



Deposited via The University of Sheffield.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/194499/>

Version: Published Version

Article:

Wellman, C.H., Cascales-Miñana, B. and Servais, T. (2023) Terrestrialization in the Ordovician. Geological Society, London, Special Publications, 532 (1). pp. 171-190. ISSN: 0305-8719

<https://doi.org/10.1144/sp532-2022-92>

Reuse

This article is distributed under the terms of the Creative Commons Attribution (CC BY) licence. This licence allows you to distribute, remix, tweak, and build upon the work, even commercially, as long as you credit the authors for the original work. More information and the full terms of the licence here:

<https://creativecommons.org/licenses/>

Takedown


If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

Terrestrialization in the Ordovician

Charles H. Wellman^{1*}, Borja Cascales-Miñana² and Thomas Servais²

¹School of Biosciences, University of Sheffield, Alfred Denny Building, Western Bank, Sheffield S10 2TN, UK

²CNRS, Université de Lille, UMR 8198 – Evo-Eco-Paleo, F-59000, Lille, France

 CHW, 0000-0001-7511-0464; BC-M, 0000-0002-3088-835X; TS, 0000-0002-4089-7874

*Correspondence: c.wellman@sheffield.ac.uk



Abstract: This contribution reviews the evidence for terrestrial organisms during the Ordovician (microbial, land plant, fungal, animal) and for the nature of the terrestrial biota. The evidence regarding the origin and early diversification of land plants combines information from both fossils and living organisms. Extant plants can be utilized in: (1) phylogenetic analyses to provide evidence for the nature of the algal–land plant transition and the characteristics of the most basal land plants; (2) evolutionary developmental biology studies of the characters that enabled the invasion of the land; (3) molecular clock analysis to provide evidence regarding timing of the origin and diversification of land plants. We conclude that the Ordovician was a critical period during the terrestrialization of planet Earth that witnessed the transition from a microbial terrestrial biota to one dominated by a vegetation of the most basal land plants.

Palaeontological research aimed at reconstructing life in the Ordovician has historically focused on the marine environment and reconstructing the ‘Great Ordovician Biodiversification Event’ and effects of the ‘End Ordovician Mass Extinction’. Studies on life in terrestrial environments has largely been neglected (but see reviews by Gray 1985; Richardson 1996; Wellman 1999; Retallack 2000; Steemans 2000; Strother 2000; Wellman and Gray 2000; Steemans and Wellman 2004; Wellman *et al.* 2013; Servais *et al.* 2019). In part this is a consequence of the paucity of Ordovician non-marine sediments and hence a dismally poor fossil record of non-marine organisms (except for those that have been transported into marine settings). But it also reflects historical research agendas based on assumptions that the first land plants did not appear until the Silurian. Since the 1980s this latter view has been challenged, and evidence has accumulated suggesting that land plants first appeared in the Ordovician and may have been accompanied by the first animals to emerge from the oceans (either directly or migrating into brackish and freshwater environments and finally venturing onto land). More recently evidence emanating from molecular biology, including phylogenetic, molecular clock and evolutionary developmental biology (evo-devo) analyses, has added to this growing body of evidence for an Ordovician terrestrial biota. In this chapter we will discuss the evidence for this terrestrial biota and attempt to reconstruct it. We argue that the Ordovician was a critical period during the terrestrialization of planet Earth.

An Early Ordovician terrestrial microbial world

The earliest terrestrial ecosystems were essentially microbial comprising freshwater ecosystems, periodically inundated microbial mats adjacent to rivers and lakes, and microbial crusts developed on rudimentary soils (reviewed in Wellman and Strother 2015). Such ecosystems are well documented from the billion-year-old Lagerstätten of the Torridonian of Scotland (Strother *et al.* 2011) and the Nonesuch Formation of the USA (Strother and Wellman 2021). They have also been shown to have persisted into the Silurian after land plants (embryophytes) had evolved and begun to colonize the continents (Tomescu and Rothwell 2006; Tomescu *et al.* 2006, 2008, 2009, 2010). The aquatic biotas included primary producers such as photosynthetic cyanobacteria (including both benthic and planktonic forms) (Strother and Wellman 2015) and a variety of other prokaryotic and eukaryotic organisms (e.g. Strother *et al.* 2021). The microbial mats and crusts were established around photosynthetic cyanobacteria. At present there is little evidence for a significant fungal or lichen component (discussed below). It seems likely that such microbial ecosystems dominated Ordovician terrestrial ecosystems until the origin of land plants in the Middle Ordovician. Figure 1 illustrates an assemblage of microbial fossils recovered from an Early Ordovician terrestrial deposit. The components are essentially identical to those described from the billion-year-old terrestrial deposits of the Torridonian Group and Nonesuch Formation.

From: Harper, D. A. T., Lefebvre, B., Percival, I. G. and Servais, T. (eds) *A Global Synthesis of the Ordovician System: Part 1*. Geological Society, London, Special Publications, **532**, <https://doi.org/10.1144/SP532-2022-92>

© 2022 The Author(s). This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>). Published by The Geological Society of London.

Publishing disclaimer: www.geolsoc.org.uk/pub_ethics

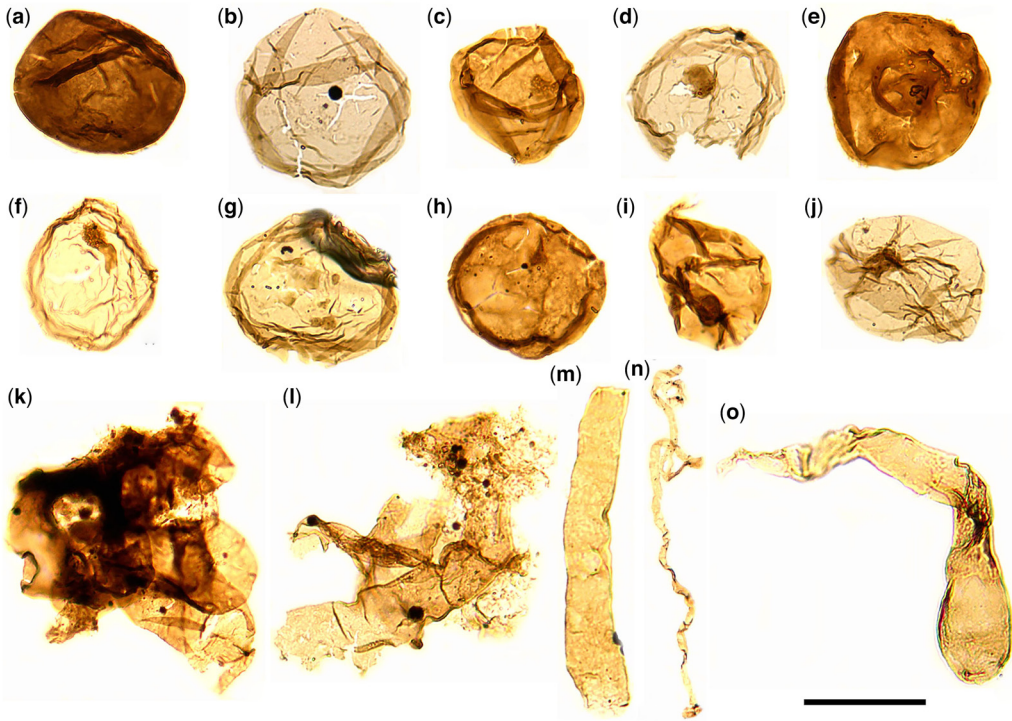


Fig. 1. Light microscope images of microbial remains recovered by palynological processing of Ordovician (Floian–? early Dapingian) continental deposits from the Ghudun Formation of Oman. (a–c) Sphaeromorph; (d) Sphaeromorph with surface spot; (e) Sphaeromorph with circular ‘hilum’; (f) Sphaeromorph with surface spot from which a tube extends; (g) and (h) Sphaeromorph; (i) and (j) Sphaeromorph with surface spot; (k) cluster of Sphaeromorphs; (l) association of tubular structures; (m) isolated wide tube; (n) isolated narrow tube (filament); (o) tube with expanded tip. Scale bars: (a–j), 30 μm ; (k–l), 40 μm ; (m), 30 μm ; (n), 100 μm ; (o), 30 μm .

The fossil record of land plants

Historically research on terrestrialization in the Ordovician has relied heavily on the fossil record. Regarding land plants, this includes plant megafossils, dispersed spores and disarticulated fragments of the plants. The latter two fossil types are generally recovered by palynological acid maceration techniques. A major hindrance to research has been the paucity of non-marine deposits recorded from the Ordovician worldwide. Land plant megafossils can be transported into marine deposits, yet the expectation is that they will be much rarer than in terrestrial deposits due to their allochthonous nature. Also, they are mixed with marine fossils and therefore it can be difficult to distinguish between fossils deriving from marine and non-marine organisms. Dispersed microfossils (spores and phytodebris) are readily transported into marine environments where they may be abundant. Again, however, the problem is that the non-marine provenance of biologically ambiguous forms cannot be confirmed.

Plant megafossils

The oldest generally accepted plant megafossils are rhyniophytoid plants, preserved as coalified compressions, from the Silurian (Wenlock) (Edwards *et al.* 1983; Libertin *et al.* 2018). These show evolutionary continuity with younger Silurian forms that possess unequivocal spore-containing sporangia, stomata and conducting tissues (in some cases true tracheids) (Edwards *et al.* 1992). Twenty-five or so Silurian localities preserve such plant megafossil assemblages, and by the Lower Devonian (Lochkovian) they are abundant with at least 30 assemblages known worldwide (most recently reviewed by Edwards and Wellman 2001; Wellman *et al.* 2013). The coalified compressions preserve little anatomical detail. However, the anatomy of these plants is now well known due to Lagerstätten yielding exquisitely preserved charcoalfied remains: Ludford Lane of Late Silurian (Pridoli) age and North Brown Clee Hill of Early Devonian (Lochkovian) age, both from the Anglo-Welsh basin of the

Terrestrialization in the Ordovician

UK (e.g. [Morris et al. 2018](#)). The Lower Devonian (Pragian–?earliest Emsian) silicified plants from the Rhynie chert Lagerstätten are also important in preserving exquisite anatomical detail of early land plants (e.g. [Edwards et al. 2017](#)).

There are regular and numerous claims for pre-Silurian plant megafossils. However, these are discounted as they can be proven to be fragments of other organisms (e.g. [Kenrick et al. 1999](#)) or they lack sufficient characters to be unequivocally assigned to land plants (e.g. [Salamon et al. 2018](#); [Naugolnykh 2019](#); [Retallack 2019](#)). Throughout the 1960s, 1970s and 1980s Banks, Chaloner and others thoroughly catalogued and discredited such claims (e.g. [Chaloner 1960, 1970](#); [Banks 1975a, b](#)). This procession continues to this day, and it is still doubtful that any claimed pre-Silurian land plant possesses sufficient unequivocal plant characters to be confidently and unequivocally proven to be a land plant. As noted by [Edwards et al. \(2021a\)](#) (p. 1453) ‘when diagnostic features are absent, such fragmentary organic materials can be misinterpreted, leading to implausible attributions (e.g. [Retallack 2019](#))’.

Occasionally spore masses or even partial sporangia have been recovered during palynological processing of Ordovician deposits ([Wellman et al. 2003](#); [Abuhmida and Wellman 2017](#)). From the Late Ordovician (Katian) of Oman [Wellman et al. \(2003\)](#) report spore masses, including some enclosed within a homogenous covering, and partial sporangia with fragments of sporangial wall attached ([Fig. 2](#)). The enclosed spores can be identified among dispersed forms (see below). These plant remains provide a tantalizing insight into Ordovician land plants and, if nothing else, demonstrate that they produced vast numbers of spores within sporangia that were extremely small but clearly highly fecund.

