GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G52648.1

Manuscript received 31 July 2024
Manuscript accepted 10 August 2024

Published online 27 August 2024

Don't mind the "charcoal gap": A reassessment of Devonian wildfire

Ian J. Glasspool[1,2,*] and Robert A. Gastaldo[1,3]
[1]Department of Geology, Colby College, Waterville, Maine 04901, USA
[2]Field Museum of Natural History, Chicago, Illinois 60605, USA
[3]Department of Paleobiology, National Museum of Natural History, Smithsonian Institution, Washington, D.C. 20560, USA

ABSTRACT

Little evidence of macrofossil charcoal, a wildfire proxy, is recorded from upper Lower to lowermost Upper Devonian rocks. Coals of this age are few, and petrographic data indicate low volumes (<10% mineral-matter free) of charcoal. This paucity of data forms the basis of the "charcoal gap," which is used to suggest an extended interval of abnormally low atmospheric oxygen (pO_2). We reassess the current evidence for this hiatus using Emsian–Eifelian charcoal from the Trout Valley and St. Froid Lake Formations, Maine (northeastern United States), and integrate the microscopic charcoal record of dispersed organic matter. We conclude there is ample evidence of fire in the Middle Devonian. This interval is not innately of low pO_2. Rather, it is one in which under-interpretation of available data has led to a perceived paucity of charcoal. This reconciliation indicates the Phanerozoic record of wildfire was substantially uninterrupted. Hence, we propose that pO_2 achieved levels >16% and remained at such levels from the Silurian through the floral and faunal colonization of land and, from our current estimates, stayed as such until the present.

INTRODUCTION

Much of the Devonian was characterized by high sea levels, high marine faunal diversity, and "widespread equable climates" (Becker et al., 2020, p. 733). Reef building was at its greatest and most latitudinally widespread extent, and the Middle Devonian remained icecap free during this mid-Phanerozoic (426–365 Ma) hothouse under moderate temperature flux (Scotese et al., 2021). Middle Emsian (ca. 401 Ma) cooling, with a global average temperature (GAT) of ~18.7 °C, was followed by the Givetian Thermal Maximum (ca. 385 Ma; GAT ~21.2 °C) before transitioning to a Frasnian cooling-warming trend peaking in the Kellwasser Thermal Maximum (ca. 375 Ma; Scotese et al., 2021, their table 4). Despite this variance, GAT is thought to have been significantly higher than that of today (Scotese et al., 2021; 14.5 °C).

Tree-sized Pseudosporochnales appeared in the Middle Devonian (Eifelian–Givetian; Stein et al., 2012, 2020; Fig. 1) when taxa, including the whole plant concept *Eospermatopteris*, well known also through its branch morphotaxon *Wattieza*, were water-dependent, fast-establishing and fast-growing, non-woody plants. By the Givetian, the group was joined by woody progymnosperms (Stein et al., 2012; Fig. 1). While still spore producing, these woody trees were more deeply rooted (Algeo et al., 2001) and less constrained by water availability (Stein et al., 2012). Based on isotopic data, the transition from the Middle to Late Devonian witnessed increasing global vegetation cover (10%–30%; Gibling and Davies, 2012). This more broadly distributed forested landscape led to major ecosystem adjustments impacting weathering, sedimentation, phosphorus mobilization, atmospheric pCO_2, and climate (Algeo et al., 2001; Berner, 2009; Gibling and Davies, 2012; Morris et al., 2015). Arborescence, especially woody archaeopterids, constituted a major wildfire-fuel source, promoting positive feedback on fire-system development and resulting in a concomitant increase of fossil charcoal (Scott and Glasspool, 2006). However, any such synchronous increase remains to be verified in the plant-fossil record (Fig. 1). Given the prevailing hothouse climate and greater fuel availability, Middle Devonian quantitative and qualitative records of macroscopic charcoal have shown surprisingly low charcoal abundance. These data delimit the late Emsian to early Frasnian "charcoal gap" (Scott and Glasspool, 2006; Lu et al., 2021).

Deep-time records of atmospheric and oceanic oxygenation are largely linked to geochemical proxies reflecting O_2 and other redox-sensitive element interactions (e.g., S, Fe, Mo; Dahl et al., 2010). Mass-balance modeling assesses carbon and sulfur isotope records to estimate net burial rates and pO_2 (Berner, 2009). Deep-time flux modeling uses Holocene rates of chemical (e.g., P, C, S) flux and applies factors to them in simplified, variable-dependent box models to estimate pO_2 (e.g., Royer et al., 2014; Lenton et al., 2018; Mills et al., 2023). Such biogeochemical models assume that photosynthetic splitting of water molecules is the main source of pO_2 (Shields and Mills, 2017). Respiration or decay reverse this process. Increases in pO_2 are driven by the sedimentary burial of organic matter, which effectively reduces carbon availability (Shields and Mills, 2017). The burial of reduced sulfur species has a comparable but lower-magnitude effect. Hence, records of high $\delta^{13}C$ are interpreted as representing periods of excess organic burial and elevated pO_2. However, predictions from these two main biogeochemical models vary.

