DEEP TIME BIOGEOMORPHOLOGY: THE CO-EVOLUTION OF LIFE AND SEDIMENTS

NEIL S. DAVIES*[1], WILLIAM J. MCMAHON[1], ANTHONY P. SHILLITO[2] and BEN J. SLATER[3]

[1]Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, United Kingdom

[2]Department of Earth Sciences, University of Oxford, South Parks Road, Oxford OX1 3AN, United Kingdom.

[3]Department of Earth Sciences, Palaeobiology, Uppsala University, Geocentrum, Villav. 16, 75236 Uppsala, Sweden.

*Corresponding author: nsd27@cam.ac.uk

Amongst all the disciplines in Earth Sciences, paleontology and sedimentary geology share a particularly striking and complicated frontier. On the one hand, some of the topics that they encompass are apparently separated by huge gulfs in methods and expertise: multiple degrees of separation need to be counted to get from, say, molecular phylogeny to sediment diagenesis, or paleophysiology to sequence stratigraphy. Yet there are arguably further areas where the boundary between the subjects is far more porous, consisting of sub-disciplines that refuse to be pigeon-holed and instead demand consensus between paleontologists and sedimentary geologists. This hazy border zone is the natural territory of PALAIOS, the remit of which is to emphasize "*the impact of life on Earth's history as recorded in the paleontological and sedimentological records*", and which has previously published seminal advances in topics such as ichnology, taphonomy, and carbonate sedimentology. Recognizing this, this first of two thematic sets in the journal, which seek to explore how the sedimentary rock record has chronicled ancient life and sediment interactions, might seem unnecessary.

Yet what makes these collected papers distinct is that they defy classification within any particular sub-discipline: rather these are either ‘paleontological’ papers that pay additional attention to sedimentological context or ‘sedimentological’ papers that emphasise the importance of life in sedimentary environments. In each instance they demonstrate the potential to understand much more about ancient Earth when the procedures of the two disciplines are undertaken in unison, and hopefully showcase avenues of exploration to inspire further research in this vein.

The collected papers demonstrate the intrinsic links between fossils and the strata that host them, with a particular emphasis on siliciclastic strata where such linkages have traditionally and oftentimes been overlooked. Together they show how investigation of these connections can reveal high-definition records of feedback between organisms and their physical environments at the time of deposition and illustrate case studies of sedimentary-stratigraphic characteristics that developed in synchronicity with the evolving biosphere at Earth’s surface (see Davies et al., 2020). The papers are necessarily selective and cannot encompass the entirety of the diverse life-sediment interactions that have existed throughout geologic history, but they serve to highlight the types of observations that can be employed and the detailed interpretations that can be made from them. This first thematic set has a loose running theme of ‘plants’, documenting examples of vegetation-environment interactions recorded in the rock record from the Mississippian to the Pliocene, and the forthcoming thematic set will follow a similar path for ‘animals’. These two kingdoms dominate the macroscopic biosphere that defines the Phanerozoic and have stamped their mark on the rock record over the last half a billion years (though this is not to understate the importance of microbiota, which have had such a clear impact on the sedimentary record (e.g., Riding, 2000) that they may warrant a similar thematic set in the future).

DEEP TIME BIOGEOMORPHOLOGY

The timeliness of the thematic sets comes from recent developments in our understanding of modern and recent geomorphic processes. Under the adage that "the present is the key to the past", modern sedimentary environments are routinely utilized as analogues to inform facies models for ancient sedimentary strata (e.g., James and Dalrymple, 2010). The epistemic link between the modern and the ancient is long accepted: observations of cause and effect in extant Earth surface processes are used to induct the laws of nature that themselves inform abductive explanations for sedimentary and paleobiological phenomena archived in the rock record (Kleinhans et al., 2010). However, the progress of different subjects shifts at different paces, and we suggest that recent advances in our understanding of modern environments, specifically from the sub-discipline of biogeomorphology (Viles, 1988), have yet to be fully realised into investigations of ancient life and environments.