Dispersed spores

Spores encased in a resistant sporopollenin wall are a synapomorphy of land plants and it seems likely that the invasion of the land by plants was coincident with development of a subaerial reproductive strategy that utilized such spores ([Blackmore and Barnes 1987](#); [Wellman 2004](#)). They have an excellent fossil record because they are produced in vast numbers, capable of dispersal over huge distances by wind and water, and are relatively resistant to degradation. Research by the early palynological pioneers established, by the 1970s, a continual record of dispersed land plant trilete spores from the early Silurian (Llandovery) onwards (e.g. [Richardson and McGregor 1986](#); [Streel et al. 1987](#)). These spores are often identical to those reported *in situ* from the earliest rhyniophytoid–rhyniophyte land plant megafossils (see above). However, in a series of ground-breaking

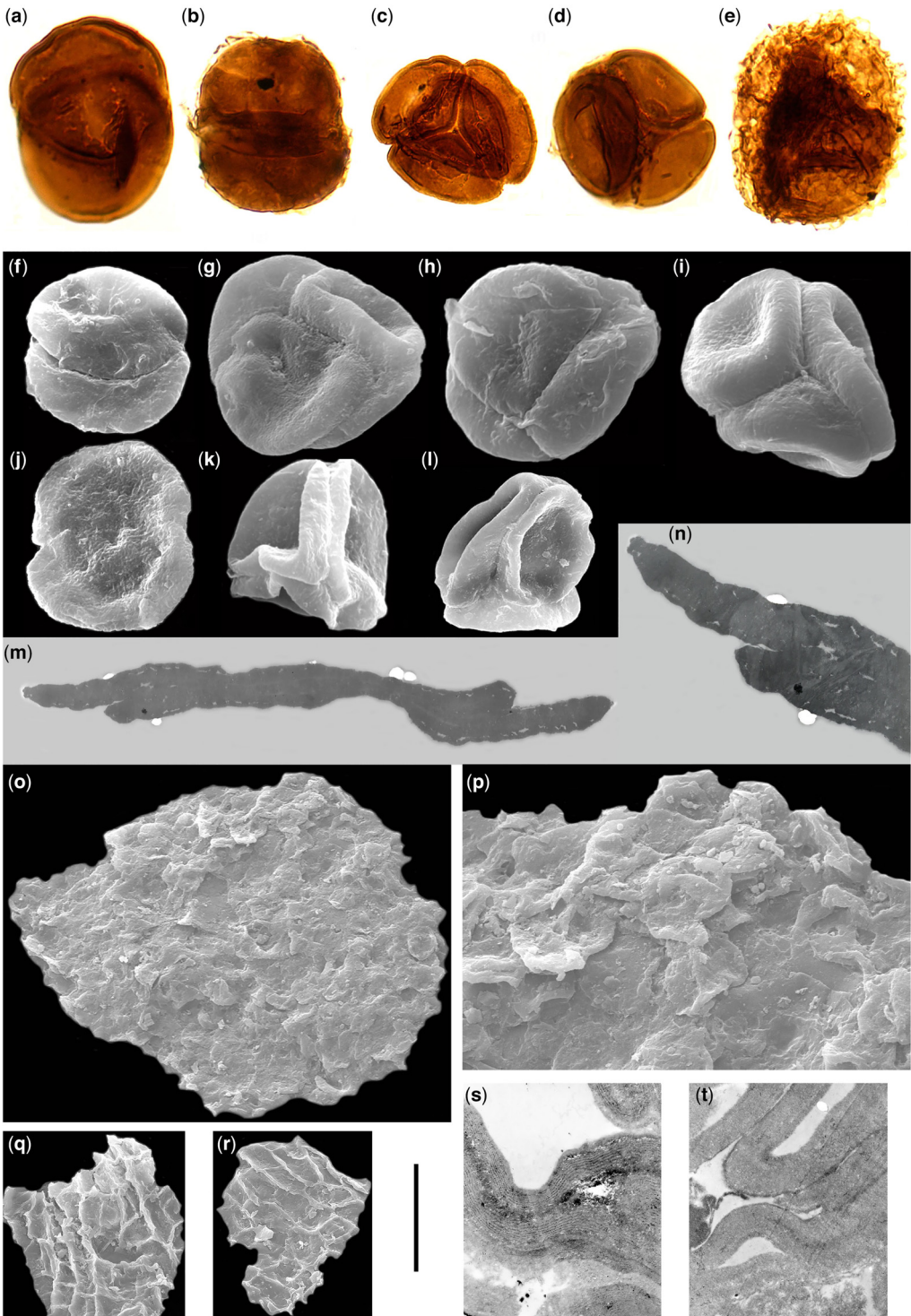
papers Jane Gray and colleagues reported on a new group of dispersed spores, extending back into the Ordovician, that were subsequently proven to be the spores of land plants ([Gray and Boucot 1971](#); [Gray et al. 1982](#); [Gray 1985, 1991](#)) produced by eophyte plants ([Edwards et al. 2021a, b, c](#)). These were called cryptospores because they occur in unusual configurations (e.g. permanent dyads and tetrads) ([Richardson 1988](#)) ([Fig. 2](#)).

The oldest reported occurrence of cryptospores clearly related to land plants is currently considered to be in the Middle Ordovician (Dapingian or Darriwilian) suggesting that land plants had successfully invaded the land by this time. They have now been reported continuously from this time point, with records from most palaeocontinents, extending through time until the end Pragian, after which they become extremely rare in the fossil record (see [Table 1](#) and [Figs 3–6](#)). Cryptospores include monads, dyads and tetrads that are either naked or enclosed within an envelope. The envelope may be laevigate or ornamented. Cryptospore taxonomy utilizes the following characters: the number of units (monad, dyad, tetrad), the nature of attachment of these units (fused or unfused), the presence/absence of an envelope, the infraornament/ornament of the wall and/or envelope. A number of Ordovician cryptospores (dispersed and *in situ*) have been examined ultrastructurally and their gross structure/wall ultrastructure evaluated with regard to evidence for biological affinities (see [Table 2](#)) ([Fig. 2](#)). More recently Ordovician cryptospores have also been examined using a synchrotron light source ([Guizar-Sicairos et al. 2015](#)).

Very similar cryptospore assemblages have been reported throughout the Ordovician (spatially and temporally). Biostratigraphic schemes have been proposed, but these tend to be rather coarse with respect to time resolution (e.g. [Richardson 1988](#); [Steemans et al. 2000](#)). This is a consequence of the morphological simplicity of cryptospores (and hence lack of characters compared to trilete spores) and their seemingly slow pace of acquisition of novel morphological characters. The palaeogeographical spread, consistency and relative stasis exhibited by cryptospore assemblages have been taken to indicate that the first flora to invade the land consisted of cosmopolitan generalists that occupied a wide range of environments and evolved relatively little throughout the course of the Ordovician ([Gray 1985](#); [Wellman 1996](#)).

Probable non-marine palynomorphs that occur as irregular clusters of dyads and other polyads (in packets) have been described from Early Ordovician (Tremadocian) and earlier Cambrian deposits ([Strother and Foster 2021](#)). These have been included with the cryptospores by some authors but are excluded by others. This is largely a semantic

C. H. Wellman *et al.*



Terrestrialization in the Ordovician

debate as several very different definitions for the term cryptospore have been proposed (see discussion in *Servais et al.* 2019). This debate centres on whether cryptospores are defined as the spores of land plants (our preferred interpretation) or represent palynomorphs produced by any non-marine organisms. The most recent interpretation for the enigmatic Cambrian–Early Ordovician palynomorphs is that they represent charophyte algal remains (*Strother and Foster* 2021) and may thus represent intermediate organisms on the freshwater green algal to terrestrial land plant lineage.

The first trilete spores, similar to those produced by Silurian rhyniophytoid plants, first appear in low numbers in the Ordovician (*Stemans et al.* 2009). They are difficult to identify because spores physically removed from cryptospore tetrads often bear a false trilete mark resulting from physical tearing as the polyads are broken apart. Similar to trilete spores, hilate cryptospores are produced by the natural dissociation of a polyad, but in this case a dyad (*Richardson* 1988). On their proximal surface they bear a circular contact area (hilum) formed where they were in contact with the other spore in the dyad. Like trilete spores, these naturally dissociated spores are common in the Silurian. They occur rarely in the Ordovician and again can be easily mistaken for spores physically separated from permanent dyads (*Stemans et al.* 2000).

Trilete spores only become common in dispersed spore assemblages in the Late Silurian whereupon they rapidly increase in abundance and diversity and have stratigraphical continuity with living trilete spore-producing plants. It has been proposed that this pattern reflects the origin and diversification of vascular plants (tracheophytes), because most Silurian–Devonian vascular plants have been shown to produce trilete spores (as do many extant basal groups of vascular plants) (e.g. *Gray* 1985; *Wellman and Gray* 2000; *Wellman et al.* 2013). The rare reports of trilete spores from the Ordovician–Early Silurian may have derived from various non-

vascular plants as trilete spores are known to be produced by some extant non-vascular plants (see *Stemans et al.* 2009) and various plant groups are likely to have evolved this basic character independently.

We can only speculate as to where the first land plants appeared and the course of their spread across the continents. The earliest generally accepted reports of cryptospores are all currently from Gondwana which has led to speculation that they may have evolved on this continent before rapidly spreading out across the other continents of the planet (*Stemans et al.* 2010; *Wellman* 2010).

Phytodebris

Plants naturally shed organs during their lifetime and on death begin to rot and disassociate. These processes produce recalcitrant fragmentary remains that are dispersed by gravity, wind and water and are ultimately incorporated into sediment from which they can be recovered by palynological processing. Such fragmentary plant remains, composed of recalcitrant biomacromolecules that survive as fossils, are termed phytodebris. They include plant cuticles composed of cutin, lignified tissues such as tracheids and reproductive propagules composed of sporopollenin (spores, megaspores, ovules and seeds), in addition to a number of more enigmatic remains. The fossil record and interpretation of phytodebris produced by early land plants was recently reviewed by *Wellman and Ball* (2021).

There are surprisingly few reports of Ordovician phytodebris, perhaps reflecting the dearth of non-marine deposits examined (*Fig. 2*). Silurian non-marine deposits usually yield a diverse array of phytodebris. These include cuticles (sometimes with stomata) and tracheids, that clearly derive from land plants. More enigmatic are cuticle-like sheets and tubular structures (including banded tubes) that are now known to derive from nematophytes. Nematophytes were recently demonstrated to have fungal and possibly also lichen affinities (*Edwards and*

Fig. 2. Land plant remains recovered by palynological processing of Ordovician (Katian) continental deposits from the Hasirah Formation of Oman. (a–e) Light microscope images of dispersed spores (cryptospores): (a) naked permanent fused dyad (pseudodyad); (b) permanent unfused dyad (true dyad) enclosed in a laevigate envelope; (c) naked permanent unfused tetrad; (d) permanent unfused tetrad enclosed in a laevigate envelope; (e) permanent unfused tetrad enclosed in an ornamented envelope. (f–l) Scanning electron microscope (SEM) images of dispersed spores (cryptospores): (f) naked permanent unfused dyad (true dyad); (g) naked permanent unfused tetrad; (h) permanent unfused tetrad enclosed in a laevigate envelope; (i) naked permanent unfused tetrad; (j) naked permanent fused dyad (pseudodyad) with microgranulate ornament; (k) naked permanent unfused tetrad; (l) naked permanent unfused tetrad. (m–n) Transmission electron microscope (TEM) images of a section cut from an individual dispersed spore (naked permanent unfused dyad): (m) entire dyad; (n) close-up of left-hand part of dyad. (o) and (p) SEM images of a spore mass: entire spore mass (o) and close up of part of the spore mass illustrating the nature of the spores (p). (q) and (r) Fragments of dispersed cuticle-like sheets. (s) and (t) TEM images of sectioned sporangia/spore masses: Sporangium containing spores with wall ultrastructure lamellate (s) and spore mass containing spores with wall ultrastructure homogeneous (t). Scale bar: (a–e), 25 µm; (f–l), 25 µm; (m), 7.25 µm; (n), 4.6 µm; (o), 75 µm; (p), 25 µm; (q), 85 µm; (r), 115 µm; (s), 1.8 µm; (t), 2.5 µm.

Table 1. *Dispersed spore assemblages reported from the Ordovician*

Location/stage	Location	Palaeocontinent	Palaeoenvironment	Age dating	References
H1 Hirnantian?	Ontario, Canada	Laurentia	Palaeokarst surface	Lithostratigraphy	Gray (1988)
H2 Hirnantian	Quebec, Canada	Laurentia	Shallow marine	Inv + Palynology	Richardson and Ausich (2007); Vecoli <i>et al.</i> (2011)
H3 Hirnantian	Southern Britain	Avalonia	Shallow marine	G	Burgess (1991)
H4 Hirnantian	Sweden	Baltica	Shallow marine	G	Badawy <i>et al.</i> (2014)
H5 Hirnantian	Estonia	Baltica	Shallow marine	Palynology	Vecoli <i>et al.</i> (2011)
H6 Hirnantian	Zhejiang, China	South China	Shallow marine	Inv	Yin and He (2000)
H7 Hirnantian	Czech Republic	PeriGondwana	Shallow marine	G	Vavrdova (1982, 1984, 1988, 1989); Gray (1988)
H8 Hirnantian?	Bulgaria	PeriGondwana	Shallow marine	Palynology	Lakova <i>et al.</i> (1992)
H9 Hirnantian	Iran	PeriGondwana	Shallow marine	Palynology	Mahmoudi <i>et al.</i> (2014); Ghavidel-Syooki (2017); Ghavidel-Syooki and Piri-Kangarshahi (2021a)
H10 Hirnantian?	Australia	Gondwana	Marine evaporites	Palynology	Foster and Williams (1991)
H11 Hirnantian	Saudi Arabia	Gondwana	Glacial shallow marine	Lithostratigraphy	Miller and Al-Ruwaili (2007); Steemans <i>et al.</i> (2009); Wellman <i>et al.</i> (2015)
H12 Hirnantian	Algeria	Gondwana	Shallow marine	Ch-Palynology	Spina (2015)
H13 Hirnantian	Libya	Gondwana	Shallow marine	G	Gray <i>et al.</i> (1982); Richardson (1988); Le Hérisse <i>et al.</i> (2013); Thusu <i>et al.</i> (2013)
H14 Hirnantian	Chad	Gondwana	Shallow marine	Ch-Palynology	Le Hérisse <i>et al.</i> (2013)
H15 Hirnantian	South Africa	Gondwana	Glacial shallow marine	Ch-Palynology	Gray <i>et al.</i> (1986)
H16 Hirnantian	Argentina	Gondwana	Shallow marine	Inv-Palynology	Rubinstein and Vaccari (2004); Rubinstein (2005)
KH1 Katian-Hirnantian?	Kentucky, USA	Laurentia	Shallow marine	Palynology	Gray (1988)
KH2 Katian-Hirnantian?	Tennessee, USA	Laurentia	Shallow marine	Palynology	Gray (1988)
KH3 Katian-Hirnantian?	Georgia, USA	Laurentia	Shallow marine	Palynology	Gray (1988)
KH4 Katian-Hirnantian?	Belgium	Avalonia	Shallow marine	Palynology	Stemans (2001)
KH5 Katian-Hirnantian?	Turkey	Gondwana	Shallow marine	Palynology	Stemans <i>et al.</i> (1996)
K1 Katian	Illinois, USA	Laurentia	Shallow marine	Inv	Strother (1991)
K2 Katian	Ohio, USA	Laurentia	Shallow marine	Ch-Palynology	Gray and Boucot (1972); Gray (1988)