Other Paleozoic pO_2 proxies exist and include Mo isotopes (Dahl et al., 2010), fluid-gas inclusion in halites (Brand et al., 2021), sedimentary pyrite (Cannell et al., 2022), and charcoal (Glasspool and Gastaldo, 2022a). While some proxies interpret a pO_2 increase in the Ediacaran (635–542 Ma) oceans, large areas remained anoxic into the early Phanerozoic (Dahl et al., 2010). One model predicts increasing pO_2 with the advent of forests at ca. 385 Ma (COPSE; Lenton et al., 2018), whereas Mo isotopes (Dahl et al., 2010) project a Silurian–Devonian wide-

Ian J. Glasspool https://orcid.org/0000-0002-7468-042X
*iglasspool@fieldmuseum.org; ian.glasspool@colby.edu

CITATION: Glasspool, I.J., and Gastaldo, R.A., 2024, Don't mind the "charcoal gap": A reassessment of Devonian wildfire: Geology, v. XX, p. ,
https://doi.org/10.1130/G52648.1

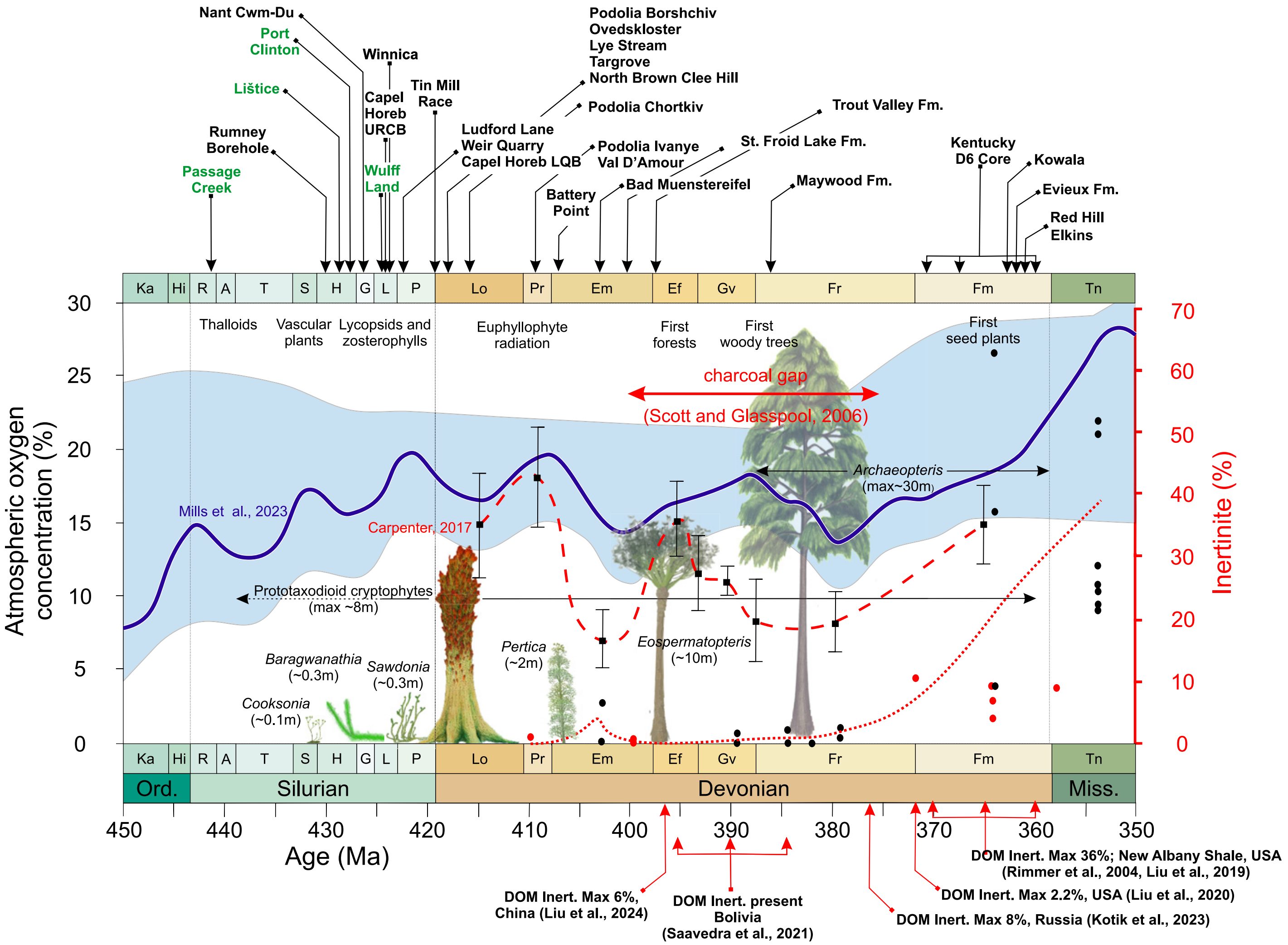

Figure 1. Global records of Silurian–Devonian fire. Arrows with black or green labels at top indicate qualitative macro- and mesofossil charcoal occurrences (see Glasspool and Gastaldo, 2022a, and Supplemental Material Table S2 [see text footnote 1]). Arrows with green labels are unconfirmed occurrences. Red arrows at bottom indicate select inertinite (inert.) and dispersed organic matter (DOM) records. Blue line and shaded area are from Mills et al. (2023). GEOCARBSULFOR model pO_2 evolution; solid blue line is median prediction, and blue area is Monte Carlo statistic ensemble range. Red dotted line is mean trend line of inertinite abundance in coal (black circles) and terrigenous clastic charcoal abundance (red circles). Red dashed line connects DOM inertinite data (black squares) of Carpenter (2017, their figure 3.46a redrafted); error bars show standard error. Both red lines are quantified against red inertinite scale; blue line against black pO_2 scale. Plant images show largest contemporaneous plants at maximum (max) height (not to scale). URCB—Upper Roman Camp Beds; LQB—Long Quarry Beds; Ka—Katian; Hi—Hirnantian; R—Rhuddanian; A—Aeronian; T—Telychian; S—Sheinwoodian; H—Homerian; G—Gorstian; L—Ludfordian; P—Přídolí; Lo—Lochkovian; Pr—Pragian; Em—Emsian; Ef—Eifelian; Gv—Givetian; Fr—Frasnian; Fm—Famennian; Tn—Tournaisian; Ord.—Ordovician; Miss.—Mississippian; Fm.—Formation.