Biogeomorphology is the umbrella term for geomorphological investigations that focus on the linkages between life and Earth surface processes and landforms, and is a field that has witnessed a considerable expansion in recent years, borne out by multiple contemporary reviews of the topic (e.g., Coombes, 2016; Phillips, 2016; Viles, 2020, 2022; Larsen et al. 2021; Mason and Sanders, 2021; Rice, 2021). The general consensus in the geomorphic community is that focussed study of biogeomorphic phenomena have cumulatively demonstrated that geomorphic-ecologic interdependencies are fundamental in modern landscapes (Viles, 2020), and underlined the futility of attempting to fully understand "abiotic" Earth surface processes without reference to the organisms that interact with them. Such an integrated understanding appears to lag in studies of ancient environments. While the evolutionary significance of ancient biogenic materials and structures such as coal, reefs and coquinas have been noted (see Davies et al., 2020), in focussed case studies it has sometimes been considered just enough to proclaim the interpreted environmental facies of a fossil of interest (see Wright, 2019), or to explain sedimentary patterns with reference only to tectonics or climate. Biogeomorphic research has underlined just how important life can be as a sedimentary-geomorphic agent and a host of seemingly esoteric interactions have ultimately been shown to be of major importance. Examples are too numerous and diverse to do justice with a simple list, but we now know how the activity of fish can help determine sediment mobility (Pledger et al., 2017), how caddisfly silk can have long-lasting impacts on bed hydraulics (Johnson et al., 2009), how the extent of earthworm bioturbation varies by climate zone (Paton et al., 1995), how the shape of coastlines can be wholly dependent on the life-history traits of the plants that colonize them (Schwarz et al., 2017), and how the interplay of predators, herbivores and riparian vegetation determines gross river morphology (Beschta and Ripple, 2012). If modern organisms are so essential to the operation of the landscapes and seascapes they occupy, it is wholly implausible that ancient organisms were passive inhabitants of their surroundings. Despite the optical illusion of museum dioramas, trilobites, lycopsids and dinosaurs did not just sit around in an unchanging trompe l'oeil of their background environment, they must have interacted and in some cases engineered the Earth surface processes around them. It must be admitted that ancient biogeomorphic phenomena recorded in the sedimentary-stratigraphic record may sometimes be underdetermined by available evidence (Davies et al., 2020), or definitively reveal only one part of a more complicated whole that remains open to reasoned interpretation. However, the papers collected here demonstrate that this is not always the case, and efforts to unravel paleobiological-sedimentological interdependencies have the potential to pay great dividends as we seek to understand how the Earth system has evolved over geologic time.

The Importance of Temporal and Spatial Scales

One aspect of recent biogeomorphological research that is especially pertinent to deep time investigations is the emerging recognition of the importance of temporal and spatial scale with respect to observations and phenomena (e.g., Post, 2019; Larsen et al., 2021; Phillips

2021). Larsen et al. (2021) consider that the intensity of known biogeomorphic feedbacks becomes more pronounced with decreasing spatial and temporal scale and have highlighted the limitation of understanding biogeomorphic feedback on greater than centennial scales, due to the finite historicity of instrumental records. Unconfined by such time limitations, the geologic perspective clearly has the potential to inform on the deep roots of modern biogeomorphic phenomena (e.g., Davies et al., 2021). Multiple studies have recognized the broad correlation between temporal and spatial scale in ecologic, geomorphologic, sedimentologic and biogeomorphic phenomena (Kleinhans et al., 2010; Miall, 2015; Post, 2019; Davies et al., 2020; Davies and Shillito, 2021; Larsen et al., 2021) (Figure 1). The sedimentary-stratigraphic record is uniquely able to attack questions about the role of life in Earth surface processes because its longevity enables the record of such to be interrogated at different scales. At outcrop, this can be at the small spatio-temporal scale familiar from modern biogeomorphology, but the sedimentary-stratigraphic record also offers a perspective across the whole planet over geological timescales.

Small scale records: biogeomorphic phenomena at outcrop

Just because something happened a long time ago doesn't mean it took a long time to happen. There is increasing recognition that the stratigraphic timescales that are archived at outcrop-scale can be discretized to surprisingly short intervals (Paola et al., 2018; Holbrook and Miall, 2020; Davies and Shillito, 2021). Although the time taken to deposit a whole stratigraphic formation or basin fill can be very long, because sedimentary basins are large, because sedimentation is localized within such basins at any one time (Runkel et al., 2008; Bhattacharya et al., 2019; Davies et al., 2019), and because the sedimentary-geomorphic elements within them generate pockets of high accommodation space (e.g., between delta lobes: Ganti et al., 2020), the snippets of basin fill that are destined to appear as rock outcrops have a high potential to sample phenomena that occurred on familiar 'human' timescales.

