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Evidence for palaeo-wildfire in the Late Permian palaeotropics – charcoalified wood from the Um Irna Formation of Jordan

D. Uhl [a,*], A. Abu Hamad [b,c], H. Kerp [b], K. Bandel [d]

[a] Palaeoecology, Institute of Environmental Biology, Faculty of Science, Utrecht University, Laboratory of Palaeobotany and Palynology, Budapestlaan 4, NL-3584 CD Utrecht, The Netherlands
[b] Forschungsstelle für Paläobotanik, Westfälische Wilhelms-Universität, Hindenburgplatz 57, D-48143 Münster, Germany
[c] The University of Jordan, Department of Environmental and Applied Geology, Amman 11942, Jordan
[d] Geologisch-Paläontologisches Institut und Museum, Universität Hamburg, Bundesstr. 55, D-20146 Hamburg, Germany

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Abstract

Charcoalified wood from the lower part of the Late Permian Um Irna Formation of Jordan is described. This charcoal represents the first evidence of palaeo-wildfire during the Late Permian in northern Gondwana. The source locality at the northeastern rim of the Dead Sea has yielded excellently preserved gymnosperm charcoal. Taxonomically most remains are identified as *Dadoxylon*-type gymnosperm wood. However, one woody specimen exhibits features that suggest a potential taxonomic relationship to the Corystospermales, a group otherwise represented at this locality by compressed fronds assigned to the genus *Dicroidium*. The occurrence of charcoal in the Um Irna Formation is in accordance with sedimentological data, as well as palaeoclimatic interpretations of this formation that suggest a tropical climate with alternating wet and dry seasons, favourable for the occurrence of wildfires. The charcoalified wood from the Late Permian of Jordan testifies for the first time to the occurrence of palaeo-wildfire in the low latitudes of northern Gondwana during this period.

Keywords: charcoal; fire; Late Permian; Jordan; northern Gondwana

1. Introduction

Plant-bearing localities from the Late Permian of Euramerica and adjacent northern Gondwana are very rare and our knowledge about plants from this period is rather incomplete. However, knowledge about these plants and their ecology is crucial for our understanding of the development of terrestrial ecosystems at the end of the Palaeozoic, prior to the greatest mass-extinction of the past 600 million years, which occurred at the Permian–Triassic boundary (e.g. Erwin, 1990; Benton and Twitchett, 2003; Erwin, 2006).

So far, only a few major Middle to Late Permian palaeofloras have been described from Arabia, which represents the easternmost part of northern Gondwana: i.e. the Late Wordian Unayazah flora (El-Khayal et al., 1980; Lemoigne, 1981; El-Khayal and Wagner, 1985) and the Early Changhsingian Jal Khartam flora (Hill and El-

* Corresponding author. Present address: Villenstraße 13, 67433 Neustadt an der Weinstraße, Germany.
E-mail address: dieter.uhl@gmx.de (D. Uhl).

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Khayal, 1983; Hill et al., 1985) from the Saudi Arabian Khuff Formation, as well as the Early Wordian Gharif flora from Oman (Broutin et al., 1995; Berthelin et al., 2003). In recent years, several new discoveries from the Um Irna Formation of Jordan added additional information about the Late Permian vegetation of this region. A hydrophilic flora, consisiting of *Doratophyllum jordanicus* Mustafa, *Gigantonoclea* sp., *Lobatannularia heianensis* (Kodaira) Kawasaki and *Pecopteris* sp. has been described by Mustafa (2003). Another flora has been discovered recently at Wadi Himara in Jordan, which is (co-)dominated by different species of the Corystosperm *Dicroidium* (Abu Hamad, 2004; Kerp et al., 2006). In addition to these reports on compression/impression floras, we describe charcoalified woods from the latter locality, which provide the first evidence of palaeo-wildfire during this period in northern Gondwana.

2. Materials and methods

2.1. Locality, source strata and fossil content

The charcoal remains were collected from a natural exposure in the lower part of the Um Irna Formation at the northeastern rim of the Dead Sea, Jordan. They have been recovered from an individual, about 0.8 m thick, siltstone bed. Charcoal fragments, with diameters from <10 mm up to 50 mm and only slight abrasions at the edges, are scattered within this siltstone bed. Woody fragments are common within this bed and so far no other charred plant organs have been found at this locality.