spread ocean anoxia to widespread oxygenation shift. Lenton et al. (2016) predicted that pO_2 reached a near modern-day steady-state level by ca. 400 Ma, which is broadly in line with charcoal and inertinite data (for discussion of charcoal and inertinite, see Scott and Glasspool, 2007). Fossil charcoal indicates that Earth's pO_2 was sufficient to support wildfire, even if episodically, by the mid-Silurian and probably as far back as the early Silurian (Glasspool and Gastaldo, 2022a). From the Middle Silurian onward, the continuity of the charcoal record remains temporally unbroken with a notable mid-Paleozoic exception (Scott and Glasspool, 2006; Rimmer et al., 2015; Lenton et al. 2016; Lu et al., 2021).

Until recently, little charcoal or inertinite was reported in and around the Middle Devonian (late Emsian to early Frasnian; Lu et al., 2021). Such observations were used to propose this interval (originally late Emsian to early Famennian) represented a putative "charcoal gap" (Scott and Glasspool, 2006), indicating $pO_2 < 16\%$. This experimentally determined and slightly uncertain threshold defines the lowest "fire window" limit interpreted to range between ~16% and 30% (cf. Cope and Chaloner, 1980; Belcher et al., 2010; Vitali et al., 2022). The lower limit defines the pO_2 below which wildfire cannot ignite and propagate (Belcher et al., 2010); the upper limit is controversial and may not exist, as $pO_2 > 35\%$ may be suitable for vegetation regeneration (Vitali et al., 2022). While the "fire window" may not be a viable concept, based on recent modeling, the lower pO_2 limit is still valid to mark a wildfire propagation threshold below which charcoal should not form.

Quantifiably, no coal in the late Emsian to early Frasnian had yet been measured in excess of 8.1% inertinite content (see Glasspool and Scott, 2010; Supplemental Material[1]); most analyses report values close to zero. Predictions

[1]Supplemental Material. Charcoal and inertinite locality and quantification data. Please visit https://doi.org/10.1130/GEOL.S.26737381 to access the supplemental material; contact editing@geosociety.org with any questions.