This means that the perspective available from individual field investigations of outcrop can witness phenomena that are directly analogous in time-length scale to modern biogeomorphic features. The counterintuitive nature of such incidents has traditionally provoked a demand for special explanation: standing Carboniferous trees have been accounted for by rapid subsidence (Bailey, 2011) and apparently contemporaneous communities of burrows on shared substrates have been dismissed as implausible (McIlroy and Garton, 2010). Yet both these instances have been shown to be more readily explainable as mundane artefacts of the relationship between the time-length scales of ancient environments and present day outcrop (Miall, 2015; Holbrook and Miall, 2020; Allport et al., 2022). Fundamentally this means that they are not surprising or exceptional: rather, they are examples of what Paola et al. (2018) termed the "strange ordinariness of the stratigraphic record".

If we consider the sedimentary record at outcrop to be essentially ordinary, this opens a huge realm of possibility to understand ancient biogeomorphic interactions. If the record is archiving day-to-day processes, and we can recognise phenomena such as plant-animal-sediment interactions in Carboniferous estuaries (McMahon et al., 2022, this issue), woody debris accumulations in Paleozoic river systems (Trümper et al., 2022, this issue), or putative beaver dams in Pliocene strata (Davies et al., 2022, this issue), then we can be confident we are witnessing normal biogeomorphic processes that are directly analogous to modern occurrences. Through further investigation, the hope is that a multitude of similar instances can be recognised and the deep time historicity and origins of a plethora of modern-day processes can be better understood (e.g., Corenblit et al., 2015).

Large scale records: biogeomorphic trends from whole rock record analyses

A vantage unique to studies of the sedimentary-stratigraphic record is that of the huge spatio-temporal scale, invisible to biogeomorphic investigations of modern environments. If global compendia of supposed biologically-dependent or biologically-influenced lithologies, materials, sedimentary structures and facies can be compiled, multi-million year secular trends can be identified that reveal step-changes in the operation of Earth surface processes throughout the planet's evolution. Examples of research in this vein have already demonstrated secular change in biogenic sediments such as carbonates or coal (e.g., Riding, 2006; Diessel, 2010), the influence of land plants on fluvial processes and landforms (e.g., Davies and Gibling, 2010; McMahon and Davies, 2018) and the impact that bioturbation had on marine and continental environments (e.g., Mángano and Buatois, 2017; Buatois et al., 2022). Such observations contextualize smaller scale biogeomorphic phenomena seen today, as well as illuminating the evolutionary trajectory of the Earth system. Further focussed study on the small scale records of individual ancient successions has the long-term promise to produce more case studies, and unveil new aspects of comparison, that can further refine these large scale perspectives. For example, prominent blindspots exist in our knowledge of the ancient record, particularly with respect to poorly recorded organisms such as fungi. The work of Gibson (2022, this issue) provides an example showing how fungi-environment interactions may be identified and should act as a spur to gather further information in this field.

The short- and long-term perspectives offered by the rock record make it a powerful but presently underutilized tool for understanding how life makes surface processes on Earth unique amongst known planets. To do this successfully, understanding the scale of observations is essential, an issue underlined by Mays and McLoughlin (2022, this issue) who highlight how the short-term archive of wildfire reveals the global significance of this phenomena, while simultaneously ruling it out as a plausible sole explanation for long term trends in the sedimentary-stratigraphic record such as the Early Triassic 'coal gap' (Retallack et al., 1996). The perspective that the long-term geological record is in many ways a granular patchwork of high-resolution short-term records presents a challenge to its interpretation, but a robust appreciation of this promises a far greater understanding of how the Earth system evolved. This further underlines the necessity of ever more case studies of life-sediment interactions in deep time. If 'paleobiogeomorphology' is to follow the successful trajectory of its modern counterpart, the first step is the accumulation of a multitude of specific examples which will together unravel the intrinsic importance of life to our planet. Etienne (2010) and Viles (2022) have argued that modern biogeomorphology has moved from 'fun' to 'fundamental' through the accrual of specific examples. If more work follows the papers collected here, the potential of the deep time record will be more fully realised, so long as the artificial border wall between sedimentology and paleontology continues to crumble.

