones of the Nimra Member at two closely located sections: Cliff/Track Section A and Roadside Section B (Fig. 3). Palynological samples were extracted by deep excavation of the mudstone

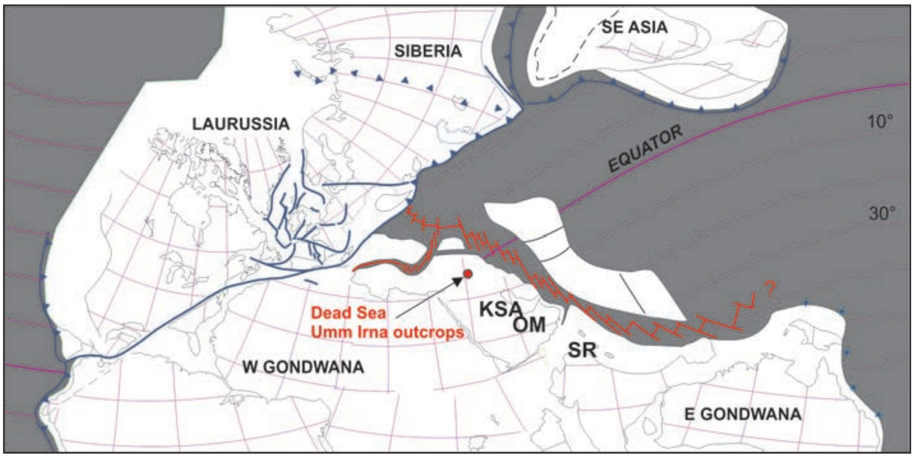

Fig. 4 - Palaeogeographical map showing the location of the Dead Sea outcrops in Late Permian time. Modified from Stephenson & Powell (2013).

and siltstone, but these proved to be barren for the Nimra Member. Palynological samples were processed as detailed in Stephenson & Powell (2013, 2014). Stained petrological thin sections of the limestones were produced for foraminiferal analysis.

Lithostratigraphy and sedimentology of the Permian-Triassic transition

Stratigraphical and sedimentological studies of the Umm Irna Formation (Bandel & Khoury 1981; Makhlouf 1987; Makhlouf et al. 1991; Powell & Moh'd 1993; Dill et al. 2010; Stephenson & Powell 2013) have demonstrated depositional environments typified by predominantly fluvial, braided to low sinuosity sandstone channels together with finer grained, red-bed interfluve sandstones and mudstones with intermittent ferruginous paleosol horizons. Organic-rich mudstones and thin immature coals (some with seatearths) are occasionally present. The overlying Triassic Ma'in Formation (Fig. 3) comprises red and green (often mottled) claystone, siltstone and fine grained sandstone (Himara Member), passing up to green, grey, buff and yellow fine-grained sandstone with thin wackestone – packstone beds (Nimra Member).

The principal lithofacies and depositional environments are summarized here; additional information on the Umm Irna Formation is outlined in Stephenson & Powell (2013).

Locality 1: Cliff/Track Section; Dyke Plateau

This composite 19.8 m section (Fig. 2), which includes the upper part of the Umm Irna Formation is located about 1.65 km south of Wadi ad Dab (Fig. 1). The upper part of the Umm Irna Formation and

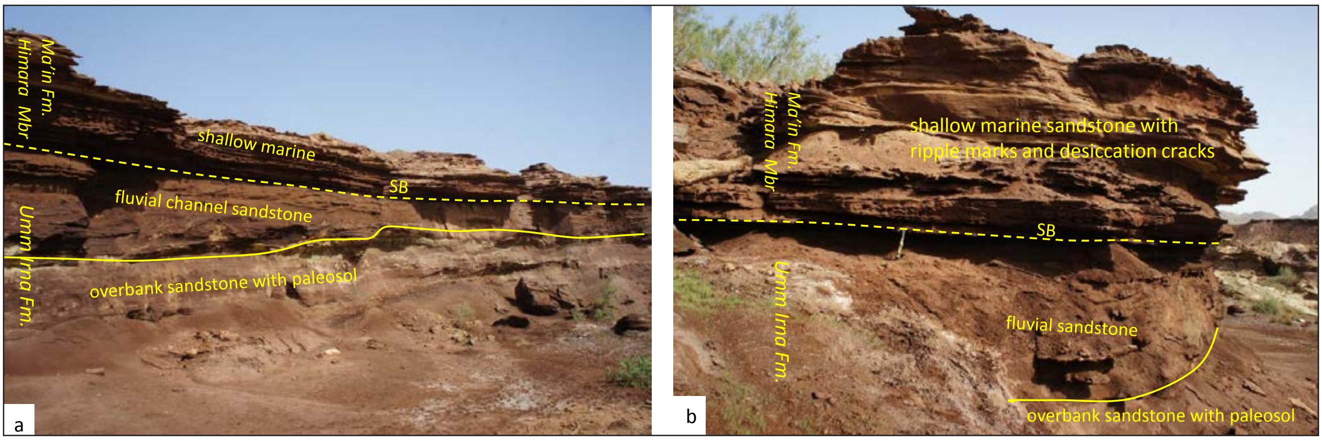

Fig. 5 - Dyke Plateau cliff. a) Sequence boundary (SB) (dashed line) separating the alluvial Umm Irna Formation from the overlying Ma'in Formation (Himara Member). Note the red-brown, cross-bedded channel fill with an erosive base (solid line) overlying pedogenically altered interfluvial sandstone, below, with sub-vertical vertisols (Umm Irna Formation); b) close up of the face approximately perpendicular to Fig. 5a. The hammer (0.30 m length) head marks the sequence boundary (SB; dashed line) between the fluvial sediments (Umm Irna Formation), below, and ripple-marked, thin-bedded sandstone (Himara Member) with desiccation cracks and faint surface burrows. See Fig. 3, Dyke Plateau cliff.