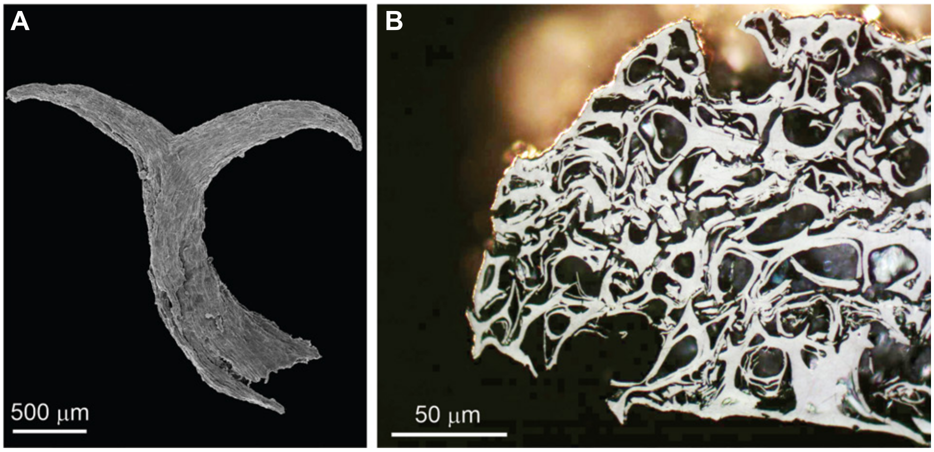

Figure 2. Charcoal from Trout Valley Formation, Maine, USA. (A) Scanning electron microscope (SEM) image of charred, anatomically preserved, bifurcating trimerophyte terminal process. (B) Reflected-light microscope image of embedded and polished partial trimerophyte terminal process showing high (silver-gray) reflectance. Gold glow is gold coating used for prior SEM analysis.

of pO_2 (Glasspool and Scott, 2010) used bulk-sampling data from economic coals. However, records of low-inertinite Middle Devonian coals are very limited in number (Supplemental Material), and the paucity of these data yields less-robust predictions of pO_2 than those estimated from the globally exploited and frequently quantified coals of the Carboniferous and Permian (see Glasspool and Scott, 2010). Therefore, we assess the significance of charcoal reports from Middle Devonian clastic rocks on our perceptions of wildfire occurrence, though not to estimate pO_2, during this interval.

Both the Trout Valley Formation and the newly named St. Froid Lake Formation, Maine, USA, contain Emsian–Eifelian macro- and mesofossil charcoal (Fig. 2; Glasspool and Gastaldo, 2024). These occurrences complement lower Frasnian macrofossil charcoal in the Maywood Formation, Wyoming, USA (Marshall et al., 2022). Despite evidence of these proxies, Middle Devonian wildfire occurrence, particularly on a global scale, is still limited. While microscopic inertinite in dispersed organic matter (DOM) is known and used as a wildfire proxy (e.g., Rimmer et al., 2015), Glasspool and Scott (2010) omitted it when quantifying Paleozoic pO_2 for reasons discussed therein. However, DOM data demonstrate charcoal distribution and frequency of occurrence and is a valid proxy for fire activity. We collate inertinite (coal), macro- and mesofossil charcoal (clastic deposits), and inertinite (DOM) records to demonstrate pervasive Middle Devonian wildfire, resulting in the abandonment of a "charcoal gap" concept.

RESULTS

Reported Devonian-age inertinite (e.g., Glasspool and Scott, 2010; Lu et al., 2021; Supplemental Material) and other charcoal-occurrence data (Glasspool and Gastaldo, 2022a, 2022b) are plotted in Figure 1 with inertinite in DOM (Supplemental Material) and recently published macro- to mesofossil charcoal occurrences (Marshall et al., 2022; Glasspool and Gastaldo, 2024). Not all data conform to the coal criteria used by Glasspool and Scott (2010) to generate their inertinite-driven pO_2 model. However, new macro-mesofossil data from Maine (Emsian–Eifelian; Fig. 2) and Wyoming (lower Frasnian) and DOM data record wildfire occurrences that fall in the hypothesized "charcoal gap" (Scott and Glasspool, 2006). These demonstrate a sparse but uninterrupted fire record over this interval. As expected, quantified inertinite data (QID) from petrography of coals and organic-rich shales (Fig. 1, dotted line) and inertinite DOM data (IDD) (Fig. 1, dashed line and red arrows) mirror a modeled pO_2 increase from the mid-Frasnian into the Tournaisian. However, despite Carpenter's (2017) remeasurement of the L'Anse-à-Brillant coal of easternmost Quebec (Table S1 in the Supplemental Material), QID in the Emsian interval of the "charcoal gap" predicts only nominal fire occurrence. The inclusion of IDD, from a broader range of taphonomic settings, greatly alters this perception. IDD data indicate fire throughout the Lochkovian–Famennian with a possible Emsian decline, although there is abundant evidence in the Middle–Late Devonian. These occurrences indicate that Devonian pO_2 did not drop below 16% for any continuously sustained interval in the Devonian. The new data show that fires proliferated at the same time as the onset of forestation and became more abundant once woody progymnosperms were established.

DISCUSSION

The master variables controlling wildfire are a source of heat for ignition, a source of fuel, and sufficient pO_2 for propagation (Cope and Chaloner, 1980). The common ignition source, lightning, is considered a constant (Glasspool and Scott, 2010), leaving the others as leading variables controlling Phanerozoic wildfire activity. The warmer Devonian temperatures (Scotese et al., 2021) would have amplified prevailing weather patterns, leading to wetter wet regions and drier dry areas. Globally, more volatile weather should have impacted fuel availability and the potential for fire propagation. Prolific evidence of fire occurs during other hothouse intervals and is attributed, in part, to an effective increase in low-moisture-content fuel (e.g., mid-Cretaceous: Brown et al., 2012; Triassic: Baker, 2022). Perhaps significantly, strata leading up to and during the Paleocene–Eocene Thermal Maximum (PETM) record frequent fires (Collinson et al., 2007), although lower Paleogene hothouse coals are charcoal poor and interpreted to represent low fire frequency (Glasspool and Scott, 2010). Rather, other limitations aside, the prevailing equable Middle Devonian hothouse should not have impeded wildfire and charcoalification but enhanced it.