PAPERS IN THIS THEMATIC SET

The papers in this first thematic set approximately follow the theme of 'plants', but inevitably other organisms also reveal their importance. **McMahon et al.** (2022, this issue) consider the sedimentary structures that are produced by different organisms, and demonstrate how, by the middle of the Palaeozoic, both plants and animals were affecting the array of phenomena archived in estuarine siliciclastic facies. With a high resolution case study from the west of Ireland, they detail some of these features and show how their distribution was controlled by their position relative to the ancient tidal prism, with plants dominating the biogenically induced/influenced features of landward facies, and animals supplanting vegetation as the dominant biogenic influence in basinward facies toward the estuary mouth.

As plants continued to colonize the interior drylands of continents throughout the late Palaeozoic, large woody debris became an increasingly important component of epiclastic systems and strata. Significantly, as arborescent gymnosperms evolved and diversified, woody plant biomass induced changes in the environments of erosion, transport and deposition of continental sedimentary systems. **Trümper et al.** (2022, this issue) provide further insights into the taphonomy and geo-engineering potential of woody debris via a detailed record of large silicified trunks that characterize Middle Pennsylvanian–early Permian strata of east-central Europe. They demonstrate how climatic seasonality in the late Palaeozoic subtropics and plant biodiversity partitioning at the local topographic scale encouraged the spread of woody gymnosperms, but that the climatic and tectonic settings of this time also favoured their preservation, offering a unique window into the plant-sediment interactions from this time.

The order of magnitude increase in biomass associated with the novel vegetation discussed by McMahon et al. (2022, this issue) and Trümper et al. (2022, this issue) also opened the door to new surface-atmospheric processes that permanently altered the sedimentary-stratigraphic record. Chief among these was the introduction of significant quantities of combustible fuel, in the form of woody material. When coupled with the increase in atmospheric oxygen – itself driven by the oxygenic photosynthesis of land plants – fire, for the first time, became a significant shaper of landscapes, ecosystems, evolution and sediments. **Mays et al.** (2022, this issue) explore such feedbacks between flora and wildfires in the context of the Permian-Triassic Boundary Event. They illustrate how wildfires likely played a role even in ever-wet settings at the time, and may in part have exacerbated extinctions.

Plants are macroscopic, complex, tissue- and organ-grade multicellular organisms. Another clade of complex multicellular eukaryotes, the fungi, are frequently associated with vegetation and are also intimately linked with Earth's lithospheric and biospheric processes via the decay and breakdown of plant biomass, binding of soils, and through the acidic bioweathering of minerals and rocks. Despite the increasing awareness of how plants and animals have shaped the sedimentary-stratigraphic record, disentangling the influence of fungi has been hampered by their woefully understudied fossil record. **Gibson** (2022, this issue) studies the rare fungal content of Zechstein palynological preparations, which provides new insight into the composition of the Zechstein forest understory, and its influence on the environment during the Permian Period.

Plant-animal interactions are also important drivers of biogeomorphic processes, and through these certain animals can have an outsized effect on entire landscapes. A fundamental tenet of modern ecology is that the behaviour of certain animal species can exert an inflated impact on the structure of entire ecosystems. **Davies et al.** (2022, this issue) consider the sedimentological impacts of one such ecosystem engineering animal that is celebrated in modern environments: the beaver. Using original field data from Pliocene strata of Arctic Canada, they construct a facies model that sheds light on how the evolution of putative beaver dams and other, passive, woody accumulations changed fluvial sedimentary signatures and habitats, and also influenced the environment occupied by other warm Arctic flora and fauna.

Cumulatively, these five papers provide snapshots of ancient life-environment interactions from across a c.350 million year period and demonstrate just how innate life has been in sculpting both landscapes and the sedimentary record. They merely scratch the surface of what may be achievable with focussed research in this area, but illustrate a fact of critical importance: many seemingly 'abiotic' features familiar in the modern world simply would not exist, or be different, had life never evolved on planet Earth.