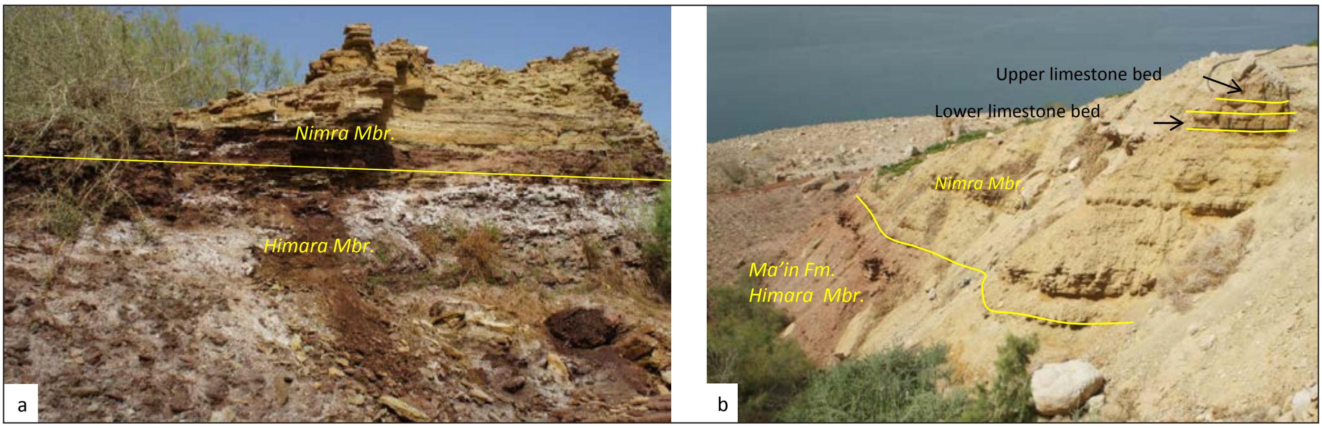

Fig. 6 - Dyke Plateau cliff. a) Gradational boundary (solid line) between the red-green, mottled Himara Member and the overlying yellow, green Nimra Member. Hammer length 0.30 m; b) transition from the Himara Member to the overlying Nimra Member also showing the position of the two thin conodont/foraminifera-bearing limestone beds; Dead Sea coast below. Height of section is approximately 16 m. See also Fig. 3.

its boundary with the overlying Ma'in Formation is well exposed along a cliff that marks a former shoreline cliff of the Dead Sea and in a number of incised east-draining wadis. The beds have gentle regional dip to the north (Fig. 5a). The composite sections, illustrated in Figs 5 and 6, extend from (N° 31 32' 13.1"; E 35° 33' 26.2"), where the boundary with the overlying Triassic Ma'in Formation (Figs 5 a,b) is exposed, to a track side locality (N 31° 32' 25.5"; E 35° 33' 30.3") shown in Fig. 7a.

Umm Irna Formation - The lower part of the main cliff section includes a predominantly red-brown, laterally accreted channel sandstone-siltstone-mudstone complex with evolved paleosols. The sections lie a few 10s of metres north of the major channel complex previously figured by Powell & Moh'd (1993, fig. 8) and in discussed detail by Stephenson & Powell (2013, plates 6, 7, 8, 9 and 10). The northern part of the cliff section is dominated by an erosively-based, fluvial sandstone channel which is exposed in three dimensions at N 31 32' 09.2"; E 35 33' 26.4". The low-sinuosity channel comprises stacked channel-fill, pebbly sandstones. Paleocurrent measurements indicate a general flow to the west-north-west and west-south-west, with a small section of the main channel unidirectional to the north-north-west (see Stephenson and Powell 2013, for details). A feature of the upper channel (Fig. 5a) is deep scouring of the base into the surrounding pedogenetically altered level-bedded, floodplain deposits (interfluves), the latter comprising mottled mudstones and siltstones with occasional glaebular, ferralitic paleosol horizons. These are characterised by red, mauve, yellow, and brown colour-mottling and the presence of granule- to pebble-size limonite and goethite soil glaebules. Locally, within the paleochannels, grey claystones and siltstones have yielded a prolific macroplant fauna and coalified logs and plant debis (Mustafa 2003; Abu Hamad et al. 2008; Stephenson & Powell 2013) that were deposited in a quiet water flow regime in both ox-bow lake clay plugs and on point-bars during waning current flow. Desiccation cracks and deep vertisol paleosol horizons are present (Figs 5a, b). The uppermost beds immediately below the sequence boundary (SB1) at this locality comprise red-brown, trough cross-bedded sandstone (Figs 5a, b).

Ma'in Formation; Himara Member - A marked sequence boundary (SB) separates the Umm Irna Formation from the Himara Member (Figs 5a, b). The boundary can be traced as a planar surface separating red-bed alluvial sediments below, from reddened shallow, marginal marine sediments above. Traced over 1 km southwards along the Dyke Plateau section the SB overlies a variety of alluvial lithofacies (e.g. channel; overbank; evolved paleosol). The beds above SB are also reddened, but consist of shallow marine lithofacies characterised by fine-grained, ripple-marked siltstone and sandstone with slightly sinuous and straight crested wave ripples on most surfaces, abundant desiccation cracks and faint surface burrows. Ripple crests are predominantly orientated NW-SE. Interbeds of red-mauve, and green siltstone and claystone are also present, but the colours become more gre-