All SEM samples as well as raw rock samples are stored in the collection of the Forschungsstelle für Paläobotanik, Universiät Münster, Germany under the acquisition numbers Pb-2500–Pb-2512.

The source locality is situated about two km from the main road that runs along the eastern shore of the Dead Sea, in the incised valley with a creek running all year named Wadi Himara. The outcrops of the Um Irna Formation are located ca. 400 m upstream along the southern branch after the main bifurcation of Wadi Himara (Fig. 1).

The Um Irna Formation was defined by Bandel and Khoury (1981). The formation locally has a thickness of 67 m and unconformably overlies the Cambrian Um Ishrin Sandstone Formation. The Um Irna Formation is unconformably overlain by the Ma'in Formation. Preliminary palynological investigations assigned a Late Permian age for the lower (W.A. Brugman, in: Bandel and Khoury, 1981), as well as the upper part (H.A. Armstrong, in: Makhlouf, 1987) of the Um Irna Formation. Also lithological correlations with drillcore sections further towards the west suggested a Late Permian age (Eshet and Cousminer, 1986). The plant-bearing layers have yielded rich and well-preserved microfloras clearly indicating a Late Permian age based on the presence of *Lueckisporites virkkiae* Potonié et Klaus, *Klausipollenites schaubergeri* Potonié et Klaus, *Nuskoisporites dulhuntyi* Potonié et Klaus and *Jugasporites delasaucei* Potonié et Klaus (Kerp et al., 2006). The palynological assemblages are dominated by bisaccate pollen grains, mainly various species of *Falcisporites* Leschik, including *F. zapfei* (Potonié et Klaus) Leschik and *F. stabilis* (de Jersey) Balme, which together may constitute over 50% of the associations (Abu Hamad, 2004).

Indirect stratigraphic control is also provided by the age of the unconformably overlying Ma'in Formation (Himara Member). The basal part of this formation has been dated as (?Early) Scythian on the basis of poor palynological assemblages recorded from subsurface samples in North Jordan (cf. Shawabekeh, 1998), whereas the second member of the Ma'in Formation has been dated as Middle to Late Scythian on the basis of bivalves (Cox, 1932) and conodonts (Huckriede and Stoppel in: Bender, 1975).

The lower part of the Um Irna Formation has been interpreted as a distal braided fluvial deposit (Makhlouf et al., 1991). Plant remains occur in organic-rich, grey to brownish silt and clay layers and lenses between 5.5 and 16 m above the base of the formation at Wadi Himara. Most of these beds yield numerous small cuticle fragments. In one bed, plant remains are very abundant, and also larger, up to 0.3 m long frond segments of the Corystosperm *Dicroidium* have been found. This layer has a thickness of up to 1.2 m and is ca. 15 m above the base of the formation. Apart from cuticles, this layer has also yielded charcoalified wood remains. The plant-bearing clay- and siltstones are here interpreted as abandoned channels. Especially in the middle and upper part of the formation several palaeosols with ferruginous pisoliths are developed, which are typically formed in hot and humid climates with a high annual rainfall and a short dry season (Driessen et al., 2001). The outcrop section with the position of the plant-bearing beds (including the charcoal) is presented in Fig. 2.

Although plant megafossils are abundant in the silty and clayey layers in the lower part of the Um Irna Formation at Wadi Himara, species diversity is low. The assemblage comprises several species of *Dicroidium* that are preserved as compressions with fine cuticular detail and a few poorly preserved, unidentifiable fern remains. Those fossils assigned to *Dicroidium* have a frond morphology (presence of characteristic bifurcation in the lower part of the frond) and epidermal anatomy characteristic of the genus (Kerp et al., 2006). Apart