REFERENCES

ALLPORT, H.A., DAVIES, N.S., SHILLITO, A.P., MITCHELL, E.G. AND HERRON, S.T., 2022, Non- palimpsested crowded *Skolithos* ichnofabrics in a Carboniferous tidal rhythmite:

Disentangling ecological signatures from the spatio- temporal bias of outcrop: Sedimentology v. 69, p. 1028-1050.

Bailey, R.J., 2011, Buried trees and basin tectonics: a discussion: Stratigraphy v. 8, p. 1-6.

Beschta, R.L. and Ripple, W.J., 2012, The role of large predators in maintaining riparian plant communities and river morphology: Geomorphology v. 157, p. 88-98.

Bhattacharya, J.P., Miall, A.D., Ferron, C., Gabriel, J., Randazzo, N., Kynaston, D., Jicha, B.R. and Singer, B.S., 2019, Time-stratigraphy in point sourced river deltas: Application to sediment budgets, shelf construction, and paleo-storm records: Earth-Science Reviews v. 199, p. 102985.

Buatois, L.A., Davies, N.S., Gibling, M.R., Krapovickas, V., Labandeira, C.C., MacNaughton, R.B., Mángano, M.G., Minter, N.J., and Shillito, A.P., 2022 In Press, The invasion of the land in deep time: Integrating Paleozoic records of paleobiology, ichnology, sedimentology, and geomorphology: Integrative and Comparative Biology.

Coombes, M.A., 2016, Biogeomorphology: diverse, integrative and useful: Earth Surface Processes and Landforms v. 41, p. 2296-2300.

Corenblit, D., Davies, N.S., Steiger, J., Gibling, M.R. and Bornette, G., 2015, Considering river structure and stability in the light of evolution: feedbacks between riparian vegetation and hydrogeomorphology: Earth Surface Processes and Landforms v. 40, p. 189-207.

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, v. 98, p. 171-200.

DAVIES, N.S., SHILLITO, A.P. AND MCMAHON, W.J., 2019, Where does the time go? Assessing the chronostratigraphic fidelity of sedimentary geological outcrops in the Pliocene–Pleistocene Red Crag Formation, eastern England: Journal of the Geological Society, v. 176, p. 1154-1168.

DAVIES, N.S., SHILLITO, A.P., SLATER, B.J., LIU, A.G. AND MCMAHON, W.J., 2020, Evolutionary synchrony of Earth's biosphere and sedimentary-stratigraphic record: Earth-Science Reviews v. 201, p. 102979.

DAVIES, N.S., BERRY, C.M., MARSHALL, J.E., WELLMAN, C.H. AND LINDEMANN, F.J., 2021, The Devonian landscape factory: plant–sediment interactions in the Old Red Sandstone of Svalbard and the rise of vegetation as a biogeomorphic agent: Journal of the Geological Society v. 178, p. jgs2020-225.

DAVIES, N.S. AND SHILLITO, A.P., 2021, True substrates: The exceptional resolution and unexceptional preservation of deep time snapshots on bedding surfaces: Sedimentology v. 68, p. 3307-3356.

DAVIES, N.S., GOSSE, J.C., ROUILLARD, A., RYBCZYNSKI, N., MENG, J., REYES, A.V., AND KIGUKTAK, J., 2022, Wood jams or beaver dams? Pliocene life, sediment and landscape interactions in the Canadian High Arctic: PALAIOS.

DIESSEL, C.F., 2010, The stratigraphic distribution of inertinite: International Journal of Coal Geology v. 81, p. 251-268.

ETIENNE, S. 2010. Biogeomorphology: as fundamental as fun: Géomorphologie: Relief, Processus, Environnement v. 16, p. 323–326.

Ganti, V., Hajek, E.A., Leary, K., Straub, K.M. and Paola, C., 2020, Morphodynamic hierarchy and the fabric of the sedimentary record: Geophysical Research Letters v. 47, p. e2020GL087921.

Gibson, M.E., 2022, First report of fungal palynomorphs from the Zechstein Group (Lopingian): Implications for the stratigraphic completeness of the Earth's Paleozoic fungal record: PALAIOS.