This correlation appears rational given that the charcoal-fossil record extends back to the mid-Silurian (Glasspool and Gastaldo, 2022a, 2022b), a time when, with the exception of some massive cryptophytes (e.g., prototaxodioids; Gensel et al., 2020; Glasspool and Gastaldo, 2022b; Fig. 1), most sporophytes afforded limited combustible biomass (Fig. 1). The diversification and increasing terrestrial plant biomass through the Middle Devonian, including Eifelian arborescence (Stein et al., 2012, 2020) and Givetian woody trees colonizing mineral soils (Stein et al., 2012; Fig. 1), should have afforded a substantial new fuel source. In line with this expectation, macro- and mesofossil data collated by Lu et al. (2021) did contract the range of the "charcoal gap" to the period from the late Emsian until the end Givetian. However, from the macrofossil charcoal evidence, this gap could have extended into the Frasnian, by which point the forests of woody archaeopterids occurred.

To date, the Middle Devonian charcoal record remains deficient of evidence to support burning of the earliest trees with the exception of charcoal from the Maywood Formation (Marshall et al., 2022). The Maywood charcoal includes well-preserved, centimeter-sized archaeopterid charcoal clasts evidencing forests did burn. Marshall et al. (2022, p. 486) consider the lower Frasnian charcoal abundance of the Maywood Formation to indicate a "high incidence of wildfires." While this argument for frequent wildfires is attractive, as with similar isolated charcoal from the mid-Silurian (e.g., Glasspool and Gastaldo, 2022b), the Maywood data must be recognized as indicative of a narrow time window.

Although complicated by the locally high metamorphic rank, an Emsian–Eifelian Trout Valley Formation paleosol, Baxter State Park, Maine, preserves abundant charcoal (Fig. 2; Glasspool and Gastaldo, 2024). This single charcoal-rich horizon, inside the "charcoal gap," is complemented by meso- to microscopic charcoal from other intervals in the formation (Glasspool and Gastaldo, 2024). Regionally, charcoal is a component of several widely spaced subbasins in the newly recognized Emsian–Eifelian St. Froid Lake Formation, Maine (Supplemental Material). While the Trout Valley Formation charcoal represents psilophyte, lycopod, and prototaxodioid charring, charcoal from the St. Froid Lake Formation is limited to smaller (millimeter-scale) poorly preserved cryptophytic bryophyte-sized plants. These preservational differences (style and taxonomy) are taphonomic, reflecting transport and deposition in more proximal and distal coastal settings.

North American Middle Devonian coals are rare due to an absence of strata of this age. Globally, most upper Lower to lower Upper Devonian (Emsian–Frasnian) coals are liptinite rich. For example, of the Melville Island coals of Canada's Nunavut and Northwestern Territories (Goodarzi and Gentzis, 2018), 14 cannel and canneloid (spore-rich) coals are liptinitic (average 1.3% inertinite mineral-matter free [mmf]) while only five are humic (average 3.6% inertinite mmf; Supplemental Material). The Luquan coals of China (Lu et al., 2021) and the Barzas coals of Estonia (Patrakov et al., 2005; Supplemental Material) are paper coals, while the Mimerdalen coal, Svalbard (Lu et al., 2021), and the L'Anse-à-Brillant coal are somewhat less cuticle rich (Glasspool and Scott, 2010). Another paper coal (upper Givetian–lower Frasnian Lithograph City Formation [Table S1, Supplemental Material]) analyzed for the current study was inertinite free. Most paper coals are upper Lower to Middle Devonian and are limited-diversity, well-cutinized floras (Gensel et al., 2020). Ultraviolet B (UV-B) radiation has been proposed as an end-Devonian terrestrial extinction-kill mechanism (Marshall et al., 2020) resulting from a weak paleomagnetic field (van der Boon et al., 2022). Given this field weakness, Marshall et al. (2020) propose that UV-B may have been elevated through a greater interval than just the latest Devonian. If Middle Devonian UV-B were high, extensive cutinization may have been a plant adaptation. Hence, any resulting over-representation of cutinite in these coals could result in an under-representation of charcoal, though other taphonomic causes cannot be excluded.

