EARTH SCIENCE

Early plants and the rise of mud

Mudrock deposition in rivers increased by an order of magnitude after plants first evolved

By **Woodward W. Fischer**

The geological record of our planet provides evidence for a handful of ways in which life has fundamentally altered processes and environments at Earth's surface. It was the evolution of photosynthesis nearly 2.5 billion years ago that oxygenated the atmosphere and oceans (*1*), greatly increasing the spectrum of minerals found in rocks (*2*). Over the past 250 million years, the production of mineral skeletons by algae in the oceans transformed the way in which sediments accumulate in marine basins (*3*). On page 1022 of this issue, McMahon and Davies (*4*) illustrate how plants, too, have left an indelible mark in the geological record, their signature written in mud.

Mudrocks (fine-grained sedimentary rocks composed of silt- and clay-sized particles) are rare in the sedimentary deposits left by Precambrian and early Paleozoic (500 million years and older) rivers, in which sand and gravel are common (*5*); and the rise of mudrocks in river deposits in the geological record somehow reflects changes in the routing of sediment by rivers associated with the evolution of plants and their colonization of the landscape (*6*). This pattern formed part of the basis for interpretation of sedimentary deposits on Mars, created where ancient rivers drained into a lake at the bottom of Gale crater. The martian deposits—like those generated on Earth before plants—contain little in the way of mudrock (*7*). Although the sedimentary trend has been well-documented on Earth, it has remained poorly quantified. McMahon and Davies set out to measure the mudrock trend and narrow down its timing.

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Geologists describe and quantify sedimentary rocks using measured stratigraphic sections, which are one-dimensional representations that capture the sequence and thickness of layers of sediment in the order in which they were deposited at a given location. McMahon and Davies collated stratigraphic sections from river deposits before and after plant evolution. They combined these observations with a survey of literature data to arrive at a data set covering hundreds of different sedimentary units, deposited on a range of continents over the past 3 billion years. From each of these sections, they extracted the percentage of mudrock present in the river deposits as a function of time.

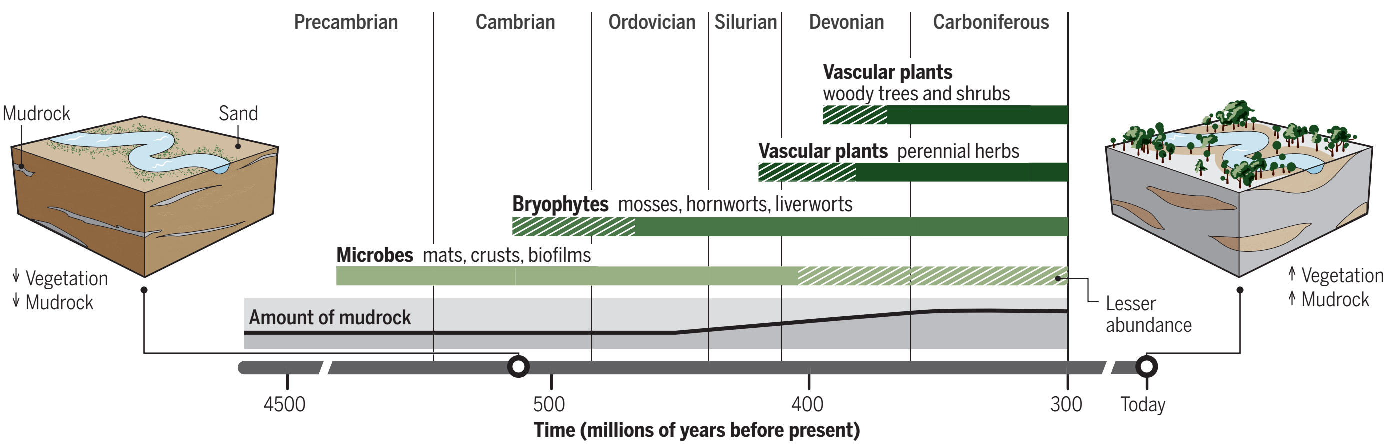
The raw data readily recapitulated the expected pattern: Mudrocks were rare before the appearance of plants and common thereafter. But to obtain more quantitative information, statistical treatment of the data was required, because the number of stratigraphic units preserved in any given interval in the record is highly uneven. This type of bias is an omnipresent feature woven into the fabric of the geological record, and taking account of this is particularly important for terrestrial deposits, which are inherently rare (*8*). Using a couple of different approaches, McMahon and Davies demonstrate that the fractional abundance of mudrock rose by an order of magnitude or more following the evolution of plants. This reflects the tremendous impact that plants have had on the distribution of sediment in river corridors.