Holbrook, J.M. and Miall, A.D., 2020, Time in the Rock: A field guide to interpreting past events and processes from siliciclastic stratigraphy: Earth-Science Reviews v. 203, p. 103121.

James, N.P. and Dalrymple, R.W., (eds.) 2010, Facies Models 4: Geological Association of Canada, St. John's, 586 p.

Johnson, M.F., Reid, I., Rice, S.P. and Wood, P.J., 2009, Stabilization of fine gravels by net- spinning caddisfly larvae: Earth Surface Processes and Landforms, v. 34, p. 413-423.

Kleinhans, M.G., Buskes, C.J. and de Regt, H.W., 2010, Philosophy of Earth Science, *in* Allhoff, F. (ed.), Philosophies of the Sciences: A Guide: Wiley-Blackwell, Chichester, p. 213-236.

Larsen, A., Nardin, W., van de Lageweg, W.I. and Bätz, N., 2021, Biogeomorphology, *quo vadis*? On processes, time, and space in biogeomorphology: Earth Surface Processes and Landforms v. 46, p. 12-23.

Mángano, M.G. and Buatois, L.A., 2017, The Cambrian revolutions: trace-fossil record, timing, links and geobiological impact: Earth-Science Reviews v. 173, p. 96-108.

Mason, R.J. and Sanders, H., 2021, Invertebrate zoogeomorphology: A review and conceptual framework for rivers: Wiley Interdisciplinary Reviews: Water v. 8, p. e1540.

Mays, C. and McLoughlin, S., 2022, End-Permian Burnout: The role of Permian-Triassic wildfires in extinction, carbon cycling, and environmental change in eastern Gondwana: PALAIOS.

McIlroy, D. and Garton, M., 2010, Realistic interpretation of ichnofabrics and palaeoecology of the pipe- rock biotope: Lethaia v. 43, p. 420-426.

McMahon, W.J. and Davies, N.S., 2018, Evolution of alluvial mudrock forced by early land plants: Science v, 359, p. 1022-1024.

McMahon, W.J., Pierik, H.J., Shillito, A.P., Salese, F., Van Der Kwaak, B., Parsons, D.R. and Kleinhans, M.G., 2022, Superimposed allogenic and biological controls on siliciclastic architecture: an early Mississippian (Visean) example from tropical Laurussia: PALAIOS.

Miall, A.D., 2015, Updating uniformitarianism: stratigraphy as just a set of 'frozen accidents': Geological Society, London, Special Publications v. 404, p. 11-36.

Miall, A.D., 2016, The valuation of unconformities: Earth-Science Reviews v. 163, p.22-71.

Paola, C., Ganti, V., Mohrig, D., Runkel, A.C. and Straub, K.M., 2018, Time not our time: Physical controls on the preservation and measurement of geologic time: Annual Review of Earth and Planetary Sciences v. 46, p.409-438.

Paton, T.R., Humphreys, G.S. and Mitchell, P.B., 1995, Soils: A New Global View: CRC Press, Boca Raton, 234 p.

Phillips, J.D., 2016, Landforms as extended composite phenotypes: Earth Surface Processes and Landforms v. 41, p.16-26.

Phillips, J.D., 2021, Landscape Evolution: Landforms, Ecosystems, and Soils: Elsevier, Amsterdam, 356 p.

PLEDGER, A.G., RICE, S.P. AND MILLETT, J., 2017, Foraging fish as zoogeomorphic agents: An assessment of fish impacts at patch, barform, and reach scales: Journal of Geophysical Research: Earth Surface v. 122, p. 2105-2123.

POST, E., 2019, Time in Ecology: Princeton University Press, Princeton, 248 p.

RETALLACK, G.J., VEEVERS, J.J. AND MORANTE, R., 1996, Global coal gap between Permian–Triassic extinction and Middle Triassic recovery of peat-forming plants: Geological Society of America Bulletin v. 108, p. 195-207.

RICE, S.P., 2021, Why so skeptical? The role of animals in fluvial geomorphology: Wiley Interdisciplinary Reviews: Water v. 8, p. e1549.