K3 Katian	Southern Britain	Avalonia	Shallow marine	Inv	Richardson (1988); Wellman (1996)
K4 Katian	Sweden	Baltica	Shallow marine	G	Badawy <i>et al.</i> (2014)
K5 Katian	Poland	Baltica	Shallow marine	G-Palynology	Stempién-Salek (2011)
K6 Katian	Estonia	Baltica	Shallow marine	Palynology	Vecoli <i>et al.</i> (2011)
K7 Katian?	Germany	?Baltica	Shallow marine	C	Reitz and Heuse (1994)
K8 Katian	Siberia, Russia	Siberia	Shallow marine	Inv + Palynology	Raevskaya <i>et al.</i> (2016)
K9 Katian	Xinjiang, China	Tarim	Shallow marine	G + C + Inv + Ch-palynology	Wang <i>et al.</i> (1997); Tang <i>et al.</i> (2017)
K10 Katian	Iran	PeriGondwana	Shallow marine	Palynology	Mahmoudi <i>et al.</i> (2014); Ghavidel-Syooki (2017); Ghavidel-Syooki and Piri-Kangarshahi (2021b)
K11 Katian	Saudi Arabia	Gondwana	Shallow marine	Ch-Palynology	Molyneux and Al-Hajri (2000); Steemans <i>et al.</i> (2009); Wellman <i>et al.</i> (2015)
K12 Katian	Oman	Gondwana	Terrestrial-nearshore marine	Ch-Palynology	Wellman <i>et al.</i> (2003)
K13 Katian	Libya	Gondwana	Shallow marine	G	Gray <i>et al.</i> (1982);
K14 Katian	Argentina	Gondwana	Shallow marine	Ch-Palynology	de la Puente and Rubinstein (2013); Rubinstein <i>et al.</i> (2016)
S1 Sandbian	Southern Britain	Avalonia	Shallow marine	Inv	Richardson (1988); Wellman (1996)
S2 Sandbian*	Sweden	Baltica	Shallow marine	C	Rubinstein and Vajda (2019)
S3 Sandbian	Poland	Baltica	Shallow marine	G-Palynology	Stempién-Salek (2011)
S4 Sandbian	Saudi Arabia	Gondwana	Shallow marine	Ch-Palynology	Molyneux and Al-Hajri (2000)
S5 Sandbian	Libya	Gondwana	Shallow marine	G	Gray <i>et al.</i> (1982)
S6 Sandbian	Argentina	Gondwana	Shallow marine	G + C	Ottone <i>et al.</i> (1999)
Dr1 Darriwilian	Czech Republic	PeriGondwana	Shallow marine	G	Corna (1970); Vavrdova (1990, 1993)
Dr2 Darriwilian	Australia	Gondwana	Shallow marine	Palynology	Spaak <i>et al.</i> (2017)
Dr3 Darriwilian	Saudi Arabia	Gondwana	Shallow marine	Ch-Palynology	McClure (1988); Strother <i>et al.</i> (1996, 2015); Molyneux and Al-Hajri (2000); Le Hérisse <i>et al.</i> (2007); Vecoli <i>et al.</i> (2017)
Dr4 Darriwilian	Libya	Gondwana	Shallow marine	Palynology	Abuhmida and Wellman (2017)
Dr5 Darriwilian	Argentina	Gondwana	Marginal marine	Palynology	Rubinstein <i>et al.</i> (2011)
Dp1 Dapingian?	Saudi Arabia	Gondwana	Marginal marine	Palynology	Vecoli <i>et al.</i> (2017)
Dp2 Dapingian**	Argentina	Gondwana	Marginal marine	Ch-Palynology	Rubinstein <i>et al.</i> (2010)

C, conodonts; Ch, chitinozoans; G, graptolites; Inv, invertebrates.

*We do not consider that any of the pre-Sandbian cryptospores illustrated in this paper represent cryptospores, but rather folded sphaeromorphs and acritarchs.

**Strother *et al.* (2015) have questioned the validity of the cryptospores described in this paper.

C. H. Wellman *et al.*

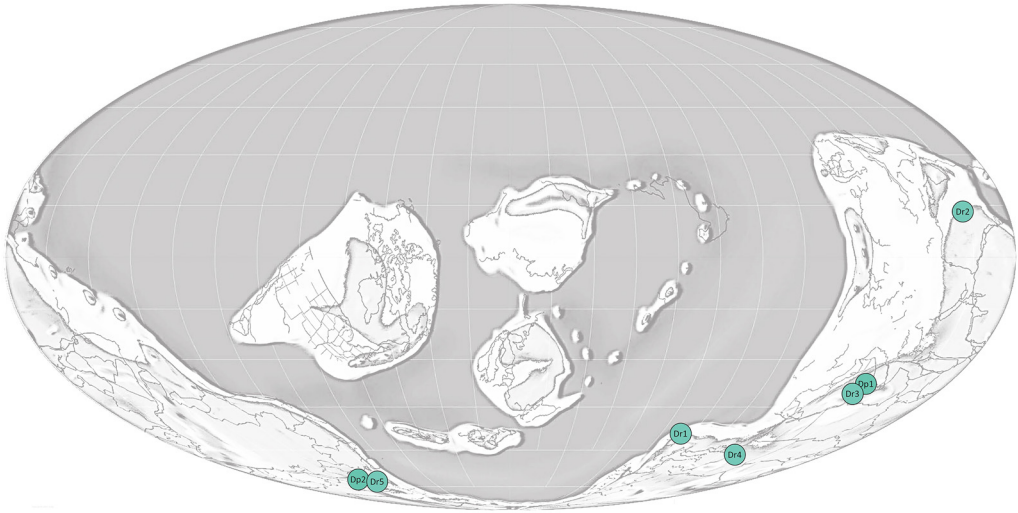


Fig. 3. Palaeogeographic map of the Dapingian and Darriwilian showing the location of dispersed spore assemblages. Locality codes refer to those used in Table 1. Modified from Scotese (2014).

Axe 2012; Edwards *et al.* 2013, 2018; Honegger *et al.* 2013, 2017). Related nematophyte remains appear not to extend back into the Ordovician. Rare cuticle-like sheets have been reported (Gray *et al.* 1982; Strother *et al.* 1996) (see Fig. 2). Ordovician tubular structures are usually smooth-walled forms (Burgess and Edwards 1991; Strother *et al.* 1996) with the reported banded tubes unconvincing (reviewed in Taylor and Wellman 2009). Because all of the reported Ordovician phytodebris are from

marine deposits it is difficult to prove if they derive from terrestrial organisms rather than any variety of marine organism.

Regarding the biological affinities of the Ordovician phytodebris, the cuticle-like sheets may possibly derive from early nematophytes, although these have not been convincingly reported from the Ordovician. They may derive from early land plants, but in the absence of a megafossil record it is difficult to make comparisons. The smooth-walled tubular

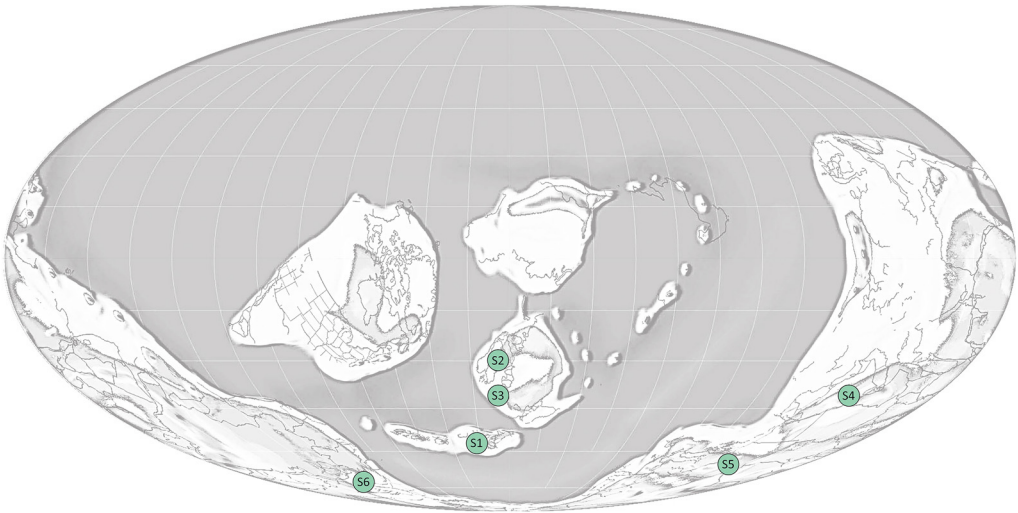


Fig. 4. Palaeogeographic map of the Sandbian showing the location of dispersed spore assemblages. Locality codes refer to those used in Table 1. Modified from Scotese (2014).

Terrestrialization in the Ordovician

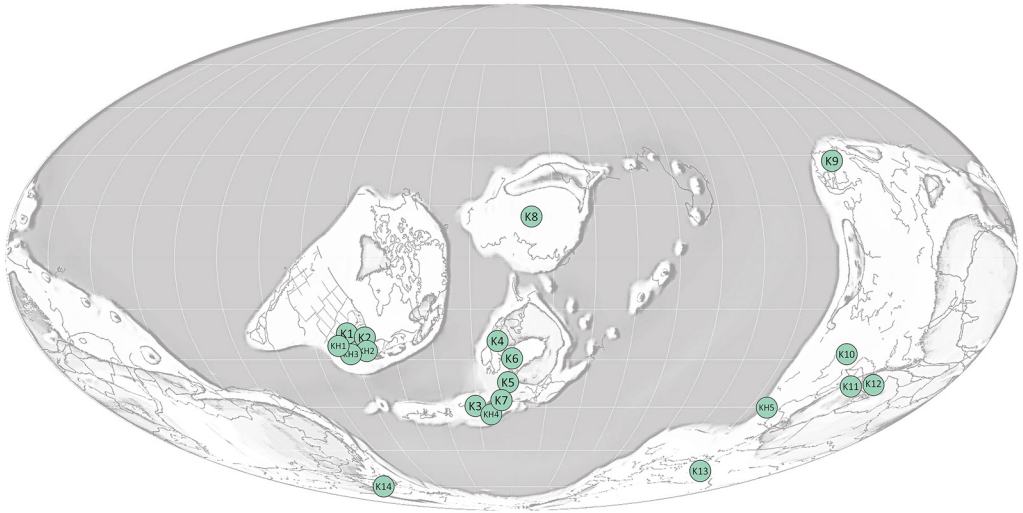


Fig. 5. Palaeogeographic map of the Katian showing the location of dispersed spore assemblages. Locality codes refer to those used in Table 1. Modified from Scotese (2014).

structures may derive from nematophytes or land plants. It is also possible that they represent cyanobacterial sheathes such as those described from the Silurian by Tomescu and colleagues (e.g. Tomescu and Rothwell 2006).

Geochemical biomarkers

In recent years reports on the first searches for early land plant biomarkers have begun to appear. For

example, Romero-Sarmiento *et al.* (2011) analysed Gondwanan Late Ordovician–Early Devonian sediments for the presence of aliphatic and aromatic biomarkers indicative of the presence of land plants (Versteegh and Riboulleau 2010). Spaak *et al.* (2017) reported on the presence of benzonaphthofurans and delta $\delta^{13}\text{C}$ -depleted mid-chain *n*-alkanes that they interpreted as indicative of the presence of bryophyte-like early land plants. This may be a fruitful area for future research as analytical techniques

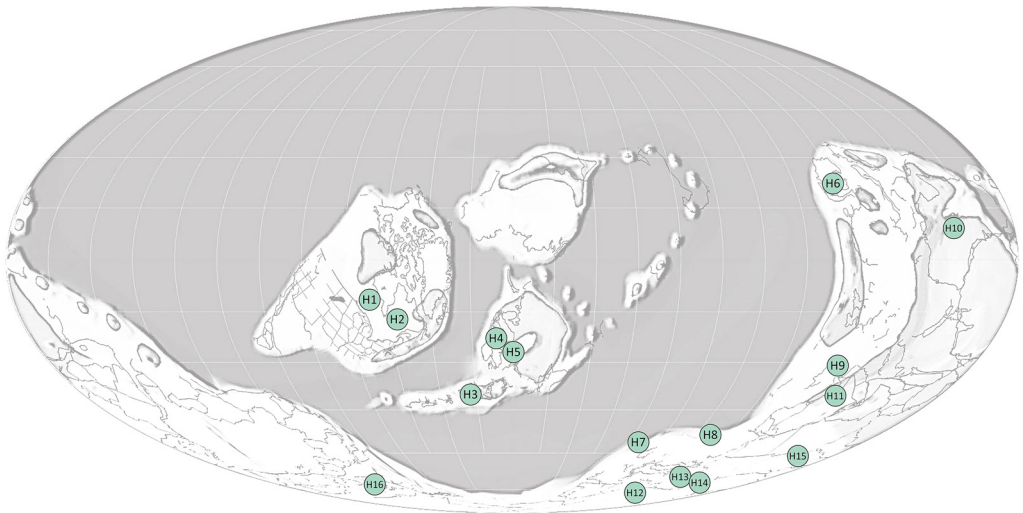


Fig. 6. Palaeogeographic map of the Hirnantian showing the location of dispersed spore assemblages. Locality codes refer to those used in Table 1. Modified from Scotese (2014).