While the Maywood Formation, St. Froid Lake Formation, and Trout Valley Formation charcoals confirm the presence of wildfire in a minimum of three instances during the late Early to earliest Late Devonian, a far more extensive record is provided by DOM charcoal. Carpenter's (2017) data (Table S1) superficially indicate a percentage decline in DOM inertinite from the Emsian to the Frasnian. However, this change is likely a sampling artifact because the data are not statistically significant (Carpenter, 2017). The concept of the "charcoal gap" (Scott and Glasspool, 2006) is entirely dependent on an absence of reported Emsian–Frasnian charcoal. Macroscopic charcoal from the Emsian–Eifelian Trout Valley Formation and the lowest Frasnian Maywood Formation, in association with Carpenter's (2017) Euramerica and Gondwana DOM data, considerably weakens this concept to the extent that the "charcoal gap" can now be considered "plugged."

CONCLUSIONS

A dearth of Middle Devonian charcoal data led to the hypothesis of a "charcoal gap," which has been used to model low pO_2 (<16%) during this interval. Macro- and mesofossil charcoal from the Emsian–Eifelian Trout Valley and St. Froid Lake Formations, Maine, coupled with DOM occurrences elsewhere, indicates the prevalence of wildfire throughout the "gap." This charcoal evidence supports pO_2 levels at, or above, the minimum for fire ignition and propagation. The perception that charcoal was absent during this interval is likely due to taphonomy and sampling.

ACKNOWLEDGMENTS

Research was supported by National Science Foundation grant EAR-0087433 to Gastaldo and 1828359 to Glasspool and Gastaldo. We acknowledge Raymond Anderson and the staff of the Iowa Geological Survey for supplying samples of the Lithograph City Formation coal. We also acknowledge helpful comments by Cortland Eble and two anonymous reviewers.

REFERENCES CITED

Algeo, T.J., Scheckler, S.E., and Maynard, J.B., 2001, Effects of the Middle to Late Devonian spread of vascular land plants on weathering regimes, marine biotas, and global climate, *in* Gensel, P.G., and Edwards, D., eds., Plants Invade the Land: Evolutionary and Environmental Perspectives: New York, Columbia University Press, p. 213–236, https://doi.org/10.7312/gens11160-013.

Baker, S.J., 2022, Fossil evidence that increased wildfire activity occurs in tandem with periods of global warming in Earth's past: Earth-Science Reviews, v. 224, https://doi.org/10.1016/j.earscirev.2021.103871.

Becker, R.T., Marshall, J.E.A., Da Silva, A.-C., Agterberg, F.P., Gradstein, F.M., and Ogg, J.G., 2020, The Devonian Period, *in* Gradstein, F.M., et al., eds., Geologic Time Scale 2020: Amsterdam, Elsevier, p. 733–810, https://doi.org/10.1016/B978-0-12-824360-2.00022-X.

Belcher, C.M., Yearsley, J.M., Hadden, R.M., McElwain, J.C., and Rein, G., 2010, Baseline intrinsic flammability of Earth's ecosystems estimated from paleoatmospheric oxygen over the past 350 million years: Proceedings of the National Academy of Sciences of the United States of America, v. 107, p. 22,448–22,453, https://doi.org/10.1073/pnas.1011974107.

Berner, R.A., 2009, Phanerozoic atmospheric oxygen: New results using the GEOCARBSULF model: American Journal of Science, v. 309, p. 603–606, https://doi.org/10.2475/07.2009.03.

Brand, U., Davis, A.M., Shaver, K.K., Blamey, N.J.F., Heizler, M., and Lécuyer, C., 2021, Atmospheric oxygen of the Paleozoic: Earth-Science Reviews, v. 216, https://doi.org/10.1016/j.earscirev.2021.103560.

Brown, S.A., Scott, A.C., Glasspool, I.J., and Collinson, M.E., 2012, Cretaceous wildfires and their impact on the Earth system: Cretaceous Research, v. 36, p. 162–190, https://doi.org/10.1016/j.cretres.2012.02.008.

Cannell, A., Blamey, N., Brand, U., Escapa, I., and Large, R., 2022, A revised sedimentary pyrite proxy for atmospheric oxygen in the Paleozoic: Evaluation for the Silurian-Devonian-Carboniferous period and the relationship of the results to the observed biosphere record: Earth-Science Reviews, v. 231, https://doi.org/10.1016/j.earscirev.2022.104062.

Carpenter, D.K., 2017, Charcoal, forests, and Earth's Palaeozoic geochemical oxygen cycle [Ph.D. thesis]: Southampton, UK, University of Southampton, 269 p.

Collinson, M.E., Steart, D.C., Scott, A.C., Glasspool, I.J., and Hooker, J.J., 2007, Episodic fire, runoff and deposition at the Palaeocene–Eocene boundary: Journal of the Geological Society, v. 164, p. 87–97, https://doi.org/10.1144/0016-76492005-185.

Cope, M.J., and Chaloner, W.G., 1980, Fossil charcoal as evidence of past atmospheric composition: Nature, v. 283, p. 647–649, https://doi.org/10.1038/283647a0.