Particularly fascinating is the timing of this transition. From the estimates of McMahon and Davies, increase in mudrock began in the Late Ordovician to Silurian (450 to 420 million years ago). This implicates land plants, but is earlier than expected. The oldest fossil plants are Ordovician in age; earlier, more equivocal Cambrian-age microfossils hint at the earliest stages in plant evolution (see the figure). But it was not really until the Late Devonian (about 370 million years ago) that plant ecosystems were sufficiently well developed to be regarded as forests.

Early plant evolution occurred over a 100-million-year interval of increasing ecophysiological complexity and landscape occupation (*9*, *10*). Primitive plants were mostly bryophytes (related to mosses and liverworts), and early vascular plants in the later Silurian and early Devonian (about 425 million years ago) had stem lengths measured in centimeters, little water-conducting tissue, no woody tissue, and were limited to wet environments. It is interesting that such primi-

Plants reshaped the sedimentary deposits left by a river

Muddy floodplains were rare on prevegetated landscapes, compared with those developed after the evolution of plants and their colonization of the landscape. The rise of mudrock coincided with some of the earliest events in plant evolution.



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tive plant ecosystems would have substantial impact on the behavior of rivers and the construction of their floodplain deposits.

According to the results of McMahon and Davies, mudrock in river deposits continued to increase through the Devonian-Carboniferous interval (about 370 to 300 million years ago) during the evolution of deeply rooted plants and true forests. If the timing of the initial increase in mudrock is correct, it suggests that the earliest plants made a substantial impression on the landscape.

What was it about these early plant-bearing ecosystems that generated so much mudrock in their deposits? There are many ideas, and little is certain. McMahon and Davies point to processes by which plants may have increased mud production during erosion and weathering. With that in mind, there are preserved Precambrian soil horizons composed of mudrocks and plenty of Precambrian marine mudrocks indicating that substantial fluxes of mud passed from the continents to marine basins before plants evolved. Our planet, it seems, has always had enough mud to go around. It is therefore likely that early plants affected the mechanics of floodplain construction. For example, the presence of plants on the landscape decreases erosion rates; and thus it was long hypothesized that erosion—in particular by wind—removed sediment from prevegetated landscapes (*11, 12*). Even if mud was deposited on prevegetated floodplains, its removal by erosion might have been efficient.

In addition to inhibiting erosion, plants also interact with river flows and promote the deposition of fine-grained sediment. This can help armor riverbanks and slow their lateral migration; such a process might also aid in preserving muddy floodplain deposits.

Whatever the exact causes, the muddy signal that plants left in the geological record is prodigious. That such seemingly simple early-appearing plant ecosystems had such sedimentary impact means that there is still much to learn about the nature of the interactions and coevolution of terrestrial ecosystems and their underlying landscapes. ■

REFERENCES

1. W. W. Fischer, J. Hemp, J. E. Johnson, *Annu. Rev. Earth Planet. Sci.* **44**, 647 (2016).
2. R. M. Hazen, *Sci. Am.* **302**, 58 (2010).
3. A. H. Knoll, *Rev. Mineral. Geochem.* **54**, 329 (2003).
4. W. J. McMahon, N. S. Davies, *Science* **359**, 1022 (2018).
5. D. Winston, in *Fluvial Sedimentology–Memoir 5*, A. D. Miall, Ed. (Canadian Society of Petroleum Geologists, Calgary, 1977), p. 343.
6. M. R. Gibling, N. S. Davies, *Nat. Geosci.* **5**, 99 (2012).
7. J. P. Grotzinger *et al.*, *Science* **350**, aac7575 (2015).
8. S. E. Peters, *J. Geol.* **114**, 391 (2005).
9. P. Kenrick, *Science* **358**, 1538 (2017).
10. C. K. Boyce, J.-E. Lee, *Annu. Rev. Earth Planet. Sci.* **45**, 61 (2017).
11. S. A. Schumm, *Geol. Soc. Am. Bull.* **79**, 1573 (1968).
12. R. H. Dott Jr., *J. Geol.* **111**, 387 (2003).