RIDING, R., 2000, Microbial carbonates: the geological record of calcified bacterial–algal mats and biofilms: Sedimentology v. 47, p. 179-214.

RIDING, R., 2006, Microbial carbonate abundance compared with fluctuations in metazoan diversity over geological time: Sedimentary Geology v. 185, p. 229-238.

RUNKEL, A.C., MILLER, J.F., MCKAY, R.M., PALMER, A.R., TAYLOR, J.F., PRATT, B.L. AND HOLMDEN, C., 2008, The record of time in cratonic interior strata: does exceptionally slow subsidence necessarily result in exceptionally poor stratigraphic completeness?: Geological Association of Canada Special Papers v. 48, p. 341–362.

SCHWARZ, C., GOURGUE, O., VAN BELZEN, J., ZHU, Z., BOUMA, T.J., VAN DE KOPPEL, J., RUESSINK, G., CLAUDE, N. AND TEMMERMAN, S., 2018, Self-organization of a biogeomorphic landscape controlled by plant life-history traits: Nature Geoscience v. 11, p. 672-677.

TRÜMPER, S., MENCL, V., OPLUŠTIL, S., NIEMIROWSKA, S., AND RÖßLER, R., 2022, Large woody debris accumulations in the Late Pennsylvanian tropics—Evolutionary signal or tectono-climatic archive?: PALAIOS.

VILES, H.A., (ED.), 1988, Biogeomorphology: Blackwell, Oxford, 365 p.

VILES, H., 2020. Biogeomorphology: Past, present and future: Geomorphology v. 366, p. 106809.

VILES, H., 2022, Biogeomorphology, *in* Burt, T.P., Goudie, A.S and Viles, H.A. (eds.), The History of the Study of Landforms or the Development of Geomorphology. Volume 5: Geomorphology in the Second Half of the Twentieth Century. Geological Society Memoir v. 58, London, https://doi.org/10.1144/M58-2022-6

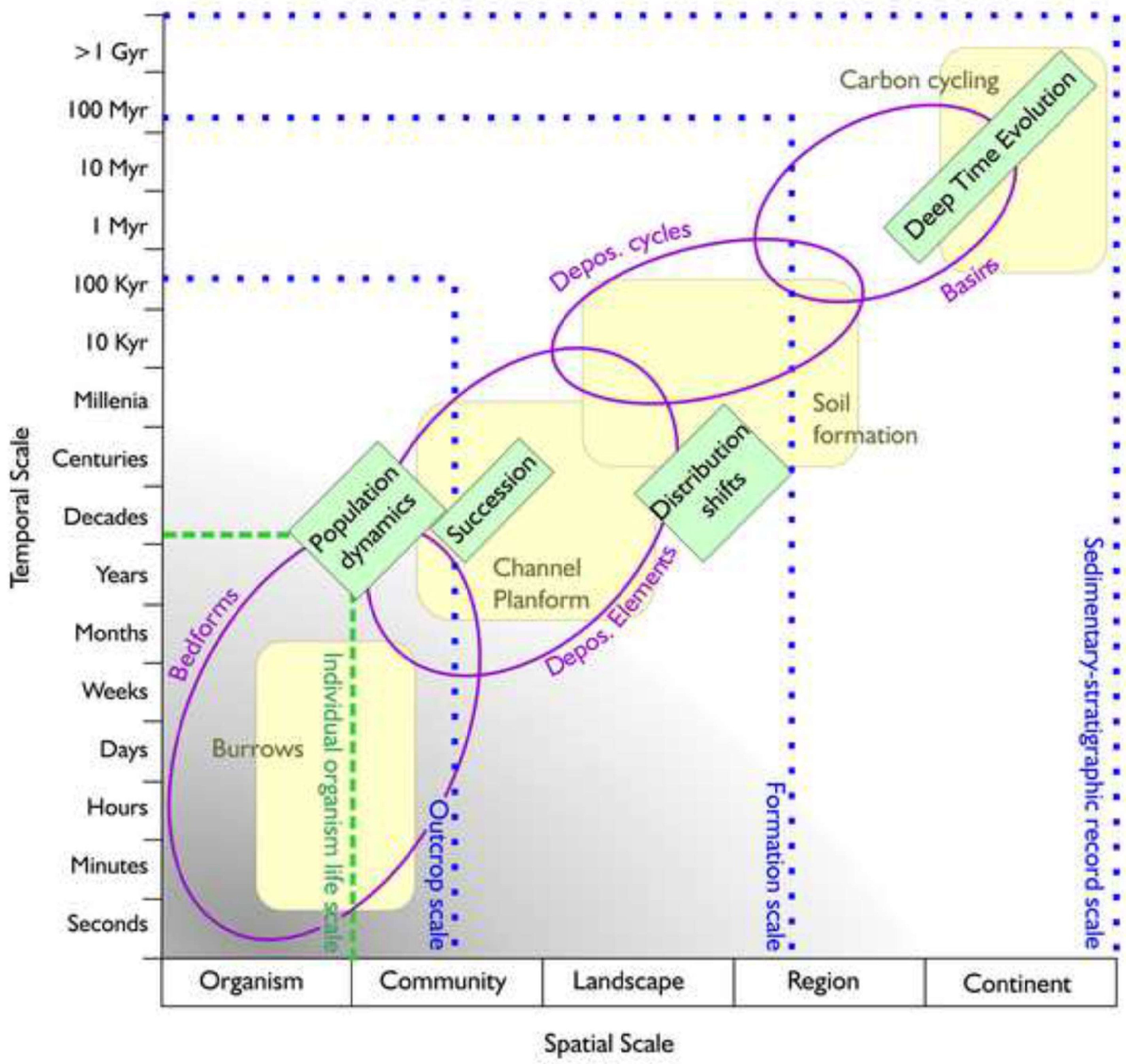
WRIGHT, V.P., 2019, Memes, false news, and the death of empiricism: Journal of Sedimentary Research v. 89, p. 310-311.