Dahl, T.W., Hammarlund, E.U., Anbar, A.D., Bond, D.P.G., Gill, B.C., Gordon, G.W., Knoll, A.H., Nielsen, A.T., Schovsbo, N.H., and Canfield, D.E., 2010, Devonian rise in atmospheric oxygen correlated to the radiations of terrestrial plants and large predatory fish: Proceedings of the National Academy of Sciences of the United States of America, v. 107, p. 17,911–17,915, https://doi.org/10.1073/pnas.1011287107.

Gensel, P.G., Glasspool, I., Gastaldo, R.A., Libertin, M., and Kvaček, J., 2020, Back to the beginnings: The Silurian–Devonian as a time of major innovation in plants and their communities, *in* Martinetto, E., et al., eds., Nature Through Time: Virtual Field Trips Through the Nature of the Past: Cham, Switzerland, Springer International Publishing, p. 367–398, https://doi.org/10.1007/978-3-030-35058-1_15.

Gibling, M.R., and Davies, N.S., 2012, Palaeozoic landscapes shaped by plant evolution: Nature Geoscience, v. 5, p. 99–105, https://doi.org/10.1038/ngeo1376.

Glasspool, I.J., and Gastaldo, R.A., 2022a, Silurian wildfire proxies and atmospheric oxygen: Geology, v. 50, p. 1048–1052, https://doi.org/10.1130/G50193.1.

Glasspool, I.J., and Gastaldo, R.A., 2022b, A baptism by fire: Fossil charcoal from eastern Euramerica reveals the earliest (Homerian) terrestrial biota evolved in a flammable world: Journal of the Geological Society, v. 180, https://doi.org/10.1144/jgs2022-072.

Glasspool, I.J., and Gastaldo, R.A., 2024, Through fire, and through water, an abundance of Mid-Devonian charcoal: PALAIOS, http://dx.doi.org/10.2110/palo.2024.009.

Glasspool, I.J., and Scott, A.C., 2010, Phanerozoic concentrations of atmospheric oxygen reconstructed from sedimentary charcoal: Nature Geoscience, v. 3, p. 627–630, https://doi.org/10.1038/ngeo923.

Goodarzi, F., and Gentzis, T., 2018, Elemental concentration and organic petrology of unique liptinite-rich humic coal, canneloid shale, and cannel coal of Devonian age from Arctic Canada: Chemical Geology, v. 485, p. 44–55, https://doi.org/10.1016/j.chemgeo.2018.03.035.

Kotik, O.S., Pronina, N.V., Inkina, N.S., and Beznosov, P.A., 2023, Compositional peculiarities of the Upper Devonian coaly rocks (the Sula River Section, North Timan): Lithology and Mineral Resources, v. 58, p. 455–468, https://doi.org/10.1134/S0024490223700220.

Lenton, T.M., Dahl, T.W., Daines, S.J., Mills, B.J., Ozaki, K., Saltzman, M.R., and Porada, P., 2016, Earliest land plants created modern levels of atmospheric oxygen: Proceedings of the National Academy of Sciences of the United States of America, v. 113, p. 9704–9709, https://doi.org/10.1073/pnas.1604787113.

Lenton, T.M., Daines, S.J., and Mills, B.J.W., 2018, COPSE reloaded: An improved model of biogeochemical cycling over Phanerozoic time: Earth-Science Reviews, v. 178, p. 1–28, https://doi.org/10.1016/j.earscirev.2017.12.004.

Liu, B., Schieber, J., Mastalerz, M., and Teng, J., 2019, Organic matter content and type variation in the sequence stratigraphic context of the Upper Devonian New Albany Shale, Illinois Basin: Sedimentary Geology, v. 383, p. 101–120, https://doi.org/10.1016/j.sedgeo.2019.02.004.

Liu, Y., Shi, W., Yuan, K., Wang, R., Xu, X., Zhang, X., Bai, L., Feng, Q., and Konhauser, K.O., 2024, Petrographic and geochemical characteristics of the Middle Devonian Eifelian Nabiao Formation in the Youjiang Basin, South China: Implications for paleoenvironment and organic matter accumulation mechanism: Geoenergy Science and Engineering, v. 232, https://doi.org/10.1016/j.geoen.2023.212419.

Liu, Z., Selby, D., Hackley, P.C., and Over, D.J., 2020, Evidence of wildfires and elevated atmospheric oxygen at the Frasnian–Famennian boundary in New York (USA): Implications for the Late Devonian mass extinction: Geological Society of America Bulletin, v. 132, p. 2043–2054, https://doi.org/10.1130/B35457.1.

Lu, M., Ikejiri, T., and Lu, Y., 2021, A synthesis of the Devonian wildfire record: Implications for paleogeography, fossil flora, and paleoclimate: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 571, https://doi.org/10.1016/j.palaeo.2021.110321.

Marshall, J.E., Lakin, J., Troth, I., and Wallace-Johnson, S.M., 2020, UV-B radiation was the Devonian-Carboniferous boundary terrestrial extinction kill mechanism: Science Advances, v. 6, https://doi.org/10.1126/sciadv.aba0768.