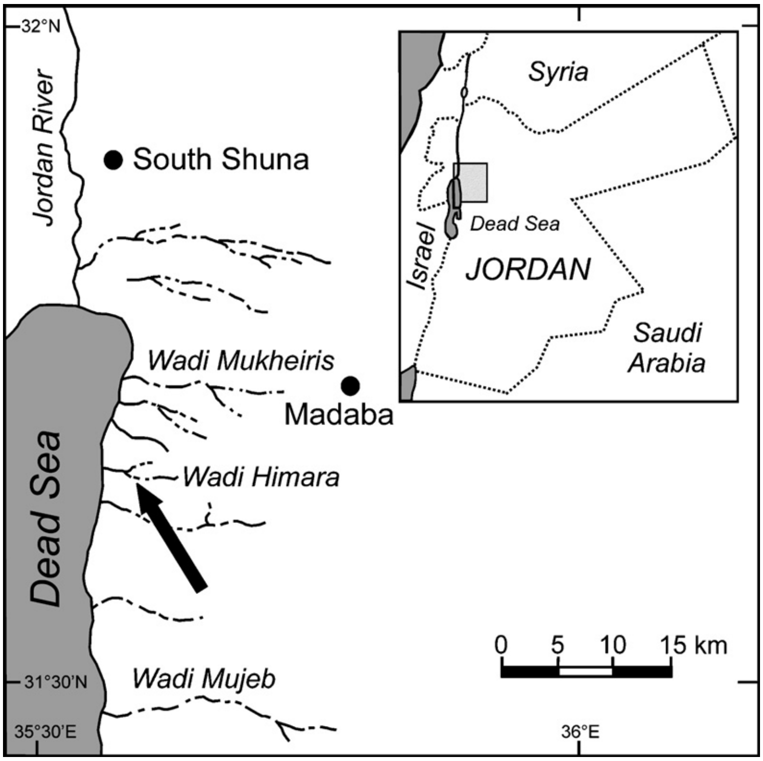


Fig. 1. Map showing the position of the sampling locality at the northeastern rim of the Dead Sea (arrow).

from this interval, the rest of Um Irna Formation at Wadi Himara has not yielded any fossils, neither megafossils nor microfossils. However, from another section of the Um Irna Formation, about 9.5 km north of Wadi Mujeb, a small macroflora has been described by Mustafa (2003).

2.2. Methods

Charcoal fragments were extracted mechanically from the sediment with the aid of preparation needles, lancets and tweezers under a binocular microscope in the laboratory. Due to their very fragile nature, they could no be cleaned with water or any acids to remove adhering mineral remains. The fragments were mounted on standard stubs with Leit C (Plano), and subsequently examined with the aid of a LEO 1450 VP GEMINI Scanning Electron Microscope (SEM) at the University of Tübingen.

3. Results and discussion

3.1. Preservation

The charcoal remains from Wadi Himara have diameters up to 50 mm and show only slight abrasions at the edges. This indicates that the remains probably have not been transported over a wide distance, although the occurrence mainly of wood may suggest at least some taphonomical sorting of the charred plant remains (Nichols et al., 2000). Such an interpretation is in agreement with the sedimentological interpretation of the plant-bearing horizon as abandoned channels of a braided fluvial system. The remains have a black color and streak, as well as silky lustre, typical for charcoal (e.g. Scott, 1989, 2000, 2001). SEM studies reveal further features, like homogenized cell walls (Plates I,2,6 and II,1), and excellently preserved anatomical details, which are considered as diagnostic for charcoal (e.g. Scott, 2000, 2001). In some of the charcoal fragments, remains of charred fungal hyphae of unknown taxonomic affinity are frequent (Plate I, 1–2).

Shattered cell walls occur in small areas in almost all of the charcoal fragments investigated, although they do not form the typical 'Bogen structures' characteristic for severe compression (Plate II, 1). Though charcoal is chemically almost inert, it is highly susceptible to mechanical stresses and cell walls may fracture easily during compaction of the embedding sediment forming these typical structures (e.g. Scott, 1989). Areas with shattered cell walls usually form weak spots, which may cause the already fragmentary charcoal remains to fragment further, as soon as the stabilizing sediment is chemically or mechanically disintegrated (e.g. during