Table 2. *Cryptospores examined ultrastructurally*

Spore taxon	Morphology	Locality	Age	References
<i>Tetraedraletes medinensis</i>	Naked permanent unfused tetrad	Ohio, USA	Katian	Taylor (1995)
<i>Pseudodyadospora</i> sp.	Naked permanent fused dyad	Ohio, USA	Katian	Taylor (1996)
<i>Segestrespora membranifera</i>	Envelope-enclosed permanent unfused dyad	Ohio, USA	Katian	Taylor (1996)
<i>Dyadospora murusattenuata</i>	Naked permanent unfused dyad	Ohio, USA	Katian	Taylor (1997)
<i>Tetraedraletes</i> spp.	Naked permanent unfused tetrad	Oman	Katian	Wellman <i>et al.</i> (2003)
<i>Dyadospora</i> spp.	Naked permanent unfused dyad	Oman	Katian	Wellman <i>et al.</i> (2003)
<i>Cryptotetras erugata</i>	Naked permanent unfused	Saudi Arabia	Darriwilian	Taylor <i>et al.</i> (2017)
<i>Pseudodyadospora</i> sp. cf. <i>P. laevigata</i>	Naked permanent fused dyad	Saudi Arabia	Darriwilian	Taylor <i>et al.</i> (2017)
Monad	Naked monad	Saudi Arabia	Darriwilian	Taylor <i>et al.</i> (2017)

continue to improve in precision and we gain a better understanding of the biological affinities of the earliest land plants and their likely biomarker trails.

Evidence from extant land plants

Phylogenetic analysis

In the early 1980s the first cladistic analyses of land plants began to appear in publications, more-or-less coincident with the recognition of an Ordovician flora (Gray *et al.* 1982). These pioneering cladistic analyses considered only extant plants and utilized morphological/anatomical characters (e.g. Mishler and Churchill 1985). The majority of these: (1) recovered a member of the charophycean green alga as sister group to the monophyletic embryophytes (land plants); (2) indicated that the bryophytes were paraphyletic with the liverworts basal and a sister group relationship between vascular plants and either hornworts or mosses. For several decades these analyses were hugely influential providing a model for the physiological/anatomical aquatic algal–subaerial land plant transition (e.g. Graham 1993; Graham and Gray 2001) and also the nature of the earliest land plants (Gray 1984, 1985, 1991). The charophycean green algae–liverwort transition was seen to mirror the origin of subaerial land plants from freshwater aquatic green algal ancestors (e.g. Graham 1993). The liverworts were regarded as the most basal extant land plants and used as a broad model for the morphology/anatomy, physiology and ecology of the first land plants (e.g. Gray 1985).

The many subsequent morphology-based analyses that followed often mirrored these findings, although just about every possible relationship among the embryophytes (liverworts, hornworts,

mosses, vascular plants) has been proposed at some point (reviewed in Kenrick and Crane 1997). A significant advance was the inclusion of fossil data in cladistic analyses. Fossil data were important in recognizing a group of fossil plants (Protracheophytes) that fell between the paraphyletic ‘bryophytes’ and vascular plants (Kenrick and Crane 1997). These included various Rhynie chert plants that preserve exquisite anatomical detail including some rather unusual character combinations, such as more-or-less isomorphic gametophyte and sporophyte generations, tracheids and stomata present in both generations, etc. (Edwards *et al.* 2017). Nevertheless, liverworts remained the model of choice for the earliest land plants.

As the molecular revolution dawned, the use of sequence data in cladistic analyses became possible. Initial analyses seemed to support the existing favoured topology. However, as more sequence data became available and ever-refined analytical techniques emerged, the tree topologies generated began to diverge from this model (recently reviewed by Wickett *et al.* 2014; Puttick *et al.* 2018; OTPTI 2019). Firstly, it began to appear that the zygnetomophycean green algae were the most likely sister group to the embryophytes. Secondly, embryophyte tree topologies changed significantly with monophyletic bryophytes and tracheophytes emerging as sister groups. Within the bryophytes the hornworts appeared as most basal and sister to a ‘setaphyte clade’ consisting of the liverworts and mosses.

The newly accepted topologies have important implications. Regarding the algal sister group, it suggests that many of the extant zygnetomophycean algae, some of which are unicellular, are highly reduced (Puttick *et al.* 2018; Cheng *et al.* 2019; Donoghue and Paps 2020; Jiao *et al.* 2020; Rensing 2020). This makes modelling of the algal–plant

Terrestrialization in the Ordovician

transition problematic based solely on consideration of the living zygmatophycean algae. In terms of the basal embryophytes, it means that the most basal of the extant vascular plants (lycopsids) are as closely related to the stem group land plants as the earliest diverging extant bryophytes (hornworts) (Puttick *et al.* 2018). It also suggests that the bryophyte groups are reduced and have lost certain characters (e.g. liverwort stomata) or are secondarily simplified (e.g. possibly bryophyte conducting tissues). A critical next step will be the inclusion of fossil data into the new phylogenetic schemes. It is important to assess the position of the Rhynie chert prottracheophytes. For example, if *Aglaophyton* can be shown to be sister group to the [bryophytes + tracheophytes] (i.e. a stem group embryophyte) it would suggest that stem group embryophytes may have been more complex than previously anticipated, possessing a more-or-less isomorphic gametophyte and sporophyte, with both generations possessing stomata and containing conducting tissues (possibly of *Aglaophyton*-type).

Recently Edwards *et al.* (2021a, b, c) recognized a new group of plants, called eophytes, among their charcoalified Late Silurian–Early Devonian plant Lagerstätte (see above). These diminutive plants exhibit a primitive anatomy based on sporophytes with food conducting cells and yield *in-situ* cryptospores. It is highly likely that these were parasitic on gametophytes characterized by transfer cells. Both stages of the lifecycle were likely poikilohydric, and thus able to desiccate and rehydrate, bearing ecological/physiological similarities to extant bryophytes as opposed to most vascular plants. Edwards *et al.* (2021a, fig. 8) place the eophytes as stem group polysporangiates, although we consider that they may represent stem group embryophytes that have a sister group relationship with a clade comprising both the bryophytes and vascular plants. Again, their relative position in the phylogeny with respect to Rhynie chert plants such as *Aglaophyton* is critical in influencing our perception of the earliest stem embryophytes. It seems likely that they are more basal than *Aglaophyton* and provide the best current model for the earliest stem group embryophytes.

Molecular clock analyses

In the early 2000s the first molecular clock analyses began to appear concerning the dating of the origin of land plants and the major land plant groupings (reviewed in Morris *et al.* 2018). Initial results indicated land plant origins far earlier than that suggested by the fossil record (as described above). Subsequently molecular clock techniques have rapidly evolved, and different strategies have been employed and a variety of palaeontological

Table 3. A summary of some proposed age ranges (Ma) from recent molecular clock analyses regarding dating the origin of land plants (embryophytes) and vascular plants (tracheophytes)

References	Land plants	Vascular plants
Heckman <i>et al.</i> (2001)	703 (±45)	
Sanderson (2003)	425–480	
Hedges <i>et al.</i> (2004)	968 (±93)	707 (±98)
Zimmer <i>et al.</i> (2007)	725	
Smith <i>et al.</i> (2010)	474–477	432–434
Clarke <i>et al.</i> (2011)	568–815	425–456
Magallón <i>et al.</i> (2013)	475	424
Morris <i>et al.</i> (2018)	515.2–473.5	450.8–430.4
Nie <i>et al.</i> (2020)	486.1	449.7
Su <i>et al.</i> (2021)	980–682	880–593

calibration systems experimented with. These analyses have provided highly variable results (reviewed in Table 3), and nearly all are incongruent with the fossil record, although the discrepancy is decreasing in some of the most recent analyses. An early origin of land plants as suggested by some molecular clock analyses, would require that these plants left no fossil record for a considerable period of Earth history, which seems unlikely if they reproduced by sporopollenin-walled spores, unless they were only present in very restricted environments and/or a very confined palaeogeographical area.

Fungi and lichens (including nematophytes)

Phylogenetic analyses and molecular clock evidence indicate that fungi originated in the Mesoproterozoic (e.g. Parfrey *et al.* 2011), but it is not clear when they first appeared in terrestrial settings (aquatic or subaerial). Fungal remains are well known from the Silurian where they occur in palynological preparations as dispersed fungal spores and hyphae (e.g. Sherwood-Pike and Gray 1985). Such remains have rarely been reported from the Ordovician, but this may reflect the paucity of non-marine deposits available for analysis. Thusu *et al.* (2013) report the enigmatic *Tortotubulus protuberans* from the Late Ordovician. This tubular structure has been interpreted as a fungus (Smith 2016), although more precise affinities are not possible (Auxier *et al.* 2016). Most of the other reported fungal remains from pre-Silurian strata are more contentious (reviewed in Taylor *et al.* 2015; Berbee *et al.* 2020; Wellman and Ball 2021). However, it is worth noting that recent molecular development research on extant charophycean algae and land plants suggests that fungal symbioses may have been crucial to the colonization of the land by plants (Berbee *et al.* 2020).

Lichenization has evolved numerous times, involving different combinations of fungi and algal/cyanobacterial hosts (Lücking and Nelsen 2018). However, recent phylogenetic analysis suggests that lichens may not have evolved until after the evolution of vascular plants (Nelsen *et al.* 2020).

The enigmatic Silurian–Devonian nematophytes have recently been demonstrated to have fungal, and possibly also lichen, affinities (Edwards and Axe 2012; Edwards *et al.* 2013, 2018; Honegger *et al.* 2013, 2017). These occur as megafossils (Lang 1937; Strother 1988) and dispersed microfossils in the form of ‘cuticle-like sheets’ and tubular structures, including ‘banded tubes’ (recently reviewed by Wellman and Ball 2021). However, no convincing nematophyte remains have been reported from the Ordovician thus far.

Land animals in the Ordovician

Silurian continental deposits have yielded a diverse array of fossil evidence for land animals indicative of diverse and complex ecosystems developed in both freshwater aquatic and fully terrestrial settings. These fossils include whole organisms such as fish (e.g. Blom *et al.* 2002) and arthropods (e.g. Jeram *et al.* 1990), dispersed arthropod cuticles recovered using palynological techniques (e.g. Gray and Boucot 1994), coprolites (e.g. Edwards *et al.* 1995) and a variety of trace fossil evidence (e.g. McCoy *et al.* 2012).

Similar evidence for Ordovician terrestrial organisms is much rarer, almost certainly reflecting the paucity of Ordovician non-marine deposits available for study. To date all reported Ordovician fish remains are considered to be from fish inhabiting nearshore shallow marine environments (Davies and Sansom 2009). There are rare reports of potential non-marine arthropods, but these are all controversial with questions remaining regarding either their age or habitat (e.g. McNamara and Trewin 1993). There are several reports of potential non-marine trace fossil assemblages. However, these are all from terrestrial deposits that are either doubtful or closely associated with nearshore marine deposits, making judgements on the habitat and mode of life of their makers doubtful. For example, it has been suggested that purported millipede burrows in Ordovician palaeosols described by Retallack and Feakes (1987) are possibly of marine origin (Davies *et al.* 2010). Ordovician non-marine arthropod traces described by Johnson *et al.* (1994) have also been re-interpreted as marine in origin (Shillito and Davies 2019), and the trackways in Cambrian–Ordovician aeolian deposits described by MacNaughton *et al.* (2002) are from a marginal marine setting. It has recently been suggested that the exquisite trace

fossils from the Tumbagoooda Sandstone of Australia (Trewin and McNamara 1994) were deposited in a littoral setting and are possibly of Silurian age (Shillito and Davies 2020).

Molecular clock studies have also been employed to ascertain when the various terrestrial arthropod groups appeared. To date most of these studies suggest that terrestrial arthropod groups invaded the land much earlier than the fossil record would indicate and by at least the Cambrian (Lozano-Fernandez *et al.* 2016). Terrestrial trace fossil assemblages from the Cambrian and earlier are all considered doubtful (reviewed by Minter *et al.* 2016).

Ordovician non-marine sediments, soils and terrestrial environment

As emphasized throughout this review, globally Ordovician non-marine deposits are extremely rare. The reasons for this are not clear (Davies and Gibling 2010) but is usually considered to be a consequence of high sea-levels and the difficulties involved in identifying Ordovician non-marine evidence that relies largely on absence of evidence. Davies and Gibling (2010) summarize the sedimentology of the best known Ordovician non-marine deposits. It is clear that many of these are actually very near-shore and are often interdigitated with marine deposits making it difficult to ascertain the degree of marine influence. None-the-less, some Ordovician palaeosols are reported (summarized by Retallack 2000).