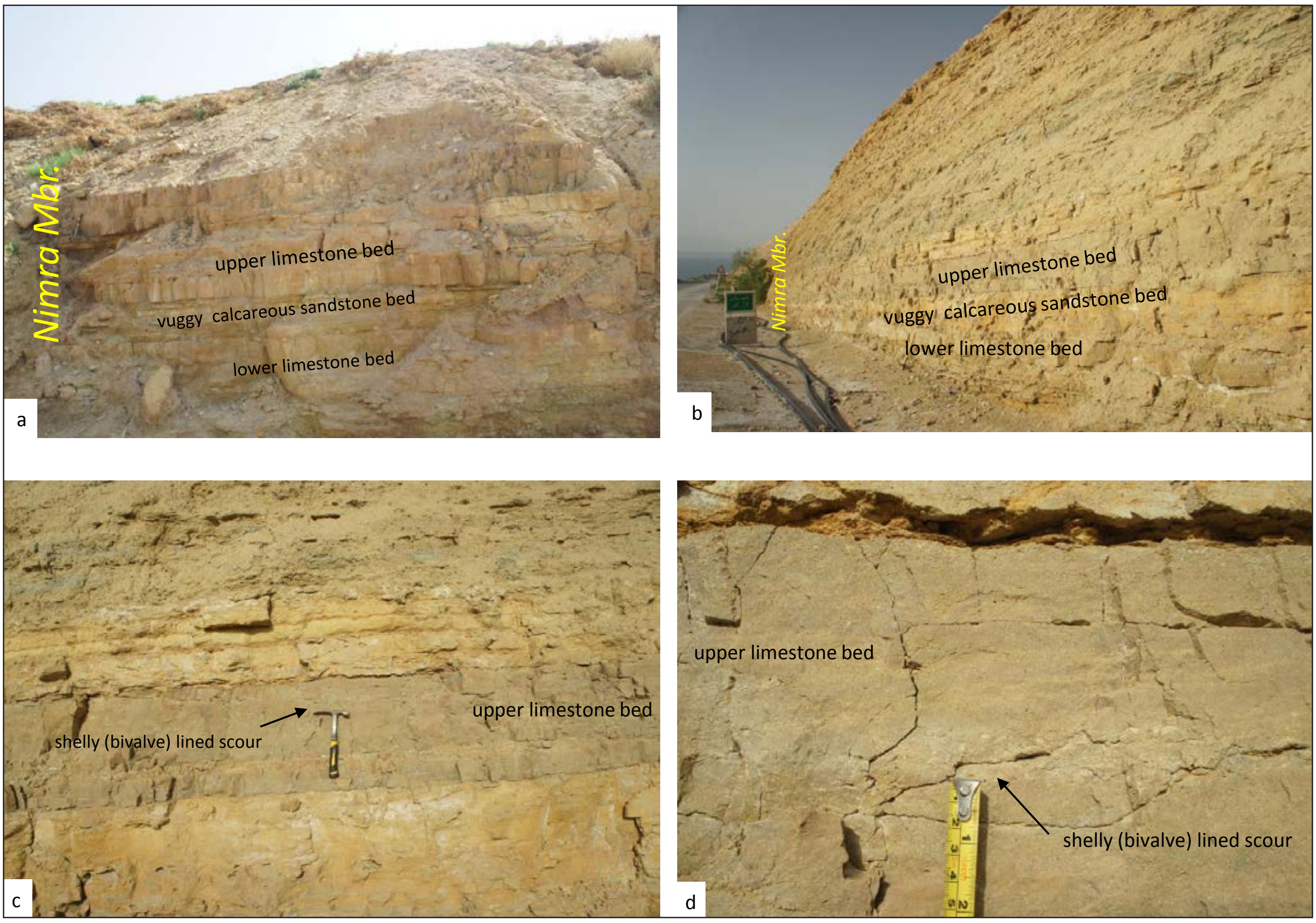

Fig. 7 - Track and roadside sections. a) Lower and upper limestone beds and intervening vuggy calcareous sandstone, Nimra Member. Hammer length 0.30 m. See also Fig. 3; track section; b) roadside section in the Nimra Member showing the two thin limestone beds and the intervening vuggy calcareous sandstone bed. Pick axe length 0.75 m.; c) close up of b) upper limestone bed (grey) (Nimra Member) showing shallow, bivalve shell-lined scours; note the small vugs, possibly after gypsum or anhydrite, in the underlying bed; hammer length 0.30 m; d) close up of the upper limestone bed showing bivalves lining the shallow scour seen in d); left-hand scale in centimetres. See also Fig. 3.

enish and mottled toward the top of this member. The lithologies, bedforms and faint surface burrows indicate a shallow, marine or estuarine sandflat environment deposited during a transgression across the low-lying Umm Irna Formation alluvial plain. The amalgamated sequence boundary marks a maximum regression and subsequent transgressive surface.

Nimra Member - This unit is marked by a colour change from predominantly red-mauve with green mottling (Himara Member) to green, grey-buff, grey and yellow siltstones and fine-grained sandstone, the latter with a carbonate cement in places (Figs 6a, b). The colour change is coincident with the abundant presence of horizontal and vertical burrows including *Phycodes, Diplopodichnus, Rusophycus and Rhizocorallium* and the casts of thin shelled bivalves and the conchostracan (clam shrimp) *Rossolimnadiopsis* Novozhilov (Abu Hamad et al. 2015). Ripple marks and ripple cross-lamination are common.

Two thin, yellow-grey, sharp-based limestone beds are present about 4.8 m above the base of the Nimra Member (Figs 6b, 7a). The lower limestone bed (0.20 m thick) is silty and contains thin-shelled bivalves. The limestone beds are separated by red-grey ripple marked sandy limestone (0.2 m) and yellow-grey fine-grained calcareous sandstone (0.25 m thick) with ovoid, partially weathered, vuggy concretions, possibly pseudomorphs after gypsum or anhydrite. The upper limestone bed (0.5 m thick) has shallow cross-laminated scours with small rounded peloids and fragments and casts of thin-shelled bivalves. The upper surface is slightly reddened and passes up to thin red, fine-grained sandstone with scattered quartz granules.

Locality 2: Roadside Section

This section (Figs 7b to d) through the limestone beds repeats the section seen in the upper part of Locality 1, and is located about 200 m to the south-southeast on the east side of the Dead Sea Highway (N. 31º 32' 27.4": E. 35º 33' 33.2"). Despite their close proximity, Locality 2 shows a number of features not seen in Locality 1 and, furthermore, as a relatively recent road-cut, the rock is less weathered.

At the base of the section, grey-yellow fine-grained calcareous sandstone with ripple marks, ripple cross-lamination and surface burrows are overlain by grey-buff, silty limestone with a rippled upper surface. The limestone is overlain by thin-bedded calcareous silty sandstone with a ripple-marked upper surface, interbedded with yellow sandstone with ovoid vugs 0.03-0.10 m diameter (Fig. 7b). The upper grey-yellow limestone (0.60 m) has a sharp base and a grainstone texture comprising small shell fragments, peloids and ooids. Shallow erosive scours lined with bivalve fragments are present in the upper part of the bed (Figs 7c, d); scours are up to 0.15 m deep and 0.60 m wide. These limestone beds yielded calcareous foraminifera in thin section, and conodonts. The upper part of the section sees a return to yellow-green and grey calcareous siltstone.

Depositional sequences

The upper part of the Umm Irna Formation in the study area has been intensively studied (Makhlouf et al. 1991; Powell & Moh'd 1993; Uhl et al. 2007; Abu Hamad et al. 2008; Dill et al. 2010; Stephenson & Powell 2013); it represents a mosaic of alluvial floodplain sediments deposited by low-sinuosity and meandering rivers in a humid to semi-arid climate that favoured the preservation of abundant plant fossils, palynomorphs and organic matter preserved in dysaerobic muds in the lower parts of the channels. In contrast the interfluve floodplains were sites of formation of highly evolved red-bed paleosols that developed in response to a fluctuating groundwater regime (Retallack 1988).

The sequence boundary can be traced throughout the Dead Sea margin outcrops including the type section of the Umm Irna Formation and its boundary with the Ma'in Formation at Wadi Himara (Stephenson & Powell 2013). It marks a major change in depositional lithofacies (Figs 5a, b) above which alluvial sediments and paleosol pedogenesis are absent. There is no evidence of an angular unconformity at this level, nor is there a continuous level of evolved paleosol development at the upper surface of alluvial lithofacies that might be expected if there were a long period of terrestrial emergence. It is notable that the beds (Himara Member) above the sequence boundary are reddened, similar to the underlying alluvial sediments, despite their shallow-marine or estuarine origin. We attribute the red (iron-pellicle) colour of this fine-grained sandstone/siltstone either as a result of reworking of underlying reddened Umm Irna Formation sediments in a littoral setting, or due to periodic emergence and oxic reddening of the sediments. As such, despite there being a disconformity at the SB, the sedimentology suggests that the time gap may be of short duration (see discussion).