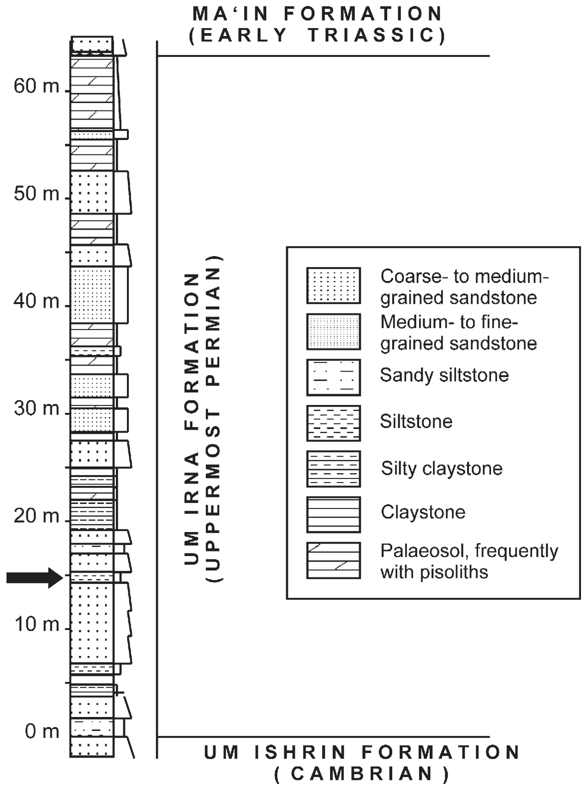


Fig. 2. Lithological profile of the Um Irna Formation at Wadi Himara. The position of the plant-bearing layer (compressions and charcoal) is indicated by the arrow.

bulk maceration). In the case of the Jordanian charcoal, this fact prevented not only the extraction of larger intact specimens from the rock matrix, but also the cleansing of the mechanically isolated small fragments with water and or acids (e.g. HCl or HF) prior to SEM studies.

In the charcoal from the Um Irna Formation of Jordan, anatomical details are excellently preserved. Not only the cell walls of the woody tracheids, but also the much more delicate cell walls of the parenchymatous ray cells have been preserved in several specimens (e.g. Plate II, 3). Also in some cases, the tori within the bordered pits are still present and in place (Plate I, 5–6). Another noteworthy detail are the cross-field pits, which can be seen in some specimens not only from the ray side (Plate II, 5), but also from the tracheid side (Plate I, 3–4). Occasionally, it can be observed that the bordered pits break away from the tracheidal walls in areas adjacent to shattered cell walls (Plate I, 7). Probably, this can be related to mechanical stress.