There has been considerable debate regarding the influence of Ordovician terrestrial life, which transitioned from microbial mat communities to those including the earliest land plants (embryophytes), on the nature of sedimentation and soil formation (Davies and Gibling 2010; Gibling and Davies 2012; Santos *et al.* 2016; Davies *et al.* 2017). This avenue of research has considered changes to weathering rate (e.g. D’Antonio *et al.* 2019), sediment stabilizing properties (e.g. Davies and McMahon 2021), patterns of sedimentation as geomorphological agents such as rivers change form (e.g. Ganti *et al.* 2019), consideration of how land plants promoted terrestrial mud deposition (e.g. McMahon and Davies 2018; Zeichner *et al.* 2021), and much more. This debate has also extended to biogeochemical effects (Lenton and Daines 2017) and how these impacted atmospheric composition (e.g. Adiatma *et al.* 2019), climate (e.g. Lenton *et al.* 2012) and so on. One avenue of research that has also recently received attention is the effects of increasing land plant cover on terrestrial biomass and thus patterns of carbon isotopes in the Ordovician sedimentary record (Tomescu *et al.* 2009; Quinton *et al.* 2021).

It should be noted that much of the above debate was focused on the assumption that Ordovician

Terrestrialization in the Ordovician

terrestrial floras comprised bryophyte-like (more specifically liverwort-like plants). This assumption was based on prevailing land plant phylogenies (see above). Thus, much of the debate utilized evidence from experiments on extant bryophytes (particularly liverworts) (e.g. Quirk *et al.* 2015). As discussed above, recent phylogenetic analyses and the recognition of eophyte plants has altered our understanding and perception of the nature of the earliest stem group land plants. However, it should be noted that workers such as Jane Gray always stressed that the earliest land plants may not be directly related to extant bryophytes/liverworts, but that these plants were probably ‘bryophyte-like’/‘liverwort-like’ in their physiology and ecology (Gray 1985, 1991), and they may thus still provide a reasonable analogue (if not ‘nearest living relative’) for the earliest land plants.

Terrestrial life and the End Ordovician glaciation and mass extinction

The dispersed spore fossil record exhibits no appreciable change from the Late Ordovician into the Early Silurian (reviewed by Gray 1985; Richardson 1996; Steemans *et al.* 2000; Strother 2000; Wellman *et al.* 2013) with a continuous increase in diversity not interrupted by the Late Ordovician extinction interval evident among marine invertebrates. Identical dispersed spore assemblages have been reported worldwide before, during and after the Hirnantian glaciation and End Ordovician mass extinction. This has been taken to suggest that terrestrial floras were relatively unaffected by these interconnected events, with speculation that the earliest land plants were immune because they were cosmopolitan generalists that flourished in a wide range of environments (Gray 1985; Wellman 1996). Indeed, dispersed spore assemblages are well known from cold, high latitude localities where they are often associated with glacial deposits (e.g. Gray *et al.* 1986).

Conclusions

It is evident from the above discussion that the Ordovician represents a critical period in Earth’s terrestrialization. It seems likely that is witnessed the transition from a terrestrial, microbial soil–vegetation system to one that included the first land plants. At the same time non-marine aquatic biotas began to increase in diversity, although it seems that the only animals on the land were probably temporary visitors that were not obligate subaerial dwellers. Our understanding of Ordovician terrestrial life will continue to improve as refined techniques in phylogenetic analysis, molecular clock studies, evo–devo research

and Earth systems modelling become available. But ultimately it seems likely that newly discovered fossils will shed most light on this subject area, particularly if convincing Ordovician plant remains can be recovered.

Acknowledgements We would like to thank Claudia Rubinstein for alerting us to some cryptospore occurrences we were not aware of and Neil Davies for advice on Ordovician terrestrial palaeoenvironments and ichnology.

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions CHW: writing – original draft (lead); BC-M: writing – review & editing (equal); TS: writing – review & editing (equal).

Funding This research was funded by various NERC grants to CHW including NE/R001324/1 and NE/V001639/1. BC-M and TS were supported by the EARTH-GREEN project (ANR-20-CE01-0002-01).

Data availability Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

References

- Abuhmida, F.H. and Wellman, C.H. 2017. Palynology of the Middle Ordovician Hawaz Formation in the Murzuq Basin, south-west Libya. *Palynology*, **41**, 31–56, <https://doi.org/10.1080/01916122.2017.1356393>
- Adiatma, Y.D., Saltzman, M.R. *et al.* 2019. Did early land plants produce a stepwise change in atmospheric oxygen during the Late Ordovician (Sandbian c. 458 Ma)? *Palaeogeography, Palaeoclimatology, Palaeoecology*, **534**, 109341, <https://doi.org/10.1016/j.palaeo.2019.109341>
- Auxier, B., Bazzicalupo, A. *et al.* 2016. No place among the living: phylogenetic considerations place the Palaeozoic fossil *T. protuberans* in Fungi but not in Dikarya. A comment on M. Smith (2016). *Botanical Journal of the Linnean Society*, **182**, 723–728, <https://doi.org/10.1111/boj.12479>
- Badawy, A.S., Mehlqvist, K., Vajda, V., Ahlberg, P. and Calner, M. 2014. Late Ordovician (Katian) spores in Sweden: oldest land plant remains from Baltica. *GFF*, **136**, 16–21, <https://doi.org/10.1080/11035897.2014.899266>
- Banks, H.P. 1975a. Early vascular land plants: proof and conjecture. *BioScience*, **25**, 730–737, <https://doi.org/10.2307/1297453>
- Banks, H.P. 1975b. The oldest vascular land plants: a note of caution. *Review of Palaeobotany and Palynology*,

- 20, 13–25, [https://doi.org/10.1016/0034-6667\(75\)90004-4](https://doi.org/10.1016/0034-6667(75)90004-4)
- Berbee, M.L., Strullu-Derrien, C., Delaux, P.-M., Strother, P.K., Kenrick, P., Selosse, M.-A. and Taylor, J.W. 2020. Genomic and fossil windows into the secret lives of the most ancient fungi. *Nature Reviews Microbiology*, **18**, 717–730, <https://doi.org/10.1038/s41579-020-0426-8>
- Blackmore, S. and Barnes, S.H. 1987. Embryophyte spore walls: origin, development and homologies. *Cladistics*, **3**, 185–195, <https://doi.org/10.1111/j.1096-0031.1987.tb00506.x>
- Blom, H., Märrs, T. and Miller, C.G. 2002. Birkeniid anaspids from the northern hemisphere. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **92**, 263–323, <https://doi.org/10.1017/S0263593300000250>
- Burgess, N.D. 1991. Silurian cryptospores and miospores from the type Llandovery area, south-west Wales. *Palaeontology*, **34**, 575–599.
- Burgess, N.D. and Edwards, D. 1991. Classification of uppermost Ordovician to Lower Devonian tubular and filamentous macerals from the Anglo-Welsh Basin. *Botanical Journal of the Linnean Society*, **106**, 41–66, <https://doi.org/10.1111/j.1095-8339.1991.tb02282.x>
- Chaloner, W.G. 1960. The origin of vascular plants. *Science Progress*, **191**, 524–534.
- Chaloner, W.G. 1970. The rise of the first land plants. *Biological reviews*, **45**, 353–377, <https://doi.org/10.1111/j.1469-185X.1970.tb01645.x>
- Cheng, S., Xian, W. *et al.* 2019. Genomes of subaerial Zygnematophyceae provide insights into land plant evolution. *Cell*, **179**, 1057–1067, <https://doi.org/10.1016/j.cell.2019.10.019>
- Clarke, J.T., Warnock, R.C.M. and Donoghue, P.C.J. 2011. Establishing a time scale for plant evolution. *New Phytologist*, **192**, 266–301, <https://doi.org/10.1111/j.1469-8137.2011.03794.x>
- Corna, O. 1970. Plant remains in the Ordovician of the Bohemian Massif. *Geologica Carpathica*, **21**, 183–186.
- D’Antonio, M.P., Ibarra, D.E. and Boyce, C.K. 2019. Land plant evolution decreased, rather than increased, weathering rates. *Geology*, **48**, 29–33, <https://doi.org/10.1130/G46776.1>
- Davies, N.S. and Gibling, M.R. 2010. Cambrian to Devonian evolution of alluvial systems: the sedimentological impact of the earliest land plants. *Earth-Science Reviews*, **98**, 171–200, <https://doi.org/10.1016/j.earscirev.2009.11.002>
- Davies, N.S. and McMahon, W.J. 2021. Land plant evolution and global erosion rates. *Chemical Geology*, **567**, 120128, <https://doi.org/10.1016/j.chemgeo.2021.120128>
- Davies, N.S. and Sansom, I.J. 2009. Ordovician vertebrate habitats: a Gondwanan perspective. *PALAIOS*, **24**, 717–722, <https://doi.org/10.2110/palo.2009.p09-040r>
- Davies, N.S., Rygel, M.C. and Gibling, M.R. 2010. Marine influence in the Upper Ordovician Juniata Formation (Potters Mill, Pennsylvania): implications for the history of life on land. *PALAIOS*, **25**, 527–539, <https://doi.org/10.2110/palo.2010.p10-025r>
- Davies, N.D., Gibling, M.R. *et al.* 2017. Discussion on ‘Tectonic and environmental controls on Palaeozoic fluvial environments: reassessing the impacts of early land plants on sedimentation’. *Journal of the Geological Society, London*, **174**, 947–950, <https://doi.org/10.1144/jgs2017-004>
- de la Puente, G.S. and Rubinstein, C.V. 2013. New palynological data from the Upper Ordovician of the Precordillera Basin, Argentina: a potential key for understanding the geological history of the Precordillera terrain. *Stratigraphy*, **10**, 229–248.
- Donoghue, P. and Paps, J. 2020. Plant evolution: assembling land plants. *Current Biology*, **30**, 81–83, <https://doi.org/10.1016/j.cub.2019.11.084>
- Edwards, D. and Axe, L. 2012. Evidence for a fungal affinity for *Nematosketum*, a close ally of *Prototaxites*. *Botanical Journal of the Linnean Society*, **168**, 1–18, <https://doi.org/10.1111/j.1095-8339.2011.01195.x>
- Edwards, D. and Wellman, C.H. 2001. Embryophytes on land: the Ordovician to Lochkovian (Lower Devonian) record. In: Gensel, P.G. and Edwards, D. (eds) *Plants Invade the Land*. Columbia University Press, New York, 3–28.
- Edwards, D., Feehan, J. and Smith, D.G. 1983. A late Wenlock flora from Co, Tipperary, Ireland. *Botanical Journal of the Linnean Society*, **86**, 19–36, <https://doi.org/10.1111/j.1095-8339.1983.tb00715.x>
- Edwards, D., Davies, K.L. and Axe, L. 1992. A vascular conducting strand in the early land plant *Cooksonia*. *Nature*, **357**, 683–685, <https://doi.org/10.1038/357683a0>
- Edwards, D., Selden, P.A., Richardson, J.B. and Axe, L. 1995. Coprolites as evidence for plant–animal interaction in Siluro-Devonian terrestrial ecosystems. *Nature*, **377**, 329–331, <https://doi.org/10.1038/377329a0>
- Edwards, D., Axe, L. and Honegger, R. 2013. Contributions to the diversity in cryptogamic covers in the mid-Palaeozoic; *Nematohallus* revisited. *Botanical Journal of the Linnean Society*, **173**, 505–534, <https://doi.org/10.1111/boj.12119>
- Edwards, D., Kenrick, P. and Dolan, L. 2017. History and contemporary significance of the Rhynie cherts—our earliest preserved terrestrial ecosystem. *Philosophical Transactions of the Royal Society Series B*, **373**, 20160489, <https://doi.org/10.1098/rstb.2016.0489>
- Edwards, D., Honegger, R., Axe, L. and Morris, J.L. 2018. Anatomically preserved Silurian ‘nematophytes’ from the Welsh Borderland (UK). *Botanical Journal of the Linnean Society*, **187**, 272–291, <https://doi.org/10.1093/botlinnean/boy022>
- Edwards, D., Morris, J.L., Axe, L., Duckett, J.G., Pressel, S. and Kenrick, P. 2021a. Piecing together the eophytes: a new group of ancient plants containing cryptospores. *New Phytologist*, **233**, 1440–1455, <https://doi.org/10.1111/nph.17703>
- Edwards, D., Morris, J.L., Axe, L., Taylor, W.A., Duckett, J.G., Kenrick, P. and Pressel, S. 2021b. Earliest record of transfer cells in Lower Devonian plants. *New Phytologist*, **233**, 1456–1465, <https://doi.org/10.1111/nph.17704>
- Edwards, D., Morris, J.L., Axe, L. and Duckett, J.G. 2021c. Picking up the pieces: new charcoalfied plant mesofossils (eophytes) from a Lower Devonian Lagerstätte in the Welsh Borderland, UK. *Review of Palaeobotany and Palynology*, **297**, 104567, <https://doi.org/10.1016/j.revpalbo.2021.104567>