The wave-rippled sandstones with occasional desiccation cracks and faint, indeterminate surface burrows immediately above the SB indicate a pulsatory marine transgression, with stacked, thin-bedded sandstone/siltstone rhythms each with a rippled upper surface. Sedimentation kept pace with slow subsidence; the absence of body fossils together with the attributes noted above indicate a shallow-marine or estuarine sand-flat. The absence of macro-fauna may also be attributed to these sediments being deposited shortly after the Permian to Triassic mass extinction event at a time where the shallow marine biota was gradually recovering. The increase in green and green-mauve mottling towards the top of the Himara Member (Figs 3 and 6) indicates an increase in temporary reducing conditions at the sediment-water interface. This increasing marine trend is shown in the overlying Nimra Member with the upwards increase of predominantly yellow-grey colours, carbonate cements, more complex burrow types (both horizontal and infaunal burrow types), and the presence of thin-shelled bivalves (generally casts) which include lingulid brachiopods and the conchostracan ("Estheria") *Rossolimnadiopsis* (Abu Hamad et al. 2015). The two limestone beds (Fig. 3) are significant because: (a) they represent the lowermost limestones above the Permian-Triassic boundary that have yielded conodonts and foraminfera in the region and, (b) these limestone beds appear to be local to the immediate study area, since when the outcrop is traced just 200 m north along the Dead Sea foreshore cliff the coeval beds are represented by calcareous san-

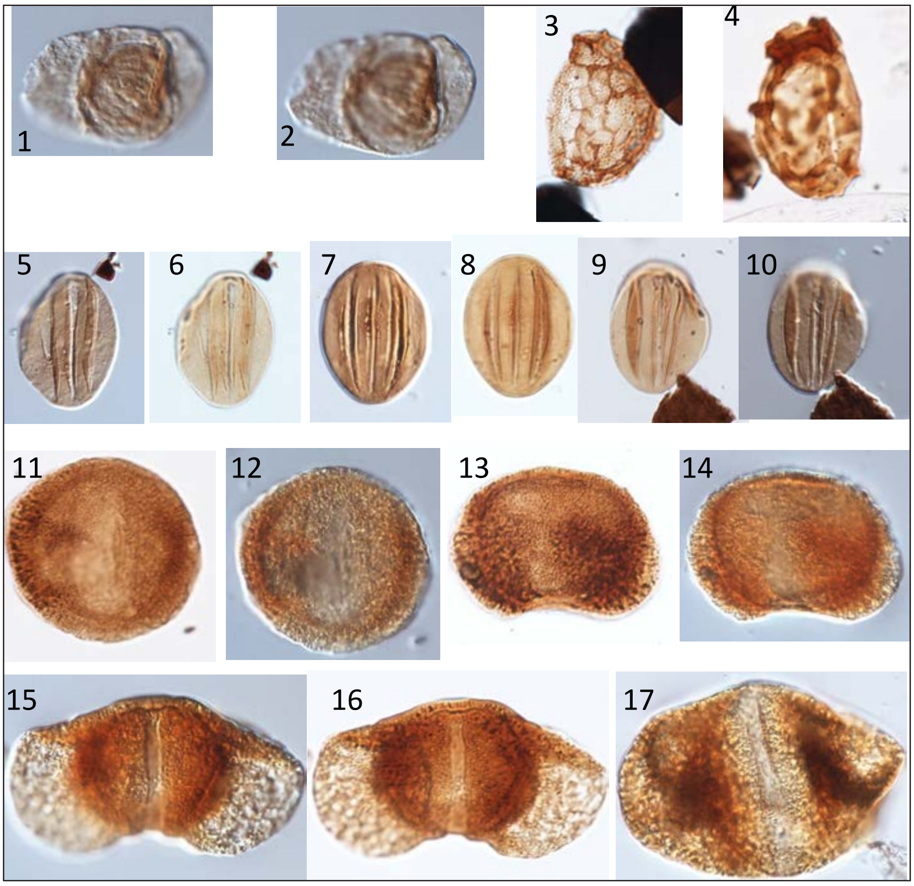

Fig. 8 - Selected palynomorphs from the Umm Irma Formation. 1, 2) *Protohaploxypinus uttingii,* M60, 62253 -2; 3, 4) *'Torispora-Thymospora* complex', 3: 62242-2, O61/2; 4: 62242-2, K68/3; 5-10) *Pretricolpipollenites bharadwajii,* 5-6: 62263, H60/4; 7-8: 62263, P68; 9-10: 62263-1, U48/1; 11-14) *Cedripites priscus*, 11-12: 62263-1, M48/1; 13-14: 62263-1, H62; 15-17) *Falcisporites stabilis*, 15-16: 62256, N63/2; 17: 62259, W44/1. Specimens and slides are in the collection of the British Geological Survey, Keyworth, Nottingham. Specimens are located by England Finder and by MPA slide code.

dstones only. We interpret the local presence of thin limestones as representing a littoral shoreline lithofacies. This is further supported by the presence of abundant ripple marks, shallow scours with shelly lags in the upper limestone, and the possibility that the vugs in the calcareous sandstone bed represent pseudomorphs after evaporites (e.g. gypsum or anhydrite) deposited in a peritidal salina or sabkha setting.

Biostratigraphy

Palynology of the Umm Irna Formation

The Umm Irna Formation has been the subject of several palynological investigations. The first detailed work was carried out by Abu Hamad (2004) in an unpublished PhD thesis, but little of the palynological work was subsequently published, since later work concentrated on plant macrofossils (e.g. Abu Hamad et al. 2008; Kerp et al. 2006). However, samples from the type section of the Umm Irna Formation yielded assemblages suggesting a Late Permian age (Abu Hamad 2004). Samples from the same locality approximately 10 m above the SB yielded low diversity assemblages dated as Early Triassic by Abu Hamad (2004).

Stephenson & Powell (2013) reported generally well-preserved assemblages from 25 samples from the Umm Irna Formation. The assemblages are very variable, but in general contain common non-taeniate bisaccate pollen (often fragmentary or too poorly preserved to be identified); those that are determinable include *Falcisporites stabilis*, *Alisporites nuthallensis*, *A. indarraensis*, and *Cedripites priscus*. The most common taeniate bisaccate pollen is *Protohaploxypinus uttingii* and *P. limpidus*. Monosaccate pollen is rare, as are spores. Biostratigraphically significant pollen taxa are illustrated in Fig. 8; details of the quantitative character of the assemblages and the stratigraphic ranges of taxa are given in Stephenson & Powell (2013).