FIGURE CAPTION

FIGURE 1 – Diagram showing examples of the relationship of approximate time and length scale in different phenomena. Length scale modified from Larsen et al. (2021) to refer to organism-related length scales. Green boxes indicate time-length scales of biological processes and dashed green line refers to dynamic time-length scales within the lifespan of an individual organism. Yellow rounded boxes illustrate a selection of bio-sedimentary phenomena (see Davies et al., 2020 for further examples). Purple ovals refer to hierarchical elements of the sedimentary record, from individual bedforms through depositional elements (e.g., channels, delta lobes), to depositional cycles and basins. Blue dotted lines show approximate scales of geological samples from individual rock outcrops through whole stratigraphic formations to entire basin fills. Grey shaded areas show the extent of biogeomorphic evidence confidently attainable from modern studies (Larsen et al., 2021). Significantly, geological samples can potentially archive any of the phenomena that occur at a smaller time-length scale, rendering the sedimentary stratigraphic record particularly suited

to identifying small scale phenomena at outcrop and large scale phenomena from holistic analysis – some of which cannot be accessed through modern biogeomorphic investigation. From a biogeomorphic perspective there is multidirectional feedback between higher and lower order phenomena that are contemporaneous: e.g., from small to large scale, community succession can influence channel planform which in turn influences basin fill; from large to small scale, the nature of depositional elements can influence the habitats of individual lifeforms that may be more or less predisposed to burrow. The diagram has been modified from components of the following figures, which the reader is recommended to consult for further details: Kleinhans et al. (2010, Fig. 2); Miall (2016, Fig. 11); Post (2019, Fig. 3.1); Davies et al. (2020, Fig. 2); Davies and Shillito (2021, Figs. 25 and 26); Larsen et al. (2021; Fig. 1).

Figure 1



Temporal Scale
> 1 Gyr
100 Myr
10 Myr
1 Myr
100 Kyr
10 Kyr
Millenia
Centuries
Decades
Years
Months
Weeks
Days
Hours
Minutes
Seconds
Spatial Scale
Organism
Community
Landscape
Region
Continent
Carbon cycling
Deep Time Evolution
Basins
Depos. cycles
Soil formation
Distribution shifts
Succession
Channel Planform
Depos. Elements
Population dynamics
Bedforms
Burrows
Individual organism life scale
Outcrop scale
Formation scale
Sedimentary-stratigraphic record scale