Terrestrialization in the Ordovician

- Foster, C.B. and Williams, G.E. 1991. Late Ordovician–Early Silurian age for the Mallowa Salt of the Carri-buddy Group, Canning Basin, Western Australia, based on occurrences of *Tetrahedraletes medinensis* Strother and Traverse 1979. *Australian Journal of Earth Science*, **38**, 223–228, <https://doi.org/10.1080/08120099108727966>
- Ganti, V., Whittaker, A.C., Lamb, M.P. and Fischer, W.W. 2019. Low gradient, single-threaded rivers prior to greening of the continents. *Proceedings of the National Academy of Sciences*, **116**, 11652–11657, <https://doi.org/10.1073/pnas.1901642116>
- Ghavidel-Syooki, M. 2017. Cryptospore and trilete spore assemblages from the Late Ordovician (Katian–Hirnantian) Ghelli Formation, Alborz Mountain Range, North-eastern Iran: palaeophytogeographic and palaeoclimatic implications. *Review of Palaeobotany and Palynology*, **244**, 217–240, <https://doi.org/10.1016/j.revpalbo.2017.05.010>
- Ghavidel-Syooki, M. and Piri-Kangarshahi, M.H. 2021a. Biostratigraphy of acritarchs, chitinozoans and miospores from Upper Ordovician sequences in Kuh-e Boghou, southwest of Kashmar, eastern central Iran: stratigraphic and paleogeographic implications. *Review of Palaeobotany and Palynology*, **284**, 104337, <https://doi.org/10.1016/j.revpalbo.2020.104337>
- Ghavidel-Syooki, M. and Piri-Kangarshahi, M.H. 2021b. Biostratigraphy of acritarchs, chitinozoans, and miospores from Upper Ordovician sequences in Kuh-e Boghou, southwest of Kashmar, eastern central Iran: stratigraphic and paleogeographic implications. *Review of Palaeobotany and Palynology*, **292**, 104337, <https://doi.org/10.1016/j.revpalbo.2020.104337>
- Gibling, M.R. and Davies, N.S. 2012. Palaeozoic landscapes shaped by plant evolution. *Nature Geosciences*, **2**, 99–105, <https://doi.org/10.1038/ngeo1376>
- Graham, L.E. 1993. *Origin of Land Plants*. John Wiley & Sons, New York.
- Graham, L.E. and Gray, L.E. 2001. The origin, morphology, and ecophysiology of early embryophytes: neontological and paleontological perspectives. In: Gensel, P.G. and Edwards, D. (eds) *Plants Invade the Land*. Columbia University Press, New York, 140–158.
- Gray, J. 1984. Ordovician–Silurian land plants: the interdependence of ecology and evolution. *Special Papers in Palaeontology*, **32**, 281–295.
- Gray, J. 1985. The microfossil record of early land plants: advanced in understanding of early terrestrialisation, 1970–1984. *Philosophical Transactions of the Royal Society London B*, **309**, 167–195, <https://doi.org/10.1098/rstb.1985.0077>
- Gray, J. 1988. Land plant spores and the Ordovician–Silurian boundary. *Bulletin of the British Museum (Natural History) (Geology)*, **43**, 351–358.
- Gray, J. 1991. Tetrahedraletes, Nodospora, and the ‘cross’ tetrad: an accretion of myth. In: Blackmore, S. and Barnes, S.H. (eds) *Pollen and Spores. Systematics Association Special Volume No. 44*. Clarendon Press, Oxford, 49–87.
- Gray, J. and Boucot, A.J. 1971. Early Silurian spore tetrads from New York: earliest New World evidence for vascular plants? *Science (New York, NY)*, **973**, 198–221.
- Gray, J. and Boucot, A.J. 1972. Palynological evidence bearing on the Ordovician–Silurian paraconformity in Ohio. *Geological Society of America Bulletin*, **83**, 1299–1314, [https://doi.org/10.1130/0016-7606\(1972\)83\[1299:PEBOTO\]2.0.CO;2](https://doi.org/10.1130/0016-7606(1972)83[1299:PEBOTO]2.0.CO;2)
- Gray, J. and Boucot, A.J. 1994. Early Silurian nonmarine animal remains and the nature of the early continental ecosystem. *Acta Palaeontologica Polonica*, **38**, 303–328.
- Gray, J., Massa, D. and Boucot, A.J. 1982. Caradocian land plant microfossils from Libya. *Geology*, **10**, 197–201, [https://doi.org/10.1130/0091-7613\(1982\)10<197:CLPMFL>2.0.CO;2](https://doi.org/10.1130/0091-7613(1982)10<197:CLPMFL>2.0.CO;2)
- Gray, J., Theron, J.N. and Boucot, A.J. 1986. Age of the Cedarberg Formation, South Africa and early land plant evolution. *Geological Magazine*, **123**, 445–454, <https://doi.org/10.1017/S0016756800033537>
- Guizar-Sicairos, M., Holler, M. et al. 2015. Ptychographic nanotomography at the Swiss Light Source. In: Lai, B. (ed.) *X-Ray Nanoimaging: Instruments and Methods II*. SPIE 9592 Optical Engineering + Applications Proceedings, 9–13 August, 95920A, <https://doi.org/10.1117/12.2188313>
- Heckman, D.S., Geiser, D.M., Eidell, B.R., Stauffer, R.L., Kardos, N.L. and Hedges, S.B. 2001. Molecular evidence for the early colonisation of land by fungi and plants. *Science (New York, NY)*, **293**, 1129–1133, <https://doi.org/10.1126/science.1061457>
- Hedges, S.B., Blair, J.E., Venturi, M.L. and Shoe, J.L. 2004. A molecular timescale of eukaryote evolution and the rise of complex multicellular life. *BMC Evolutionary Biology*, **4**, 2, <https://doi.org/10.1186/1471-2148-4-2>
- Honegger, R., Edwards, D. and Axe, L. 2013. The earliest records on internally stratified cyanobacterial and algal lichens from the Lower Devonian of the Welsh Borderland. *New Phytologist*, **197**, 264–275, <https://doi.org/10.1111/nph.12009>
- Honegger, R., Edwards, D., Axe, L. and Strullu-Derrien, C. 2017. Fertile *Prototaxites taiti*: a basal ascomycete with inoperculate, polysporous asci lacking croziers. *Philosophical Transactions of the Royal Society B*, **373**, 1–14, <https://doi.org/10.1098/rstb.2017.0146>
- Johnson, E.W., Briggs, D.E.G., Suthren, R.J., Wright, J.L. and Tunnicliff, S.P. 1994. Non-marine arthropod traces from the subaerial Ordovician Borrowdale Volcanic Group, English Lake District. *Geological Magazine*, **131**, 395–406, <https://doi.org/10.1017/S0016756800011146>
- Jeram, A.J., Selden, P.A. and Edwards, D. 1990. Land animals in the Silurian: Arachnids and Myriapods from Shropshire, England. *Science (New York, NY)*, **250**, 658–661, <https://doi.org/10.1126/science.250.4981.658>
- Jiao, C., Sorensen, I. et al. 2020. The *Penium margaritaceum* genome: hallmarks of the origins of land plants. *Cell*, **181**, 1097–1111, <https://doi.org/10.1016/j.cell.2020.04.019>
- Kenrick, P. and Crane, P.R. 1997. *The Origin and Early Diversification of Land Plants: A Cladistics Study*. Smithsonian Institution Press, Washington and London.
- Kenrick, P., Kvacek, Z. and Bengtson, S. 1999. Semblant land plants from the Middle Ordovician of the Prague Basin reinterpreted as an animal. *Palaeontology*, **42**, 991–1002, <https://doi.org/10.1111/1475-4983.00106>

- Lakova, I., Gocev, P.M. and Yanev, S. 1992. Palynostratigraphy and geological setting of the Lower Palaeozoic allocthon of the Derwent Heights, SE Bulgaria. *Geologica Balcanica*, **22**, 71–88.
- Lang, W.H. 1937. On the plant-remains from the Downtonian of England and Wales. *Philosophical Transactions of the Royal Society of London Series B: Biological Sciences*, **227**, 245–291.
- Le Hérisse, A., Al-Ruwaili, M., Miller, M. and Vecoli, M. 2007. Environmental changes reflected by palynomorphs in the early Middle Ordovician Hanadir Member of the Qasim Formation, Saudi Arabia. *Revue de micropaléontologie*, **50**, 3–16, <https://doi.org/10.1016/j.revmic.2007.01.010>
- Le Hérisse, A., Paris, F. and Steemans, P. 2013. Late Ordovician – earliest Silurian palynomorphs from northern Chad and correlation with contemporaneous deposits of southeastern Libya. *Bulletin of Geosciences*, **88**, 483–504, <https://doi.org/10.3140/bull.geosci.1383>
- Lenton, T.M. and Daines, S.J. 2017. Matworld – the biogeochemical effects of early life on land. *New Phytologist*, **215**, 505–507, <https://doi.org/10.1111/nph.14338>
- Lenton, T.M., Crouch, M., Johnson, M., Pires, N. and Dolan, L. 2012. First plants cooled the Ordovician. *Nature Geoscience*, **5**, 86–89, <https://doi.org/10.1038/ngeo1390>
- Libertin, M., Kvaceck, J., Bek, J., Zarsky, J., Zarsky, V. and Storch, P. 2018. Libertin Sporophytes of polysporangiate land plants from the early Silurian period may have been photosynthetically autonomous. *Nature Plants*, **4**, 269–271, <https://doi.org/10.1038/s41477-018-0140-y>
- Lozano-Fernandez, J., Carton, R. *et al.* 2016. A molecular palaeobiological exploration of arthropod terrestrialization. *Philosophical Transactions of the Royal Society B*, **371**, 20150133, <https://doi.org/10.1098/rstb.2015.0133>
- Lücking, R. and Nelsen, M.P. 2018. Ediacarans, protolichens, and lichen-derived penicillium: a critical reassessment of the evolution of lichenization in fungi. *In*: Krings, M., Harper, C.J., Cuneo, N.R. and Rothwell, G.W. (eds) *Transformative Paleobotany*. Academic Press, 551–590.
- MacNaughton, R.B., Cole, J.M., Dalrymple, R.W., Braddy, S.J., Briggs, D.E.G. and Lukie, T.D. 2002. First steps on land: arthropod trackways in Cambrian–Ordovician eolian sandstone, southeast Ontario, Canada. *Geology*, **5**, 391–394, [https://doi.org/10.1130/0091-7613\(2002\)030<0391:FSOLAT>2.0.CO;2](https://doi.org/10.1130/0091-7613(2002)030<0391:FSOLAT>2.0.CO;2)
- Magallón, S., Hilu, K.W. and Quandt, D. 2013. Land plant evolutionary timeline: gene effects are secondary to fossil constraints in relaxed clock estimation of age and substitution rates. *American Journal of Botany*, **100**, 556–573, <https://doi.org/10.3732/ajb.1200416>
- Mahmoudi, M., Sabouri, J., Alimohammadian, H. and Majidifard, M.R. 2014. The first report of cryptospore assemblages of Late Ordovician in Iran, Ghelli Formation, Eastern Alborz. *Geopersia*, **4**, 125–140, <https://doi.org/10.22059/JGEOPE.2014.52714>
- McClure, H.A. 1988. Chitinozoan and acritarch assemblages, stratigraphy and biogeography of the Early Palaeozoic of Northwest Arabia. *Review of Palaeobotany and Palynology*, **56**, 41–60, [https://doi.org/10.1016/0034-6667\(88\)90073-5](https://doi.org/10.1016/0034-6667(88)90073-5)
- McCoy, V.E., Strother, P.K. and Briggs, D.E.G. 2012. A possible tracemaker of *Arthropycus alleghaniensis*. *Journal of Paleontology*, **86**, 996–1001, <https://doi.org/10.1666/11-133R1.1>
- McMahon, W.J. and Davies, N.S. 2018. Evolution of alluvial mudrock forced by early land plants. *Science (New York, NY)*, **359**, 1022–1024, <https://doi.org/10.1126/science.aan4660>
- McNamara, K.J. and Trewin, N.H. 1993. A euthycarcinoid arthropod from the Silurian of Western Australia. *Palaentology*, **36**, 319–335.
- Miller, M.A. and Al-Ruwaili, M.H. 2007. Preliminary palynological investigation of Saudi Arabian Upper Ordovician glacial sediments. *Revue de micropaléontologie*, **50**, 17–26, <https://doi.org/10.1016/j.revmic.2007.01.002>
- Minter, N.J., Buatois, L.A., Mángano, M.G., MacNaughton, R.B., Davies, N.S. and Gibling, M.R. 2016. The prelude to continental invasion. *In*: Mángano, M.G. and Buatois, L.A. (eds) *The Trace Fossil Record of Major Evolutionary Events. Volume 1: Precambrian and Paleozoic*. Springer, 157–204.
- Mishler, B.D. and Churchill, S.P. 1985. Transition to a land flora: phylogenetic relationships of the green algae and bryophytes. *Cladistics*, **1**, 305–328, <https://doi.org/10.1111/j.1096-0031.1985.tb00431.x>
- Molyneux, S.G. and Al-Hajri, S. 2000. Palynology of a problematic Lower Palaeozoic lithofacies in Central Saudi Arabia. *In*: Al-Hajri, S. and Owens, B. (eds) *Stratigraphic Palynology of the Palaeozoic of Saudi Arabia*. GeoArabia, Bahrain, **1**, 18–41.
- Morris, J.L., Puttick, M.N. *et al.* 2018. The timescale for early land plant evolution. *Proceedings of the National Academy of Sciences*, **115**, 2274–2283, <https://doi.org/10.1073/pnas.1719588115>
- Nelsen, M.P., Lücking, R., Boyce, C.K., Lumbsch, H.T. and Ree, R.H. 2020. No support for the emergence of lichens prior to the evolution of vascular plants. *Geobiology*, **18**, 3–13, <https://doi.org/10.1111/gbi.12369>
- Naugolnykh, S.V. 2019. Plants of the first terrestrial ecosystems. *Herald of the Russian Academy of Sciences*, **89**, 502–511, <https://doi.org/10.1134/S101933161905006X>
- Nie, Y., Foster, C.S.P., Zhu, T., Yao, R., Duchene, D.A., Ho, S.Y.W. and Zhong, B. 2020. Accounting for uncertainty in the evolutionary timescale of green plants through clock-partitioning and fossil calibration strategies. *Systematic Biology*, **69**, 1–16, <https://doi.org/10.1093/sysbio/sy032>
- OTPTI. 2019. One thousand plant transcriptomes and the phylogenomics of green plants. *Nature*, **574**, 679–685, <https://doi.org/10.1038/s41586-019-1693-2>
- Ottone, E.G., Albanesi, G.L., Ortega, G. and Holfeltz, G.D. 1999. Palynomorphs, conodonts and associated graptolites from the Ordovician Los Azules Formation, central Precordillera, Argentina. *Micropaleontology*, **45**, 225–250, <https://doi.org/10.2307/1486135>
- Parfrey, L.W., Lahr, D.J.G., Knoll, A.H. and Katz, L.A. 2011. Estimating the timing of early eukaryotic diversification with multigene molecular clocks. *Proceedings of the National Academy of Sciences*, **108**, 13624–13629, <https://doi.org/10.1073/pnas.1110633108>
- Puttick, M.N., Morris, J.L. *et al.* 2018. The interrelationships of land plants and the nature of the ancestral