3.2. Taxonomic affinities

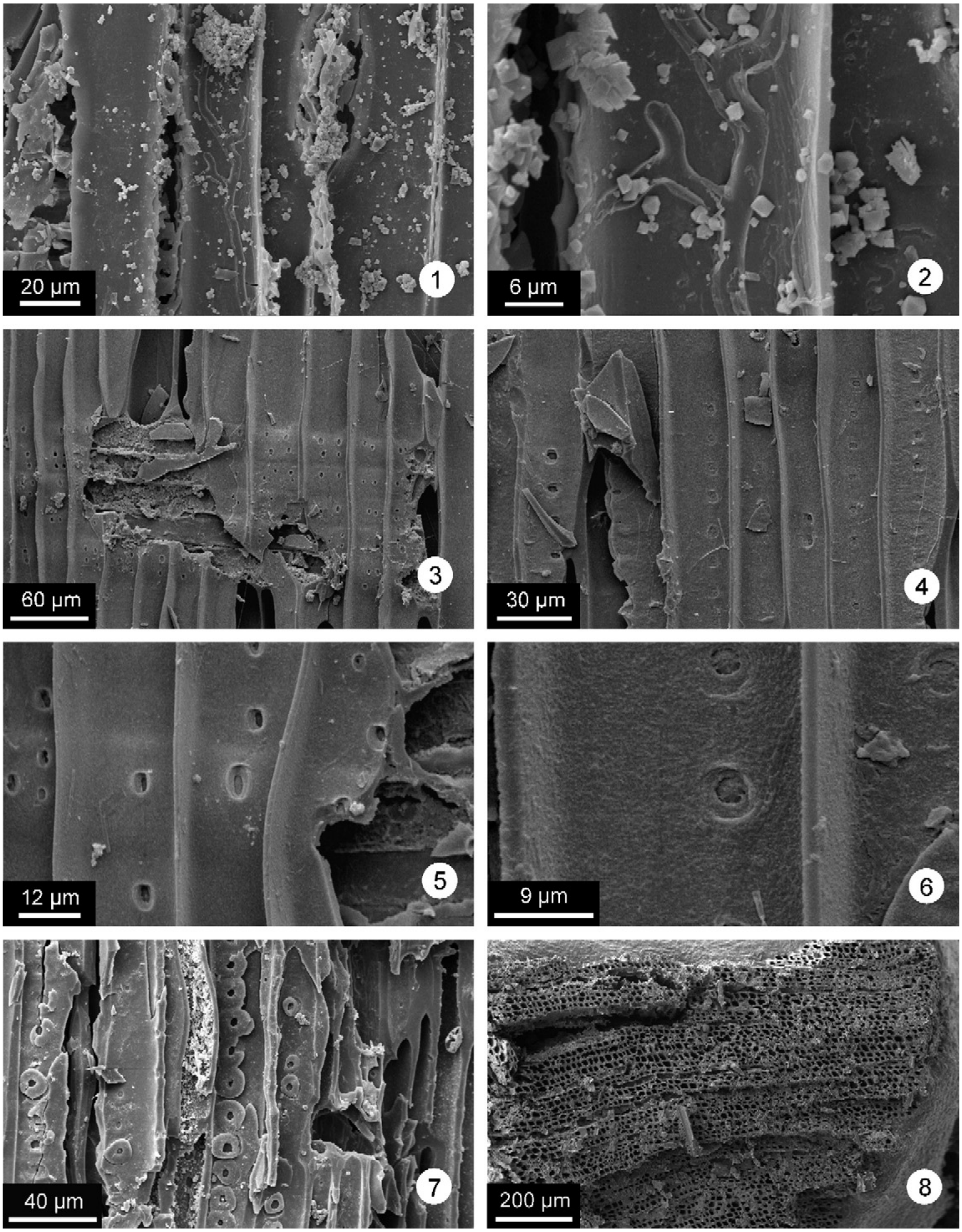
As demonstrated above, the charcoal remains investigated here show excellently preserved anatomical details, even compared to many permineralized specimens from this time period. However, in almost all

Plate I. Charcoal of *Dadoxylon*-type wood, Um Irna Formation, Late Permian, Jordan.

1. Tracheids in radial view with charred fungal hyphae (Pb-2505/1).
2. Enlargement of (1) showing details of the branching patterns of the hyphae.
3. Tracheids and wood rays in radial view (Pb-2503/1).
4. Enlargement of (3) showing details of cross-field-pitting from the tracheid side.
5. Tracheids in radial view with preserved tori in some of the pits (Pb-2503/1).
6. Enlargement of (5) showing the preserved tori.
7. Tracheids in radial view with bordered pits breaking away from the tracheidal walls (Pb-2504/2).
8. Xylem in transverse view (Pb-2504/1).