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OPTICS

Fermi arcs connect topological degeneracies

Surface or bulk Fermi arcs are engineered in photonic structures to connect ideal Weyl points or exceptional points

By **Şahin K. Özdemir**

In condensed matter and photonics, topology is defined with respect to the energy bands in momentum space (*1*). The boundary between two topologically different phases (for example, supporting right- versus left-handed particles) appears as degeneracies where two linear dispersion bands intersect. Fundamental point degeneracies in two-dimensional (2D) and 3D Hermitian systems—known as Dirac and Weyl points, respectively—have been observed in photonic structures (*2*–*6*) but not the ideal Weyl points and the helicoidal dispersion, which leads to the open Fermi arcs connecting points of opposite chirality. On page 1013 of this issue, Yang *et al.* (*7*) demonstrate an ideal Weyl system with four Weyl points (*8*, *9*) and helicoidal surface Fermi arcs interconnecting them in a 3D photonic crystal composed of metallic inclusions. On page 1009 of this issue, Zhou *et al.* (*10*) explore non-Hermitian topological photonics in which radiative losses come into play, and demonstrate the emergence of bulk Fermi arc and half topological charges in a 2D-periodic photonic crystal.

> ***"...the reported observations... will surely help to explore photonics in new regimes..."***

The observation of Weyl points at microwave (*2*, *3*) and optical frequencies (*4*) serves as a fingerprint of the topological nature of the corresponding photonic system and guarantees the existence of Fermi arcs, which act as pipelines connecting Weyl points of opposite chirality (*5*, *6*). However, further development and potential applications have been hindered by the lack of an ideal Weyl system (*8*, *9*) in which all Weyl points are symmetry-related, exist at the same energy, and are free from nontopological bands.

Despite both being degeneracies of a Hermitian system (that is, one with no energy exchange with the environment), Dirac and Weyl points differ in critical ways. For example, any perturbation that breaks parity (*P*) or time-reversal (*T*) symmetry lifts the 2D Dirac point degeneracy and opens a band gap; the Dirac point splits and loses its topological protection. However, creation of topologically protected Weyl points actually requires the breaking of *P*- or *T*-symmetry, or both (see the figure) (*11*, *12*). Hermitian perturbations only shift Weyl points but cannot lift their degeneracy. A Weyl point is annihilated only by bringing together two points of opposite chirality (for example, ones with chirality of +1 or –1).

The minimum number of Weyl points in systems respecting *P*-symmetry (system breaks *T*-symmetry) is two, whereas in systems respecting *T*-symmetry (system breaks *P*-symmetry), it is four. Weyl points with nonzero chirality have been previously reported in systems with broken *P*- and *T*-symmetry. However, Weyl points in those studies were not ideal because they were at different frequencies and were not symmetry-related.

Yang *et al.* succeeded to create four ideal Weyl points with different topological chirality (two with +1 and two with –1) in the microwave regime by using a specially designed meta-crystal that breaks *P*-symmetry but leaves *T*-symmetry untouched. They characterized the band structure of their meta-crystal using angle-resolved transmission spectroscopy by using a near-field antenna as the stationary excitation point-source on the crystal surface and measuring the near field with a scanning antenna on the opposite side. Fourier analysis of the acquired spatial distribution of the electric field at each angle and excitation frequency was used to determine the band structure of the surface states at each angle, confirming the linear band crossings of the surface states around the Weyl points.

In order to characterize the surface arcs, Yang *et al.* probed their meta-crystal using two different configurations of transmission near-field scanning system in which

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