Terrestrialization in the Ordovician

- embryophyte. *Current Biology*, **28**, 733–745, <https://doi.org/10.1016/j.cub.2018.01.063>
- Quirk, J., Leake, J.R., Johnson, D.A., Taylor, L.L., Saccone, L. and Beerling, D.J. 2015. Constraining the role of early land plants in Palaeozoic weathering and global cooling. *Proceedings of the Royal Society of London B: Biological Sciences*, **282**, 20151115, <https://doi.org/10.1098/rspb.2015.1115>
- Quinton, P.C., Rygel, M.C. and Heins, M. 2021. Sequence stratigraphy and carbon isotopes from the Trenton and Black River Groups near Union Furnace, PA: constraining the role of land plants in the Ordovician world. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **574**, 110440, <https://doi.org/10.1016/j.palaeo.2021.110440>
- Raevskaya, E., Dronov, A., Servais, T. and Wellman, C.H. 2016. Cryptospores from the Katian (Upper Ordovician) of the Tungus Basin: the first evidence for early land plants from the Siberian paleocontinent. *Review of Palaeobotany and Palynology*, **224**, 4–13, <https://doi.org/10.1016/j.revpalbo.2015.10.010>
- Reitz, E. and Heuse, T. 1994. Palynofazies im Oberordovizium des Saxothuringikums. *Neues Jahrbuch für Geologie und Paläontologie Monatshefte*, **6**, 348–360, <https://doi.org/10.1127/njgpm/1994/1994/348>
- Rensing, S.A. 2020. How plants conquered the land. *Cell*, **181**, 964–966, <https://doi.org/10.1016/j.cell.2020.05.011>
- Retallack, G.J. 2000. Ordovician life on land and early Paleozoic global change. In: Gastaldo, R.A. and Dimichele, W.A. (eds) *Phanerozoic Terrestrial Ecosystems*. The Paleontological Society Papers, **6**, 21–45.
- Retallack, G.J. 2019. Ordovician land plants and fungi from Douglas Dam, Tennessee. *The Palaeobotanist*, **68**, 173–205.
- Retallack, G.J. and Feakes, C.R. 1987. Trace fossil evidence for Late Ordovician animals on land. *Science (New York, NY)*, **235**, 61–63, <https://doi.org/10.1126/science.235.4784.61>
- Richardson, J.B. 1988. Late Ordovician and Early Silurian cryptospores and miospores from northeast Libya. In: El-Arnauti, A., Owens, B. and Thusu, B. (eds) *Subsurface Palynostratigraphy of Northeast Libya*. Garyounis University, Benghazi, Libya, 89–109.
- Richardson, J.B. 1996. Lower and Middle Palaeozoic records of terrestrial palynomorphs. In: Jansonius, J. and McGregor, D.C. (eds) *Palynology: Principles and Applications*. American Association of Stratigraphic Palynologists Foundation, **2**, 555–574.
- Richardson, J.G. and Ausich, W.I. 2007. Late Ordovician-Early Silurian cryptospore occurrences on Anticosti Island (Île d'Anticosti), Quebec, Canada. *Canadian Journal of Earth Sciences*, **44**, 1–7, <https://doi.org/10.1139/e06-100>
- Richardson, J.B. and McGregor, D.C. 1986. Silurian and Devonian spore zones of the Old Red Sandstone Continent and adjacent regions. *Geological Survey of Canada Bulletin*, **364**, 1–79.
- Romero-Sarmiento, M.F., Riboulleau, A., Vecoli, M. and Versteegh, G.J.M. 2011. Aliphatic and aromatic biomarkers from Gondwanan sediments of Late Ordovician to early Devonian age: an early terrestrialisation approach. *Organic Geochemistry*, **42**, 605–617, <https://doi.org/10.1016/j.orggeochem.2011.04.005>
- Rubinstein, C.V. 2005. Ordovician to Lower Silurian palynomorphs from the Sierras subandinas (Subandean ranges), northwestern Argentina: a preliminary report. *Carnets de Géologie*, **2005/02**, 51–56, <https://doi.org/10.4267/2042/4363>
- Rubinstein, C.V. and Vaccari, N.E. 2004. Cryptospore assemblages from the Ordovician/Silurian boundary in the Puna region, North-west Argentina. *Palaeontology*, **47**, 1037–1061, <https://doi.org/10.1111/j.0031-0239.2004.00388.x>
- Rubinstein, C.V. and Vajda, V. 2019. Baltica cradle of early land plants? Oldest record of trilete spores and diverse cryptospore assemblages; evidence from Ordovician successions of Sweden. *GFF*, **141**, 181–190, <https://doi.org/10.1080/11035897.2019.1636860>
- Rubinstein, C.V., Gerrienne, P., de la Puente, G.S., Astini, R.A. and Steemans, P. 2010. Early Middle Ordovician evidence for land plants in Argentina (eastern Gondwana). *New Phytologist*, **188**, 365–369, <https://doi.org/10.1111/j.1469-8137.2010.03433.x>
- Rubinstein, C.V., Vecoli, M. and Astini, R.A. 2011. Biostratigraphy and paleoenvironmental characterization of the Middle Ordovician from the Sierras Subandinas (NW Argentina) based on organic-walled microfossils and sequence stratigraphy. *Journal of South American Earth Sciences*, **31**, 124–138, <https://doi.org/10.1016/j.jsames.2010.07.006>
- Rubinstein, C.V., de la Puente, G.S., Delabroye, A. and Astini, R.A. 2016. The palynological record across the Ordovician/Silurian boundary in the Cordillera Oriental, Central Andean Basin, northwestern Argentina. *Review of Palaeobotany and Palynology*, **224**, 14–25, <https://doi.org/10.1016/j.revpalbo.2015.06.011>
- Salamon, M.A., Gerrienne, P. et al. 2018. Putative Late Ordovician land plants. *New Phytologist*, **218**, 1305–1309, <https://doi.org/10.1111/nph.15091>
- Sanderson, M.J. 2003. Molecular data from 27 proteins do not support a Precambrian origin of land plants. *American Journal of Botany*, **90**, 954–956, <https://doi.org/10.3732/ajb.90.6.954>
- Santos, M.G.M., Mountney, N.P. and Peakall, J. 2016. Tectonic and environmental controls on Palaeozoic fluvial environments: reassessing the impacts of early land plants on sedimentation. *Journal of the Geological Society, London*, **174**, 393–404, <https://doi.org/10.1144/jgs2016-063>
- Scotese, C.R. 2014. Atlas of Silurian and Middle-Late Ordovician Paleogeographic Maps (Mollweide Projection), Maps 73 – 80, Volume 5, The Early Paleozoic, PALEOMAP Atlas for ArcGIS, PALEOMAP Project, Evanston, IL.
- Servais, T., Cascales-Miñana, B., Cleal, C.J., Gerrienne, P., Harper, D.A.T. and Neumann, M. 2019. Revisiting the Great Ordovician Diversification of land plants: recent data and perspectives. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **534**, 109280, <https://doi.org/10.1016/j.palaeo.2019.109280>
- Sherwood-Pike, M.A. and Gray, J. 1985. Silurian fungal remains: probable records of the class Ascomycetes. *Lethaia*, **18**, 1–20, <https://doi.org/10.1111/j.1502-3931.1985.tb00680.x>
- Shillito, A. and Davies, N.S. 2019. Death on the shoreline, not life on land: Ordovician arthropod trackways in the

- Borrowdale Volcanic Group, UK. *Geology*, **47**, 55–58, <https://doi.org/10.1130/G45663.1>
- Shillito, A. and Davies, N.S. 2020. The Tumblegooda Sandstone revisited: exceptionally abundant trace fossils and geological outcrop provide a window into Palaeozoic littoral habitats before invertebrate terrestrialization. *Geological Magazine*, **157**, 1939–1970, <https://doi.org/10.1017/S0016756820000199>
- Smith, M.R. 2016. Cord-forming Palaeozoic fungi in terrestrial assemblages. *Botanical Journal of the Linnean Society*, **180**, 452–460, <https://doi.org/10.1111/boj.12389>
- Smith, S.A., Beaulieu, J.M. and Donoghue, M.J. 2010. An uncorrelated relaxed-clock analysis suggests an earlier origin for flowering plants. *Proceedings of the National Academy of Sciences*, **107**, 5897–5902, <https://doi.org/10.1073/pnas.1001225107>
- Spaak, G., Edwards, D.S., Foster, C.B., Pages, A., Summons, R.E., Sherwood, N. and Grice, K. 2017. Environmental conditions and microbial community structure during the Great Ordovician Biodiversification Event; a multi-disciplinary study from the Canning Basin, Western Australia. *Global and Planetary Change*, **159**, 93–112, <https://doi.org/10.1016/j.gloplacha.2017.10.010>
- Spina, A. 2015. Latest Ordovician (Hirnantian) miospores from the NI-2 well, Algeria, North Africa, and their evolutionary significance. *Palynology*, **39**, 205–219, <https://doi.org/10.1080/01916122.2014.944626>
- Stempién-Salek, M. 2011. Palynomorph assemblages from the Upper Ordovician in northern and central Poland. *Annales Societatis Geologorum Poloniae*, **81**, 21–61.
- Stemans, P. 2000. Miospore evolution from the Ordovician to the Silurian. *Review of Palaeobotany and Palynology*, **113**, 189–196, [https://doi.org/10.1016/S0034-6667\(00\)00059-2](https://doi.org/10.1016/S0034-6667(00)00059-2)
- Stemans, P. 2001. Ordovician cryptospores from the Oostduinkerke borehole, Brabant Massif, Belgium. *Geobios*, **34**, 3–12, [https://doi.org/10.1016/S0016-6995\(01\)80038-3](https://doi.org/10.1016/S0016-6995(01)80038-3)
- Stemans, P. and Wellman, C.H. 2004. Miospores and the emergence of land plants. In: Webby, B.D., Paris, F., Droser, M.L. and Percival, I.G. (eds) *The Great Ordovician Biodiversification Event*. Columbia University Press, New York, 361–366.
- Stemans, P., Le Hérisse, A. and Bozdogan, N. 1996. Ordovician and Silurian cryptospores and miospores from southeastern Turkey. *Review of Palaeobotany and Palynology*, **93**, 35–76, [https://doi.org/10.1016/0034-6667\(95\)00119-0](https://doi.org/10.1016/0034-6667(95)00119-0)
- Stemans, P., Higgs, K.T. and Wellman, C.H. 2000. Cryptospores and trilete spores from the Llandoverly, Nuayyim Borehole, Saudi Arabia. *Special GeoArabia Publication*, **1**, 92–115.
- Stemans, P., Le Hérisse, A., Melvin, J., Miller, M.A., Paris, F., Verniers, J. and Wellman, C.H. 2009. Origin and radiation of the earliest vascular land plants. *Science (New York, NY)*, **324**, 353, <https://doi.org/10.1126/science.1169659>
- Stemans, P., Wellman, C.H. and Gerrienne, P. 2010. Palaeogeographic and palaeoclimatic considerations based on Ordovician to Lochkovian vegetation. *Geological Society, London, Special Publications*, **339**, 49–58, <https://doi.org/10.1144/SP339.5>
- Streel, M., Higgs, K., Loboziak, S., Riegel, W. and Steemans, P. 1987. Spore stratigraphy and correlation with faunas and floras in the type marine Devonian of the Ardenne–Rhenish regions. *Review of Palaeobotany and Palynology*, **50**, 211–229, [https://doi.org/10.1016/0034-6667\(87\)90001-7](https://doi.org/10.1016/0034-6667(87)90001-7)
- Strother, P.K. 1988. New species of *Nematothallus* from the Silurian Bloomsburg Formation of Pennsylvania. *Journal of Paleontology*, **62**, 967–982, <https://doi.org/10.1017/S0022336000030237>
- Strother, P.K. 1991. A classification schema for the cryptospores. *Palynology*, **15**, 219–236, <https://doi.org/10.1080/01916122.1991.9989397>
- Strother, P.K. 2000. Cryptospores: the origin and early evolution of the terrestrial flora. In: Gastaldo, R.A. and Dimichele, W.A. (eds) *Phanerozoic Terrestrial Ecosystems*. The Paleontological Society Papers, **6**, 3–20.
- Strother, P.K. and Foster, C. 2021. A fossil record of land plant origins from charophyte algae. *Science (New York, NY)*, **373**, 792–796, <https://doi.org/10.1126/science.abj2927>
- Strother, P.K. and Wellman, C.H. 2015. Palaeoecology of a billion-year-old non-marine cyanobacterium from the Torridon Group and Nonesuch Formation. *Palaeontology*, **59**, 89–108, <https://doi.org/10.1111/pala.12212>
- Strother, P.K. and Wellman, C.H. 2021. The Nonesuch Formation Lagerstätte: a rare window into freshwater life one billion years ago. *Journal of the Geological Society, London*, **178**, jgs2020-123, <https://doi.org/10.1144/jgs2020-133>
- Strother, P.K., Al-Hajri, S. and Traverse, A. 1996. New evidence for land plants from the lower Middle Ordovician of Saudi Arabia. *Geology*, **24**, 55–58, [https://doi.org/10.1130/0091-7613\(1996\)024<0055:NEFLPF>2.3.CO;2](https://doi.org/10.1130/0091-7613(1996)024<0055:NEFLPF>2.3.CO;2)
- Strother, P.K., Battison, L., Brasier, M.D. and Wellman, C.H. 2011. Earth's earliest non-marine eukaryotes. *Nature*, **473**, 505–509, <https://doi.org/10.1038/nature09943>
- Strother, P.K., Traverse, A. and Vecoli, M. 2015. Cryptospores from the Hanadir Shale Member of the Qasim Formation, Ordovician (Darriwilian) of Saudi Arabia: taxonomy and systematics. *Review of Palaeobotany and Palynology*, **212**, 97–110, <https://doi.org/10.1016/j.revpalbo.2014.08.018>
- Strother, P.K., Brasier, M.D., Wacey, D., Timpe, L., Saunders, M. and Wellman, C.H. 2021. A possible billion-year-old holozoan with differentiated multicellularity. *Current Biology*, **31**, 2658–2665, <https://doi.org/10.1016/j.cub.2021.03.051>
- Su, D., Yang, L., Shi, X., Ma, X., Zhou, X., Blair-Hedges, S. and Zhong, B. 2021. Large-scale phylogenomic analyses reveal the monophyly of bryophytes and Neoproterozoic origin of land plants. *Molecular Biology and Evolution*, **38**, 3332–3344, <https://doi.org/10.1093/molbev/msab106>
- Tang, P., Wang, Y., Xu, H.H., Jiang, Q., Yang, Z.L., Zhan, J.Z. and Zhang, X.L. 2017. Late Ordovician (late Katian) cryptospores and chitinozoans from the Mannan-1 borehole, south Tarim basin, China. *Palaeoworld*, **26**, 50–63, <https://doi.org/10.1016/j.palwor.2016.01.004>
- Taylor, W.A. 1995. Ultrastructure of *Tetrahedraletes medinensis* (Strother and Traverse) Wellman & Richardson, from the Upper Ordovician of southern Ohio. *Review of*