Stephenson & Powell (2014) discussed in more detail the age implications of the Umm Irna Formation assemblages. The common occurrence of the distinctive trisulcate pollen *Pretricolpipollenites bharadwajii* suggested a tentative re-appraisal of the age suggested by Stephenson & Powell (2013), since its range appears to be latest Permian to Triassic; indeed in the Middle East its occurrences are

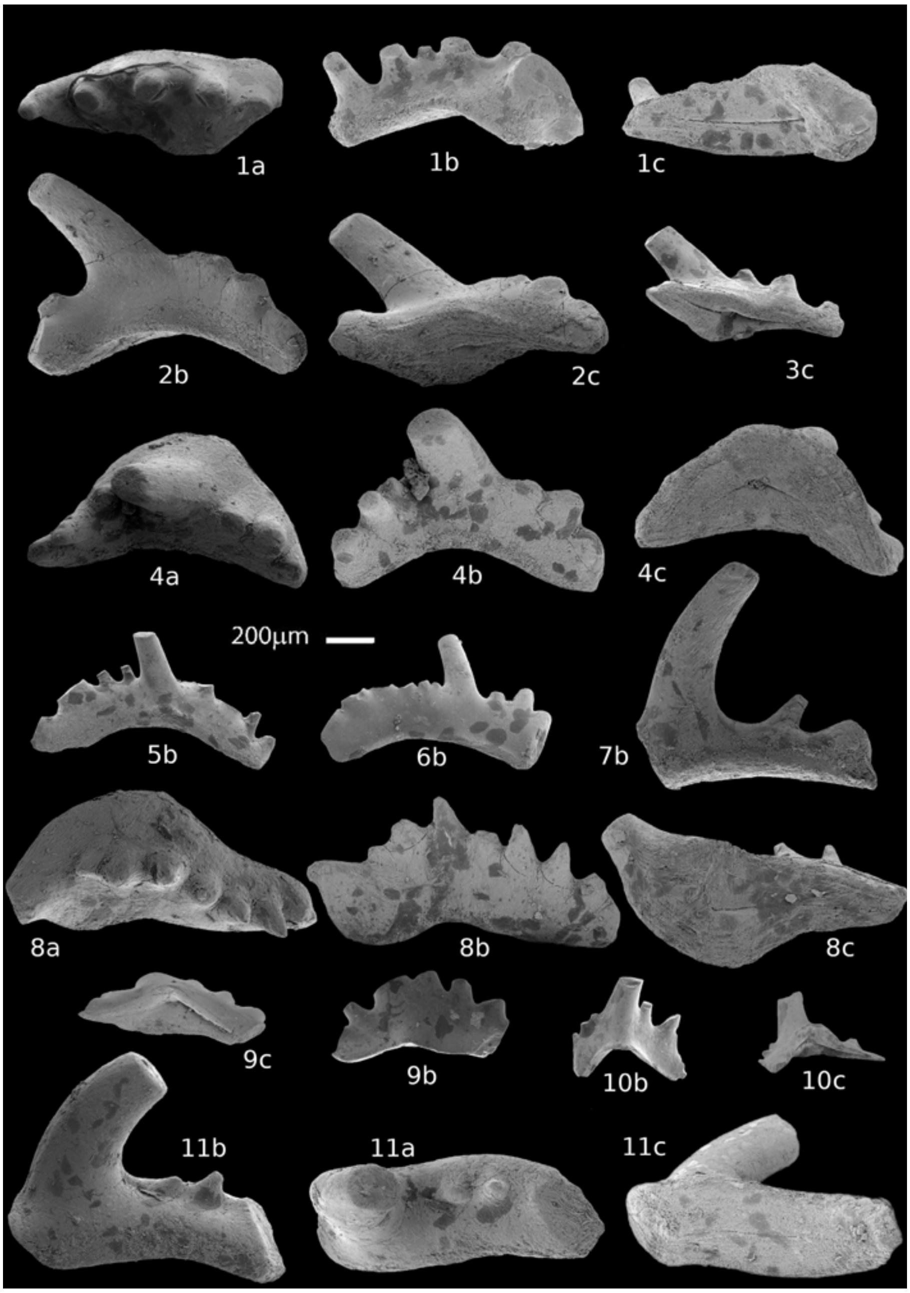

Fig. 9 - Conodonts from the lower Nimra Member (Ma'in Formation) limestones. Sample MS2 is from Cliff/Track section A; sample MS18 from Road Side section B. 1) *Hadrodontina aequabilis* Staesche 1964, sampleMS2, M element: a) upper view; b) lateral view; c) lower view. 2) *Hadrodontina aequabilis* Staesche 1964, sampleMS2, Pb element: b) lateral view, c) lower view. 3) *Hadrodontina aequabilis* Staesche 1964, sample MS2, Pb element: c) lower view. 4) *Hadrodontina/Ellisonia* sp., sample MS2, Pa element: a) upper view; b) lateral view; c) lower view. 5) *Hadrodontina aequabilis* Staesche 1964, sample MS2, Sb element: b) lateral view. 6) *Hadrodontina aequabilis* Staesche 1964, sample MS2, Sb element: b) lateral view. 7) *Hadrodontina aequabilis* Staesche 1964, sample MS2, Sc element: b) lateral view. 8) *Hadrodontina/Ellisonia* sp., sample MS2, Pa element: a) upper view; b) lateral view; c) lower view. 9) *Hadrodontina/Ellisonia* sp., sample MS2, Pb element: c) lower view; b) lateral view. 10) *Hadrodontina aequabilis* Staesche 1964, sample MS18, M element: b) lateral view; c) lower view. 11) *Hadrodontina/Ellisonia* sp., sample MS18, Sc element: b) lateral view; a) upper view; c) lower view.

almost entirely confined to the Triassic. Mazroui-Kilani et al. (1988), Kilani-Mazraoui et al. (1990) and Kamoun et al. (1994) recorded it spanning the Lower to Upper Triassic in Tunisia; similarly, Geleta & Wille (1998) recorded the taxon from the Middle Triassic (Ladinian) of west-central Ethiopia. It was first described from the Changhsingian (see Wardlaw & Pogue 1995) of the Salt Range of Pakistan where it reportedly occurs only in the 'upper 12 feet or so of the Chhidru Formation' (Balme 1970, p. 406). Hermann et al. (2012) and Schneebeli-Hermann & Bucher (2015) in recent surveys of the Salt Range of Pakistan recorded *P. bharadwajii* and *Pretricolpipollenites* spp. between their units PTr1 and PTr2 (earliest Triassic). Thus palynology appears to indicate a possible latest Permian age for the Umm Irna Formation.