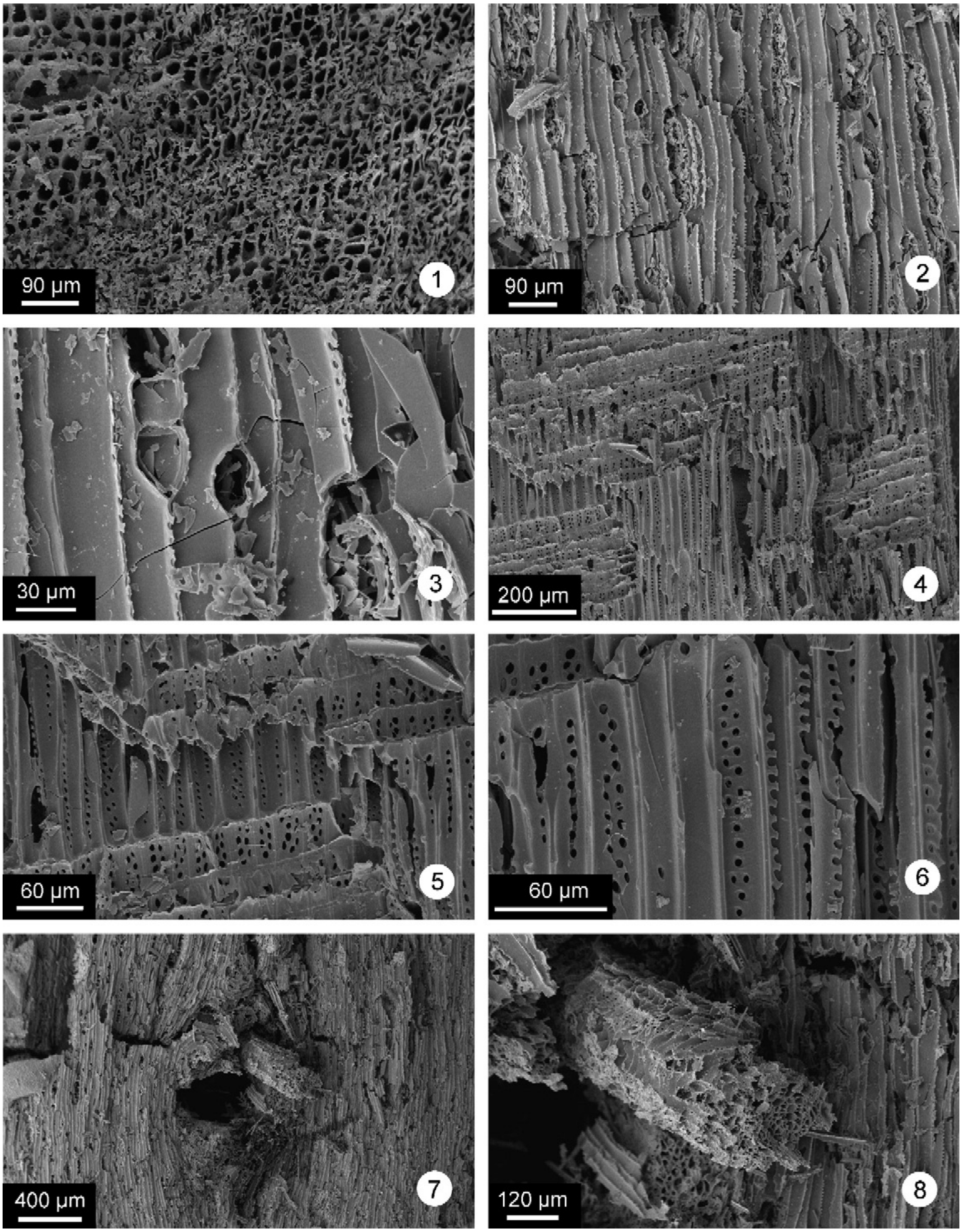
cases, the taxonomic determination of woods does not solely rely on such small scale anatomical characters, but also on the organization of the wood and in many cases on the ontogenetic development of the wood (e.g. Jane, 1962). Due to the fragmentary nature of the charcoal remains investigated here, nothing can be said about these important taxonomic and systematic characters. Without these characters, however, most of the charcoal remains can only be determined as being of the *Dadoxylon*-type of gymnospermous wood.

However, one specimen from the Um Irna Formation of Jordan exhibits some anatomical details, which may



allow a more specific taxonomic delimitation (Plate II, 1–8). The anatomy of this particular specimen is therefore described in detail:

In transverse view tracheids polygonal to square, 20–40 μm wide (Plate II, 1), with uniseriate and biseriate (rarely multiseriate) bordered pitting on radial walls (Plate II, 4–6). Pits contiguous, with circular or elliptical apertures (3–7 μm in diameter) (Plate II, 4–6). Where pits are bi- or multiseriate, they are alternately arranged (Plate II, 4–6). Rays abundant, uniseriate, 1–9 cells high (Plate II, 2–3), composed of parenchymatous cells, 110–150 μm long and 30–50 μm high (Plate II, 2–3). No ray tracheids could be observed. Cross-field pitting consists of 6–9, alternately arranged circular to elliptical



pits (5–12 μm in diameter) per field (Plate II, 5). No growth rings visible. Leaf vascular system organized in (two?) pairs of traces, each strand 270–280 μm in diameter (Plate II, 7–8).

