



# Exploring the aftermath of the Cambrian explosion: The evolutionary significance of marginal- to shallow-marine ichnofaunas of Jordan

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## ABSTRACT

The middle Cambrian Hanneh Member of the Burj Formation and the middle to upper Cambrian Umm Ishrin Formation of the Dead Sea area, Jordan, contain well-preserved and abundant ichnofaunas. Trace fossils are present in a wide variety of depositional environments, from tide-dominated shelf to prodelta, delta front and interdistributary-bay tidal flats. Twelve trace fossil assemblages have been identified within a number of sequence-stratigraphic settings, namely early transgressive subtidal dune and bar complex, late transgressive isolated dune patches and dune-field abandonment, highstand deltaic progradation, and forced-regressive deltaic progradation. These ichnofaunas provide information that helps us to understand the nature of Cambrian ecosystems in the aftermath of the Cambrian radiation. The Jordan ichnofaunas display evidence of firm ground conditions at or near the sea bottom. These include (1) well-preserved scratch marks in most *Cruziana* and *Rusophycus* ichnospecies, (2) adhering *Gyrolithes polonicus* burrows, and (3) unlined passively filled *Diplocraterion* isp. penetrating into underlying mudstone. Whereas the *Diplocraterion* isp. occurrences are a classic example of the *Glossifungites* ichnofacies linked to erosional exhumation, the firmground *G. polonicus* is associated to a maximum flooding surface with no erosion involved. The trace fossil suites dominated by trilobite structures are firmground examples of the *Cruziana* ichnofacies, raising issues with respect to the substrate affinities of this ichnofacies, which is typically considered indicative of softgrounds. Our study underscores evolutionary controls on this ichnofacies, suggesting that lower Paleozoic occurrences, which are dominated by trilobite trails and trackways, reflect firm substrates and younger ones represent the typical softground examples. The occurrence of abundant bilobate trace fossils, scratch marks and trackways in interdistributary-bay tidal flats within a braidplain delta complex in the Umm Ishrin Formation provides evidence that arthropods were able to foray into marginal-marine brackish-water settings during the Cambrian. Analysis of the tiering structure indicates relatively simple communities and limited use of the infaunal ecospace. Low-energy fully marine and marginal-marine ichnofabrics are dominated by shallow-tier deposit- and detritus-feeding trace fossils. Deep-tier structures of detritus feeders are present in ichnofabrics from fully marine low-energy settings, whereas deep-tier trace fossils of suspension feeders are dominant in high-energy subtidal zones.

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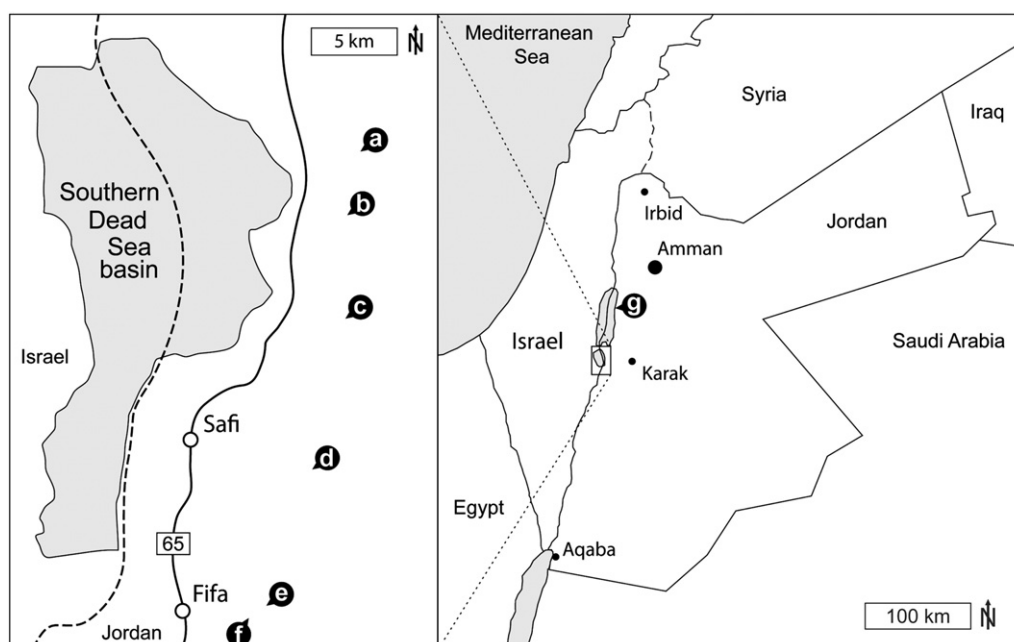
## 1. Introduction