Conodonts

Five small (< than 200 g) samples from the lower Nimra Member (Ma'in Formation) have been investigated for conodonts. Samples MS1 and MS2 are from Cliff/Track section (A), and MS17, MS18, MS19 are from the Road Side section (B) (Fig. 3). With the exception of MS19, all of the samples have been productive. The CAI (Colour Alteration Index, Epstein et al. 1977) is 1, corresponding to a burial temperature of 50°-

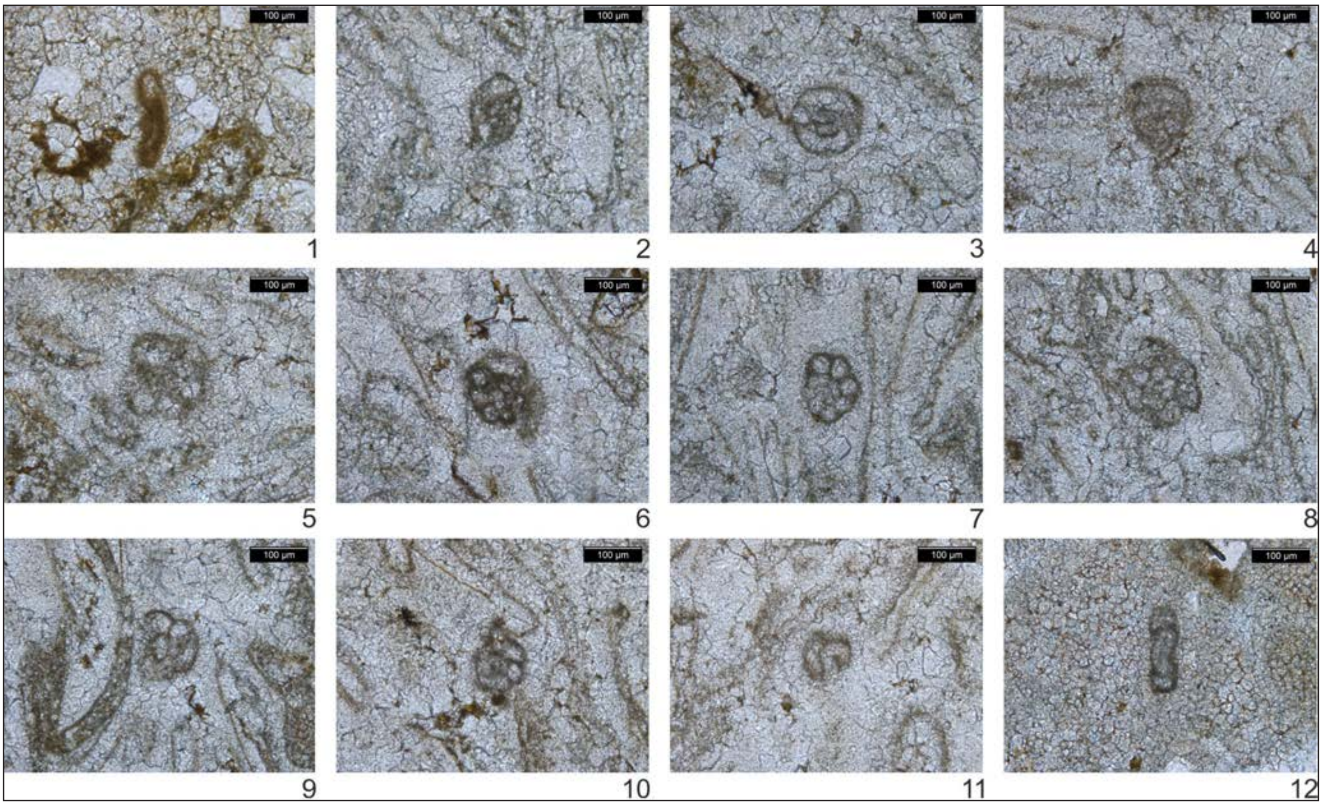

Fig. 10 - Foraminifera (thin sections) from the lower Triassic limestones. 1) Lower Nimra Member limestone (sample MS6): quartz packstone with "*Cornuspira*" *mahajeri* (Bronnimann et al. 1972) and fragments of bivalves and echinoids; 2-11) upper Dardun Formation packstone with *Meandrospira pusilla* (Ho 1959) (samples MS8 2-6; MS10 7-11); 12) upper Dardun Formation, partly recrystallized fine-grained packstone with *"Cornuspira" mahajeri* (centre). Scale bar 100 microns.

80°C. The conodont fauna is relatively abundant (Fig. 9) although the specimens are small in size. Conodonts are represented mainly by elements of the apparatus of *Hadrodontina aequabilis* Staesche, 1964 and by a few elements of other ellisonids (Fig. 9). Those last elements, characterized by a wide, flat to slightly concave basal cavity, could be representative of elements in Pa/Pb position of an unknown apparatus referable to *Ellisonia* or *Hadrodontina* genus. Absence of Sa elements in the studied faunas did not allow the identification of the genus. Ellisonids indicate a shallow-water euryhaline environment. The studied fauna shows affinities with those reported from the Southern Alps, Italy (Huckriede 1958; Staesche 1964; Perri 1986, 1991; Perri & Andraghetti 1987; Perri & Farabegoli 2003; Farabegoli & Perri 2012), Dinarides, Slovenia (Kolar-Jurkovsek et al. 2011), northernmost Pakistan (Perri et al. 2004), northeastern Sichuan Province, Southwest China (Yang et al. 2014). The conodont association from the sampled limestones is Induan to Early Olenekian in age (Staesche 1964; Perri 1986, 1991; Perri & Andraghetti 1987; Perri & Farabegoli 2003; Orchard 2007).

Foraminifera

The thin sections studied comprise packstones with bivalves, echinoid fragments, and gastropods. Some of the investigated samples contain ooids and siliciclastic grains. Foraminifers (Fig. 10) are present in samples MS 6 (Nimra Member, Ma'in Formation), and MS 8, 10 and 12 (Upper Carbonate Member, Dardun Formation). Foraminifera are rare and only represented by two typically Early Triassic species: "*Cornuspira*" *mahajeri* (Bronnimann et al. 1972) (= *Postcladella kalhori sensu* Krainer & Vachard 2005) whose First Occurrence has been recorded in sample MS6 (lower limestone in Roadside Section B; Fig. 3) and *Meandrospira pusilla* (Ho 1959) whose first occurrence has been recorded in sample MS8. The latter sample is from the stratigraphically higher Upper Carbonate Member (Dardun Formation) (Bandel & Khoury 1981) that overlies the Nimra Member (Ma'in Formation) in Wadi Dardun (N 31° 41' 23"; E 35° 35'

25.2") (Fig. 2).

These two dominant species characterize the Early Triassic and, in particular, the acme of "*Cornuspira" mahajeri* is considered as late early Induan in age, whilst *Meandrospira pusilla* is typical of the Olenekian Stage (Broglio Loriga et al. 1990; Rettori 1995).