Remarks: Like all other charcoalified specimens from Wadi Himara, this specimen cannot be determined to a generic or even specific level, except as being of the *Dadoxylon*-type of gymnospermous wood. However, when we have a closer look on the paired leaf trace (Plate II, 7), we see a gap in the tracheids directly adjacent to this pair. The course of the tracheids at the margins of this gap is not linear, as in normal areas of the wood, but curved. This observation leads to the impression that a second pair of leaf traces may be missing at the position of the gap. A comparable configuration with a complex leaf vascular system has been considered by Meyer-Berthaud et al. (1993) as typical for the Mesozoic seed fern order Corystospermales. Additionally to the configuration of the leaf traces, Meyer-Berthaud et al. (1993) defined other characteristics for the wood of this order. When we compare these proposed corystospermalean characteristics with the anatomy of the here described specimen (Table 1), we see that most characters are in agreement with each other. However, some of the details proposed to be characteristic for the Corystosperms can not be observed in our specimen. Though it cannot be proved on the base of our anatomical data the possibility remains that the here described specimen may belong to the Corystospermales. Especially when seen in the light of the fact that fronds of the Corystosperm *Dicroidium* are the major component of the compression/impression taphoflora at Wadi Himara (Abu Hamad, 2004; Kerp et al., 2006).

3.3. Palaeoenvironmental significance

From the occurrence of charcoal in the Late Permian sediments at Wadi Himara, it can be stated that the source-vegetation must have experienced fire, though at the moment very little can be said about the frequency or intensity of these wildfire activity. Today, wildfires occur frequently in vegetation types which are characterized by a well marked dry season and many ecosystems show a tendency towards higher fire frequencies with increasing aridity of the environment (e.g. Martin, 1996; Brown, 2000; Paysen et al., 2000). One of the reasons for higher fire frequencies in such environments, apart from the general dry conditions, is the slow decomposition of leaf litter and wood, leading to an increased accumulation of potential fuels (e.g. Harrington and Sackett, 1992). Even in tropical rain forests occasional droughts can promote the spread of wildfires, leading to catastrophic burns over large areas (e.g. Johnson, 1984). From this we can assume, that the Late Permian palaeoflora growing during the deposition of the Um Irna Formation may have experienced more or less dry conditions at least during some time of the year, an interpretation which is also supported by the occurrence of palaeosols with ferruginous pisoliths in the Wadi Himara profile. However, up to now, we have no direct palaeobotanical evidence, like growth rings, for such a seasonallity (see below) and we have to keep in mind that this is a period with probable high atmospheric oxygen concentration so wildfires may have been more widespread (Scott and Glasspool, 2006). On the other hand, such a climatic interpretation is in full agreement with sedimentological data for the Um Irna Formation, which indicate a low latitude tropical savannah climate, with alternating wet and dry seasons (Bandel and Khoury, 1981; Makhlouf et al., 1991). These interpretations are corroborated by the results of climate modelling, which predicted a monsoonal climate in Arabia during the Late Permian, with summer precipitation. Such a climate would favour the establishment of a warm and seasonally humid climate with a more or less marked dry season (Fluteau et al., 2001). Today, such a climate and the regular occurrence of wildfire would allow savannah to perpetuate (Bond and Keely, 2005) (although this botanical term may be somewhat misleading when applied to Late Palaeozoic vegetation, due to the lack of grass during this period).

The excellent preservation of anatomical features relatively susceptible to decay, like the parenchymatous cell walls of the ray cells, may indicate that the plants

Plate II. Charcoal of potential corystospermalean affinity, Um Irna Formation, Late Permian, Jordan (Pb-2500/1).

1. Secondary xylem in transverse view.
2. Secondary wood in tangential view.
3. Enlargement of (2) showing details of rays.
4. Secondary wood in radial view.
5. Enlargement of (4) showing details of cross-field-pitting.
6. Enlargement of (4) showing details of araucariod pitting on the tracheid walls.
7. Secondary wood in tangential view with a pair of leaf traces and adjacent gap in the wood.
8. Enlargement of (7) showing details of a leaf trace.