By the end of the early Cambrian, the Cambrian explosion was essentially over, and the body-fossil record shows no further increases in diversity and disparity during the rest of the period (Marshall, 2006). The ichnology of the Ediacaran–Cambrian transition has been explored in a number of papers (e.g. Crimes, 1992, 1994; Jensen, 2003; Seilacher et al., 2005; Jensen et al., 2006). However, the aftermath of the explosion has received considerably less attention because few ichnologic studies

focus on the middle Cambrian. Superbly exposed outcrops of marginal- to shallow-marine rocks are present in the southern Dead Sea area of Jordan (Fig. 1). In particular, the middle Cambrian Hanneh Member of the Burj Formation displays a complex facies mosaic, including tide-dominated shelf and deltaic deposits (Amireh et al., 1994; Hofmann et al., 2012). The overlying middle to upper Cambrian Umm Ishrin Formation also locally contains trace fossils preserved in marginal-marine deposits. Trace fossils are abundant in these units, providing an excellent opportunity to document the ichnology of Cambrian marginal- to shallow-marine ecosystems right after the most dramatic evolutionary radiation in the history of life. The aim of this paper is to discuss how ichnologic information can illuminate our understanding of shallow-marine to coastal ecosystems in the aftermath of the Cambrian radiation. Some of the relevant evolutionary aspects involve landward

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**Fig. 1.** Map of Jordan and the Southern Dead Sea Area showing the positions of the studied localities. a, Wadi Issal ( $31^{\circ}11'21.1''\text{N}$ ,  $35^{\circ}33'16.2''\text{E}$ ); b, Wadi Uhaymir ( $31^{\circ}9'7.0''\text{N}$ ,  $35^{\circ}33'45.5''\text{E}$ ); c, Wadi Qunai ( $31^{\circ}5'48.8''\text{N}$ ,  $35^{\circ}33'27.1''\text{E}$ ); d, Wadi Al Hisa ( $31^{\circ}0'50.2''\text{N}$ ,  $35^{\circ}32'20.6''\text{E}$ ); e, Wadi Umm Jafna ( $30^{\circ}56'39.40''\text{N}$ ,  $35^{\circ}29'58.30''\text{E}$ ); f, Wadi Fifa ( $30^{\circ}55'54.00''\text{N}$ ,  $35^{\circ}28'42.00''\text{E}$ ); and g, Zerqa Ma'in ( $31^{\circ}37'52.1''\text{N}$ ,  $35^{\circ}34'27.9''\text{E}$ ).

expansion of benthic faunas and colonization of marginal-marine settings. Accordingly, placing these ichnofaunas within a paleoenvironmental and sequence-stratigraphic framework is a pre-requisite for a sound evaluation of the evolutionary implications.

## 2. Stratigraphy, depositional setting and age

The Burj and Umm Ishrin formations are exposed near the southern portion of the Dead Sea, Jordan (Figs. 1, 2). The Burj Formation occurs above the mostly continental lower Cambrian Salib Formation, and consists of three members, Tayan, Numayri and Hanneh (Bender, 1974; Powell, 1989; Amireh et al., 1994; Rushton and Powell, 1998; Schneider et al., 2007; Shinaq and Elicki, 2007). The lower Cambrian–middle Cambrian transition is placed close to the base of the Numayri member, based on trilobites and various microfauna (Rushton and

Powell, 1998; Geyer and Langing, 2004; Shinaq and Elicki, 2007; Elicki, 2011; Elicki and Geyer, in press).

The lower two members and the lower interval of the Hanneh Member represent a transgressive succession, recording the transition from shallow-intertidal to supratidal siliciclastics (Tayan Member) to marginal- and open-marine carbonates (Numayri Member) and tide-dominated shallow-marine siliciclastics (Hanneh Member) (Amireh et al., 1994; Elicki, 2007; Shinaq and Elicki, 2007). Within the Hanneh Member, a maximum flooding surface separates subtidal deposits of the lower part of the member from prodelta to delta-front deposits recorded in the upper part (Hofmann et al., 2012).

The Burj Formation is sharply overlain by the Umm Ishrin Formation, which records an abrupt basinward facies migration as a result of a forced regression. The base of this formation is, therefore, considered as a regressive surface of marine erosion. The Umm Ishrin Formation



**Fig. 2.** General view of the studied units in Wadi Uhaymir.

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