"*Cornuspira" mahajeri* forms depauparate assemblages in Early Triassic beds of western and eastern Tethyan area (Rettori 1995; Groves & Altiner 2005; Krainer & Vachard 2011). The taxon is generally present in microbialites or in their stratigraphic proximity and in ooidal grainstones, and it is interpreted as a species belonging to a disaster form genus (Groves & Altiner 2005). Disaster forms are characteristic of the survival phase after a mass extinction event and they are generally dominant before the recovery phase. The Early Triassic, in fact, is considered as a survival interval characterized by a proliferation of disaster forms and low generic diversity. The "*Cornuspira" mahajeri* assemblage is present in the late early Induan and its decreasing abundance and eventual disappearance is followed by the increasing presence of *Meandrospira pusilla* which is common and abundant during the Olenekian before the recovery phase, which after the P/T mass extinction does not occur until the Middle Triassic (Anisian) (Song et al. 2009; Song et al. 2011). "*Cornuspira" mahajeri,* like most ecological generalist and opportunist populations, normally exists in low numbers, but its bloom occurs during environmental crisis. The disappearance of dominant Wuchiapingian-Changhsingian cornuspirid foraminifers was not complete after the end-Permian crisis and the genus "*Cornuspira"* occurs, represented by the species *mahajeri* just above the P/T boundary, perhaps because of its high tolerance of environmental stress.

Later in the early Triassic the "*Cornuspira" mahajeri* assemblage decreases and *Meandrospira pusilla* appears (Olenekian) although very rare specimens of "*Cornuspira*" *mahajeri* can still exist. Finally, the part of the succession containing the samples studied can be referred to the late part of the Induan and the beginning of the Olenekian on the basis of the slow increasing of *Meandrospira pusilla* in association with the last specimens of "*Cornuspira*" *mahajeri* (Broglio Loriga et al. 1990; Rettori 1995; Groves et al. 2005; Groves & Altiner 2005; Krainer & Vachard 2011; Song et al. 2009; Song et al. 2011).

Discussion

The Permian-Triassic boundary in Jordan is marked by a major sequence boundary which is equivalent to Arabian Plate transgression Tr 10 of Sharland et al. (2001, 2004). It separates the underlying alluvial plain lithofacies (Umm Irna Formation), of latest Permian age, from the shallow marine lithofacies (Ma'in Formation) of Early Triassic age. The constrained age of the section between the top of the Umm Irna Formation and the age tie point in the lowest limestone bed in the Nimra Member indicates that this section contains the Permian-Triassic boundary either within the hiatus represented by the sequence boundary or within the lower marine beds above that level. The transition therefore appears to span the most significant extinction event in the Phanerozoic (Benton & Twitchett 2003; Heydari & Hassanzadeh 2003; Wignall 2001). Previous dating of the transition succession has been hampered by a reliance on terrestrial flora (palynology and macro-plant fossils in the Umm Irna Formation) and lack of marine microfauna (conodonts and foraminifera) in the Ma'in Formation. A latest Permian age based on the presence of abundant *Pretricolpipollenites bharadwajii* has been determined for the uppermost alluvial plain sediments preserved immediately below the sequence boundary (Stephenson & Powell 2013, 2014). However, until now the oldest biostratigraphically significant fauna from the Triassic succession in Jordan came from conodonts of 'Scythian age' from the Upper Carbonate Member of the Dardun Formation (Huchkriede in Bender 1968). The presence of the conodonts (e.g. *Hadrodontina aequabilis*) and foraminifera (e.g. "*Cornuspira*" *mahajeri*) from the newly discovered thin limestones in the lower Nimra Member, about 15 m above the top of the sequence boundary, helps to constrain the age of the earliest Triassic sediments.

The presence of the foraminfera "*Cornuspira*" *mahajeri* indicates a late early Induan age in the Nimra Member wackestones that exhibit a low diversity fauna. This taxon is interpreted as an opportunistic 'disaster species' (Groves & Altiner 2005) characteristic of the survival phase after a mass extinction event; furthermore, the dominance and acme of this species is generally occurs before the recovery phase. Decreasing upward abundance and eventual disappearance of this species is mirrored by the increasing presence of *Meandrospira pusilla,* which is common and abundant during the Olenekian Upper Carbonate Member (Dardun Formation), also before the faunal recovery phase. Similarly, the low diversity conodont fauna including *Hadrodontina aequabilis* (and other ellisonids) indicate shallow-water euryhaline environments and an Induan to Early Olenekian age for the lowermost Nimra limestones. *Hadrodontina aequabilis* appears near the base of the Griesbachian staeschi Zone of the lower Induan (Perri 1991; Perri & Farabegoli 2003; Orchard 2007); these and other ellisonids with robust elements favoured shallow water and tolerated restricted-marine environments (Orchard 2007) typified by the Nimra Member.

Above the sequence boundary, the red-bed Himara Member (Figs 3, 5 and 6) is faunally barren except for sparse surface trace fossils in ripple-marked siltstones and fine-grained sandstones. A shallow, restricted marine environment is envisaged, but the red colouration may be due to reworking of underlying red-bed alluvial sediments (Umm Irna Formation) rather than primary reddening, although the presence of desiccation cracks indicates temporary emergence and the possibility of primary reddening. The initial marine transgression is marked by successive thin beds of ripple-marked thin bedded siltstone and sandstone indicating repeated incursions in a shallow marine embayment. The geomorphic gradient of the littoral zone must have been very low because there is no paleotopographical relief preserved below the sequence boundary; this allowed a widespread marine incursion over the low-lying alluvial plain during earliest Triassic times. The absence of body fossils and the presence of surface burrows (rather than vertical in-faunal burrows) points to a low-diversity/low abundance marine fauna following the P/T extinction event (Twitchett & Wignall 1996). Increasing occurrence of less oxidising conditions is marked by the incoming of green claystone laminae and a general gradational passage to green-grey-yellow beds across the Himara-Nimra boundary, with concomitant increase in vertical in-faunal burrows, conchostracans and casts of thin-shelled bivalves (Fig. 3) that also suggest an upward transition over this 15 m interval from oxidised marginal shallow marine to normal shallow marine environments. The latter interpretation is supported by the fauna in the first limestones (e.g. low-diversity euryhaline conodont and 'disaster recovery' foraminfera taxa), wackestone-packstone lithologies and reworked thin-shelled bivalves lining shallow scours. The presence of the conchostracan *Rossolimnadiopsis* (Abu Hamad et al. 2015) and lingulid brachiopods suggest a marginal marine environment. Northwards wedging-out of the thin limestones over 200 m distance from the sampled outcrop indicates these carbonates were preferentially deposited locally in a shallow-water, proximal shoreline environment. The end Permian extinction is thought by some authors to represent a period of anoxia or even euxinia in the world's oceans (Payne et al. 2004) but the red, oxidised nature of the Himara sediments together with surface burrows indicates that by this early Triassic time the shallow seas on the Arabian Platform were at least oxygenated, with this trend increasing in time through the Himara-Nimra transition.