Terrestrialization in the Ordovician

- Palaeobotany and Palynology*, **85**, 183–187, [https://doi.org/10.1016/0034-6667\(94\)00129-8](https://doi.org/10.1016/0034-6667(94)00129-8)
- Taylor, W.A. 1996. Ultrastructure of lower Paleozoic dyads from southern Ohio. *Review of Palaeobotany and Palynology*, **92**, 269–279, [https://doi.org/10.1016/0034-6667\(96\)00109-1](https://doi.org/10.1016/0034-6667(96)00109-1)
- Taylor, W.A. 1997. Ultrastructure of lower Paleozoic dyads from southern Ohio II: *Dyadospora murusattenuata*, functional and evolutionary considerations. *Review of Palaeobotany and Palynology*, **97**, 1–8, [https://doi.org/10.1016/S0034-6667\(96\)00068-1](https://doi.org/10.1016/S0034-6667(96)00068-1)
- Taylor, W.A. and Wellman, C.H. 2009. Ultrastructure of enigmatic phytoclasts (banded tubes) from the Silurian–Lower Devonian: evidence for affinities and role in early terrestrial ecosystems. *PALAIOS*, **24**, 167–180, <https://doi.org/10.2110/palo.2008.p08-046r>
- Taylor, T.N., Krings, M. and Taylor, E.L. 2015. *Fossil Fungi*. Academic Press.
- Taylor, W.A., Strother, P.K., Vecoli, M. and Al-Hajri, S. 2017. Wall ultrastructure of the oldest embryophytic spores: implications for early land plant evolution. *Revue de Micropaléontologie*, **60**, 281–288, <https://doi.org/10.1016/j.revmic.2016.12.002>
- Thusu, B., Rasul, S., Paris, F., Meinhold, G., Howard, J.P., Abutaruma, Y. and Whitham, A.G. 2013. Latest Ordovician–Earliest Silurian acritarchs and chitinozoans from subsurface samples in Jebel Asba, Kufra Basin, SE Libya. *Review of Palaeobotany and Palynology*, **197**, 90–118, <https://doi.org/10.1016/j.revpalbo.2013.05.006>
- Tomescu, A.M.F. and Rothwell, G.W. 2006. Wetlands before tracheophytes: Thalloid terrestrial communities of the Early Silurian Passage Creek biota. *Geological Society of America, Special Paper*, **399**, 41–56, [https://doi.org/10.1130/2006.2399\(02\)](https://doi.org/10.1130/2006.2399(02))
- Tomescu, A.M.F., Rothwell, G.W. and Honegger, R. 2006. Cyanobacterial macrophytes in an Early Silurian (Llandovery) continental biota: Passage Creek, lower Massanutten Sandstone, Virginia, USA. *Lethaia*, **39**, 329–338, <https://doi.org/10.1080/00241160600876719>
- Tomescu, A.M.F., Honegger, R. and Rothwell, G.W. 2008. Earliest fossil record of bacterial–cyanobacterial mat consortia: the Early Silurian Passage Creek biota (440 Ma, Virginia, USA). *Geobiology*, **6**, 120–124, <https://doi.org/10.1111/j.1472-4669.2007.00143.x>
- Tomescu, A.M.F., Rothwell, G.W. and Honegger, R. 2009. A new genus and species of filamentous microfossil of cyanobacterial affinity from Early Silurian fluvial environments (lower Massanutten Sandstone, Virginia, USA). *Botanical Journal of the Linnean Society*, **160**, 284–289, <https://doi.org/10.1111/j.1095-8339.2009.00980.x>
- Tomescu, A.M.F., Tate, R.W., Mack, N.G. and Calder, V.J. 2010. Simulating fossilization to resolve the taxonomic affinities of thalloid fossils in Early Silurian (ca. 425 Ma) terrestrial assemblages. In: Nash, T.H., III (ed.) *Biology of Lichens: Symbiosis, Ecology, Environmental Monitoring, Systematics, Cyber Applications*. Bibliotheca Lichenologica, **105**, 183–190.
- Trewin, N.H. and McNamara, K.J. 1994. Arthropods invade the land: trace fossils and palaeoenvironments of the Tumbagoona Sandstone (?Late Silurian) of Kalbarri, Western Australia. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **85**, 177–210, <https://doi.org/10.1017/S026359330000359X>
- Vavrdova, M. 1982. Recycled acritarchs in the uppermost Ordovician of Bohemia. *Casopis pro Mineralogii a Geologii*, **27**, 337–345.
- Vavrdova, M. 1984. Some plant microfossils of the possible terrestrial origin from the Ordovician of central Bohemia. *Vestník Ceskeho Geologickeho Ustavu*, **59**, 165–170.
- Vavrdova, M. 1988. Further acritarchs and terrestrial plant remains from the Late Ordovician at Hlasna Treban (Czechoslovakia). *Casopis pro Mineralogii a Geologii*, **33**, 1–10.
- Vavrdova, M. 1989. New acritarchs and miospores from the Late Ordovician of Hlasna Treban, Czechoslovakia. *Casopis pro Mineralogii a Geologii*, **34**, 403–420.
- Vavrdova, M. 1990. Coenobial acritarchs and other palynomorphs from the Arenig/Llanvirn boundary. *Prague basin Vestník Ceskeho Geologickeho Ustavu*, **65**, 237–242.
- Vavrdova, M. 1993. Acritarch assemblages in the Arenig Series of the Prague Basin, Czech Republic. *Special Papers in Palaeontology*, **48**, 125–139.
- Vecoli, M., Delabroye, A., Spina, A. and Hints, O. 2011. Cryptospore assemblages from Upper Ordovician (Katian-Hirmantian) strata of Anticosti Island, Québec, Canada, and Estonia: palaeophytogeographic and palaeoclimatic implications. *Review of Palaeobotany and Palynology*, **166**, 76–93, <https://doi.org/10.1016/j.revpalbo.2011.05.006>
- Vecoli, M., Wellman, C.H., Gerrienne, P., Le Hérisse, A. and Steemans, P. 2017. Middle Ordovician cryptospores from the Saq-Hanadir transitional beds in the QSIM-801 well, Saudi Arabia. *Revue de Micropaléontologie*, **60**, 319–331, <https://doi.org/10.1016/j.revmic.2017.06.003>
- Versteegh, G.J.M. and Riboulleau, A. 2010. An organic geochemical perspective on terrestrialisation. *Geological Society, London, Special Publications*, **339**, 11–36, <https://doi.org/10.1144/SP339.3>
- Wang, Y., Li, J. and Wang, R. 1997. Latest Ordovician cryptospores from southern Xinjiang, China. *Review of Palaeobotany and Palynology*, **99**, 61–74, [https://doi.org/10.1016/S0034-6667\(97\)00033-X](https://doi.org/10.1016/S0034-6667(97)00033-X)
- Wellman, C.H. 1996. Cryptospores from the type area of the Caradoc Series in Southern Britain. *Special Papers in Palaeontology*, **55**, 103–136.
- Wellman, C.H. 1999. Ordovician land plants: evidence and interpretation. *Acta Universitatis Carolinae – Geologica*, **43**, 275–277.
- Wellman, C.H. 2004. Origin, function and development of the spore wall in early land plants. In: Kurmann, M.H. and Hemsley, A.R. (eds) *The Evolution of Plant Architecture*. Royal Botanic Gardens, Kew, 43–63.
- Wellman, C.H. 2010. The invasion of the land by plants: when and where? *New Phytologist*, **188**, 306–309, <https://doi.org/10.1111/j.1469-8137.2010.03471.x>
- Wellman, C.H. and Ball, A.C. 2021. Early land plant phytodebris. *Geological Society, London, Special Publications*, **511**, 309–320, <https://doi.org/10.1144/SP511-2020-36>
- Wellman, C.H. and Gray, J. 2000. The microfossil record of early land plants. *Philosophical Transactions of the Royal Society London B*, **355**, 717–732, <https://doi.org/10.1098/rstb.2000.0612>
- Wellman, C.H. and Strother, P.K. 2015. The terrestrial biota prior to the origin of land plants (embryophytes):

C. H. Wellman *et al.*

- a review of the evidence. *Palaeontology*, **58**, 601–627, <https://doi.org/10.1111/pala.12172>
- Wellman, C.H., Osterloff, P.L. and Mohiuddin, U. 2003. Fragments of the earliest land plants. *Nature*, **425**, 282–285, <https://doi.org/10.1038/nature01884>
- Wellman, C.H., Steemans, P. and Vecoli, M. 2013. Palaeophytogeography of Ordovician–Silurian land plants. *Geological Society, London, Memoirs*, **38**, 461–476, <https://doi.org/10.1144/M38.29>
- Wellman, C.H., Steemans, P. and Miller, M.A. 2015. Spore assemblages from Upper Ordovician and lowermost Silurian sediments recovered from the Qusaiba-1 shallow core hole, Qasim region, central Saudi Arabia. *Review of Palaeobotany and Palynology*, **212**, 111–126, <https://doi.org/10.1016/j.revpalbo.2014.09.003>
- Wickett, N.J., Mirarab, S. *et al.* 2014. Phylotranscriptomic analysis of the origin and early diversification of land plants. *Proceedings of the National Academy of Sciences*, **111**, 4859–4868, <https://doi.org/10.1073/pnas.1323926111>
- Yin, L. and He, S. 2000. Palynomorphs from the transitional sequences between Ordovician and Silurian of north-western Zhejiang, South China. *In*: Song, Z. (ed.) *Palynofloras and Palynomorphs of China*, University of Science and Technology of China Press, 186–202.
- Zeichner, S.S., Nghiem, J., Lamb, M.P., Takashima, N., de Leeuw, J., Ganti, V. and Fischer, W.W. 2021. Early plant organics increased global terrestrial mud deposition through enhanced flocculation. *Science (New York, NY)*, **371**, 526–529, <https://doi.org/10.1126/science.abd0379>
- Zimmer, A., Lang, D., Richardt, S., Frank, W., Reski, R. and Rensing, S.A. 2007. Dating the early evolution of plants: detection and molecular clock analyses of orthologs. *Molecular Genetics and Genomics*, **278**, 393–402, <https://doi.org/10.1007/s00438-007-0257-6>