Table 1
Comparison of wood anatomical characters typical for the Corystospermales (sensu Meyer-Berthaud et al., 1993) and the here described wood from the Late Permian Um Irna Formation of Jordan

	Characters typical for the wood of the Corystospermales (sensu Meyer-Berthaud et al., 1993)	Here described wood
Wood pycnocylic	+	+
Rays uniseriate	+	+
Tracheids in secondary wood with 'araucariod' pitting	+	+
Cross-field pits simple, tend to be few and wide	+	+
Pith with sclerotic nests and lacunae or secretory structures	+	?
Leaf vascular system complex, originating from several axial bundles	+	+ (?)

were burnt while they were still alive or shortly after their death. Also no evidence of 'checking' of cell walls could be observed so far, which would indicate desiccation of dead wood prior to charring (Jones, 1993). It is not clear whether the observed charred fungal hyphae were growing before the wood died or not. However, the occurrence of fungal hyphae in (decaying?) wood is not very surprising and has also been reported from other occurrences of fossil charcoals (e.g. Scott, 2000). Recently, Diéguez and López-Gómez (2005) stated a possible relationship between the abundant occurrence of fungal remains in a permineralized *Dadoxylon* specimen from the Late Permian of Spain with the end-Permian fungal-spike. Considering the widespread occurrence of fungal remains within fossil woods from other periods (e.g. Creber and Ash, 1990; Scott, 2000), such an interpretation of fungal remains in Late Permian wood does not appear to be convincing.

The charcoal fragments investigated so far show no signs of true or even false growth rings (e.g. Plate I, H), which would indicate seasonally changing environmental conditions, for example changing water availability, light regime (day light) or temperature. Such non-seasonal environments are common in the tropics, in areas where there is little change in climatic and environmental conditions during the year, except some minor variation in rainfall. Under such conditions, growth is more or less uniform and growth rings are weekly developed or totally absent (Creber, 1977). However, the lack of growth rings in the specimens investigated from Wadi Himara, does not indicate that there were no such seasonal changes. It is known from other Late Palaeozoic wood remains that even under seasonally changing climatic and/or environmental conditions not all taxa did produce growth rings (e.g. conifers from the Upper Permian Zechstein deposits of Central Europe: Schweitzer, 1962, 1986; Uhl, 2004). Nevertheless, the lack of growth rings in all specimens investigated may point to the fact that the source plants grew under favourable conditions, well within the limits of their climatic and environmental tolerance. This may reflect very local conditions with enough moisture near the abandoned channels during all the year, in contrast to the regional climate which has been reconstructed as a low latitude tropical savannah climate, with alternating wet and dry seasons (Bandel and Khoury, 1981; Makhlouf et al., 1991; Fluteau et al., 2001).

4. Conclusions

From our results, we can state the following conclusions:

(1) Charcoalified wood from the Late Permian Um Irna Formation of Jordan testifies for the first time to the occurrence of palaeo-wildfire in the low latitudes of northern Gondwana during this period.
(2) The charred wood fragments are excellently preserved and most remains are identified as belonging to the *Dadoxylon*-type of gymnosperm wood.
(3) One woody specimen exhibits features that suggest a potential taxonomic relationship to the Corystospermales, a group otherwise represented at the source locality by compressed fronds assigned to the genus *Dicroidium* (Kerp et al., 2006).
(4) The occurrence of charcoal is in accordance with sedimentological data from the source locality, as well as palaeoclimatic interpretations of this formation that suggest a tropical climate with alternating wet and dry seasons, favourable for the occurrence of wildfires.

Fossil charcoal, as direct evidence of palaeo-wildfires, has so far been reported from the Late Permian of Cathaysia (e.g. Wang and Chen, 2001), Central Europe (Uhl and Kerp, 2002, 2003) and the high latitudes of Southern Gondwana (e.g. Glasspool, 2000). The here described charcoalified wood from the Late Permian of Jordan testifies for the first time to the occurrence of palaeo-wildfires in the low latitudes (palaeotropics) of northern Gondwana during this period and represents a small but important addition to our knowledge of tropical terrestrial ecosystems during the latest Palaeozoic.

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