The sequence boundary is interpreted as equivalent to the Tr 10 unconformity taken at the base of the Khartam Member of the Kuff Formation in the Unayzah area of central Saudi Arabia (Sharland et al. 2004) and in the subsurface near the top of Kuff B (Le Nindre et al. 1990). At outcrop in the Unayzah area, the Triassic marine flooding event (Tr 10) is similarly marked by marine shales with an open marine fauna, overlying channelized fluvial sandstones with plant remains (Sharland et al. 2004, fig. 4.32).

The recent discovery of a fully marine succession spanning the Permian to Triassic transition characterised by distal siliciclastic and ramp carbonates in the coastal plain of Israel (Korngreen et al. 2013) suggest that the Dead Sea outcrops represent a coeval landward succession, with the transgressive marine environment only established in earliest Triassic time (Nimra Member) as a result of sea-level rise. Consideration of the lithofacies, faunas and biostratigraphy indicates that the Ma'in Formation, above the sequence boundary, represents a recovering marine phase and progressive transgressional systems tract that post-dates the P/T extinction event. Ongoing research on the Ma'in Member may reveal additional chronostratigraphical and biostratigraphical information. Previuos studies indicated a significant time gap marked by the sequence boundary that may span all or part of the latest Wuchiapingian-Changhsingian (base 254.2 Ma) to the Induan (base 252.2 Ma) a duration of about 2 million years, with the initial Triassic transgressive

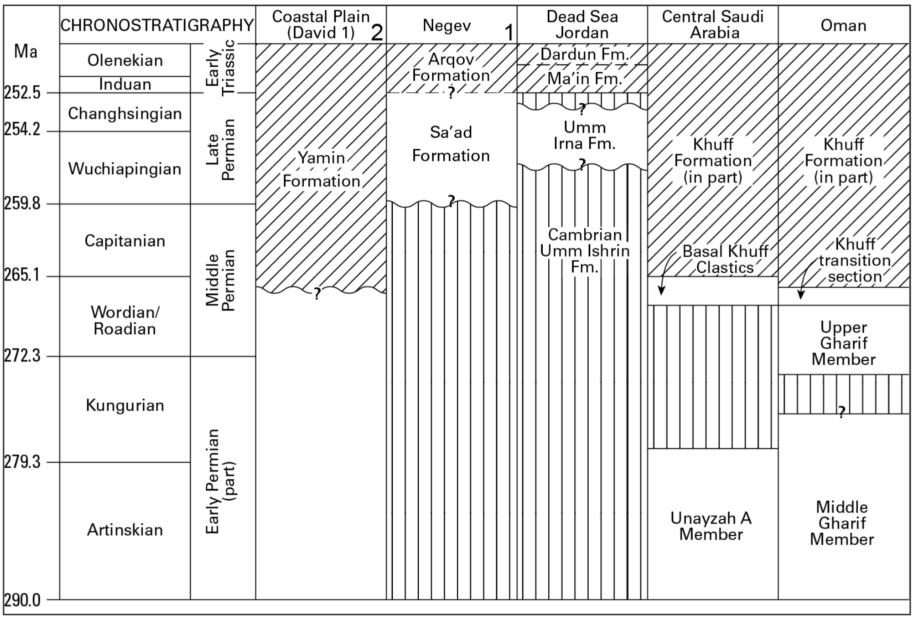

Fig. 11 - Correlation of the Permian-Triassic successions in the Levant and Arabian Plate. Cross-hachuring indicates predominantly marine strata. 1) (Negev) after Eshet and Cousminer (1986): these authors regard the Arqov Formation as Permian in age; 2) Coastal Plain (David 1) after Korngreen et al. (2013); Dead Sea, Jordan, this paper; central Saudi Arabia and Oman after Angiolini et al. (2003) and Stephenson (2006).

event dated at late early Induan (Stephenson & Powell 2013, 2014). The paleoclimate during deposition of the Late Permian (uppermost Umm Irna Formation) was humid-tropical, but with seasonal fluvial discharge resulting in highly evolved pisolitic ferruginous paleosols on the interfluves contrasting with low-sinuosity rivers where organic matter was preserved, in-channel (Makhlouf et al. 1991; Stephenson & Powell 2013). A hot arid climate during the early Triassic in this region is also supported by reddening and desiccation features in the Himara Member and the presence of shallow water microbial carbonates in the Nimra Member, adding to the evidence for the region lay about 15 to 20 degrees south of the paleo-equator at the northern margin of the Arabian (Stampfli & Borel 2002) during a period of global warming through the Permian to Triassic transition.

Conclusions

The Permian to Triassic transition in Jordan is constrained within the hiatus represented by the sequence boundary, or within the marine beds overlying it. The sequence boundary may represent a relatively short time interval depending on the reliability of the age for the beds below it, suggested by palynology. The disconformity is planar over a wide area with no preserved paleotopography, suggesting that the marine transgression advanced rapidly across a low lying coastal plain.

Above the sequence boundary, reddened shallow-marine beds characterised by ripple cross-laminated, siltstones/sandstone with desiccation cracks and sparse surface burrows mark the initial Triassic marine transgression in the region. Absence of body fossils and vertical infaunal burrows may reflect low-diversity ecosystems following the Permian-Triassic extinction event, or a result of stressed shallow marine environments. A gradational upward increase in grey, green and yellow siltstones beds accompanied by a concomitant increase in bioturbation (and infaunal vertical burrows), thin-shelled bivalves and lingulids at the Himara-Nimra member boundary indicates colonisation of the substrate under more normal shallow marine conditions during the recovery phase following the extinction event. This trend is marked by the presence of two thin limestone (packestone) beds, local to the study area, with shallow scours and bivalve lags. The limestones have yielded a low diversity assemblage of conodonts (e.g. *Hadrodontina aequabilis*) and foraminifera ("*Cornuspira*" *mahajeri*) that are interpreted as euryhaline recovery taxa that characterise the early Induan following the P/T extinction event. The Early Triassic marine transgression can be traced widely across the Arabian Plate where overlying thick carbonates (Khuff Formation) represent one of the world's most prolific hydrocarbons reservoirs (Fig. 11).

A humid-tropical climate during the Permian to Triassic transition is suggested by the presence of highly evolved paleosols (interfluves) and abundant macro-plant fossils and palynomorphs preserved in-channel in the latest Permian sediments, and the presence of reddened ripple marked siliciclastics with desiccation cracks in the earliest Triassic sediments.

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