Marshall, J.E., Holterhoff, P.F., El-Abdallah, S.R., Matsunaga, K.K., Bronson, A.W., and Tomescu, A.M., 2022, The archaeopterid forests of lower Frasnian (Upper Devonian) westernmost Laurentia: Biota and depositional environment of the Maywood Formation in northern Wyoming as reflected by palynoflora, macroflora, fauna, and sedimentology: International Journal of Plant Sciences, v. 183, p. 465–492, https://doi.org/10.1086/720736.

Mills, B.J., Krause, A.J., Jarvis, I., and Cramer, B.D., 2023, Evolution of atmospheric O_2 through the Phanerozoic, revisited: Annual Review of Earth and Planetary Sciences, v. 51, p. 253–276, https://doi.org/10.1146/annurev-earth-032320-095425.

Morris, J.L., et al., 2015, Investigating Devonian trees as geo-engineers of past climates: Linking palaeosols to palaeobotany and experimental geobiology: Palaeontology, v. 58, p. 787–801, https://doi.org/10.1111/pala.12185.

Patrakov, Y.F., Kamyanov, V.F., and Fedyaeva, O.N., 2005, A structural model of the organic matter of Barzas liptobiolith coal: Fuel, v. 84, p. 189–199, https://doi.org/10.1016/j.fuel.2004.08.021.

Rimmer, S.M., Thompson, J.A., Goodnight, S.A., and Robl, T.L., 2004, Multiple controls on the preservation of organic matter in Devonian–Mississippian marine black shales: Geochemical and petrographic evidence: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 215, p. 125–154, https://doi.org/10.1016/j.palaeo.2004.09.001.

Rimmer, S.M., Hawkins, S.J., Scott, A.C., and Cressler, W.L., 2015, The rise of fire: Fossil charcoal in Late Devonian marine shales as an indicator of expanding terrestrial ecosystems, fire, and atmospheric change: American Journal of Science, v. 315, p. 713–733, https://doi.org/10.2475/08.2015.01.

Royer, D.L., Donnadieu, Y., Park, J., Kowalczyk, J., and Goddéris, Y., 2014, Error analysis of CO_2 and O_2 estimates from the long-term geochemical model GEOCARBSULF: American Journal of Science, v. 314, p. 1259–1283, https://doi.org/10.2475/09.2014.01.

Saavedra, J.G.V., Poiré, D.G., Vergani, G.D., Salfity, J.A., Rubinstein, C.V. and Pérez Leytón, M.A., 2021, Paleoenvironment and age of Los Monos Formation (Devonian), Tarija Basin, Argentina and Bolivia: Latin American Journal of Sedimentology and Basin Analysis, v. 28, p. 1–36.

Scotese, C.R., Song, H., Mills, B.J.W., and van der Meer, D.G., 2021, Phanerozoic paleotemperatures: The earth's changing climate during the last 540 million years: Earth-Science Reviews, v. 215, https://doi.org/10.1016/j.earscirev.2021.103503.

Scott, A.C., and Glasspool, I.J., 2006, The diversification of Paleozoic fire systems and fluctuations in atmospheric oxygen concentration: Proceedings of the National Academy of Sciences of the United States of America, v. 103, p. 10,861–10,865, https://doi.org/10.1073/pnas.0604090103.

Scott, A.C. and Glasspool, I.J., 2007, Observations and experiments on the origin and formation of inertinite group macerals: International Journal of Coal Geology, v. 70, p. 53–66, https://doi.org/10.1016/j.coal.2006.02.009.

Shields, G.A., and Mills, B.J.W., 2017, Tectonic controls on the long-term carbon isotope mass balance: Proceedings of the National Academy of Sciences of the United States of America, v. 114, p. 4318–4323, https://doi.org/10.1073/pnas.1614506114.

Stein, W.E., Berry, C.M., Hernick, L.V., and Mannolini, F., 2012, Surprisingly complex community discovered in the mid-Devonian fossil forest at Gilboa: Nature, v. 483, p. 78–81, https://doi.org/10.1038/nature10819.

Stein, W.E., et al., 2020, Mid-Devonian *Archaeopteris* roots signal revolutionary change in earliest fossil forests: Current Biology, v. 30, p. 421–431, https://doi.org/10.1016/j.cub.2019.11.067.

van der Boon, A., et al., 2022, A persistent non-uniformitarian paleomagnetic field in the Devonian?: Earth-Science Reviews, v. 231, https://doi.org/10.1016/j.earscirev.2022.104073.

Vitali, R., Belcher, C.M., Kaplan, J.O., and Watson, A.J., 2022, Increased fire activity under high atmospheric oxygen concentrations is compatible with the presence of forests: Nature Communications, v. 13, 7285, https://doi.org/10.1038/s41467-022-35081-z.

Printed in the USA