# Evolutionary synchrony of Earth's biosphere and sedimentary-stratigraphic record

Neil S. Davies[1], Anthony P. Shillito[1], Ben J. Slater[2], Alexander G. Liu[1], William J. McMahon[3]

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

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

[3]*Faculty of Geosciences, Utrecht University, Princetonlaan 8a, Utrecht, 3584 CB, Netherlands.*

## Abstract

The landscapes and seascapes of Earth's surface provide the theatre for life, but to what extent did the actors build the stage? The role of life in the long-term shaping of the planetary surface needs to be understood to ascertain whether Earth is singular among known rocky planets, and to frame predictions of future changes to the biosphere. Modern geomorphic observations and modelling have made strides in this respect, but an under-utilized lens through which to interrogate these questions resides in the most complete tangible record of our planetary history: the sedimentary-stratigraphic record (SSR). The characteristics of the SSR have been frequently explained with reference to changes in boundary conditions such as relative sea level, climate, and tectonics. Yet despite the fact that the long-term accrual of the SSR was contemporaneous with the evolution of almost all domains of life on Earth, causal explanations related to biological activity have often been overlooked, particularly within siliciclastic strata. This paper explores evidence for the ways in which organisms have influenced the SSR throughout Earth history and emphasizes that further investigation can help lead us towards a mechanistic understanding of how the planetary surface has co-evolved with life. The practicality of discerning life signatures in the SSR is discussed by: 1) distinguishing biologically-dependent versus biologically-influenced sedimentary signatures; 2) emphasizing the importance of determining relative time-length scales of processes and demonstrating how different focal lengths of observation (individual geological outcrops and the complete SSR) can reveal different insights; and 3) promoting an awareness of issues of equifinality and underdetermination that may hinder the recognition of life signatures. Multiple instances of life signatures and their historic range within the SSR are reviewed, with examples covering siliciclastic, biogenic and chemogenic strata, and trigger organisms from across the spectrum of Earth's extant and ancient life. With this novel perspective, the SSR is recognised as a dynamic archive that expands and complements the fossil and geochemical records that it hosts, rather than simply being a passive repository for them. The SSR is shown to be both the record and the result of long-term evolutionary synchrony between life and planetary surface processes.

## 1. Introduction

The sedimentary-stratigraphic record (SSR) is formed of sedimentary rock strata: geological materials generated at the interface of lithosphere and atmosphere at the planetary surface, through the physical dynamic interactions of mineral grains and fluids, or chemical precipitation from solution. Where it is tractable, in exposed outcrop, cores or seismic sections, the SSR has immense value as a record of ancient surface processes. It is the primary repository of deep time geochemical and fossil evidence, and the only tangible chronicle of $3.8\text{x}10^9$ years of Earth history (Moorbath, 2009; Peters and Husson, 2017).

The objective of this contribution is to illustrate that the long-term evolution of Earth's SSR is causally-related to the evolution of life at the planetary surface, and how this is reflected in the distribution of material properties of sedimentary rocks by age. When considered at a granular scale (a particular outcrop, basin, or time interval) it is most common to interrogate the depositional controls on the SSR with reference to autogenic sediment-transport dynamics (e.g., Hajek and Straub, 2017) or allogenic controls such as tectonics, climate or sea-level (e.g., Allen, 2017) – processes that have been continual, cyclic, or recurrently episodic throughout the historic accrual of the SSR (Bradley, 2011). However, if we view the Earth surface as the factory in which the SSR was created, it must be acknowledged that the machinery functioning there has changed substantially through geological time as the biosphere has evolved. In other words, the characteristics of ancient strata need not exclusively be explained by tectonics, climate and sea-level. Biological and evolutionary controls may 1) have been overlooked, and 2) be equally or more likely to be culpable for many sedimentary motifs.

Sediments, the raw material of the SSR, occur at the Earth surface: a space that they share with as much as 87% of the planet's extant biomass (Bar-On et al., 2018), and where interactions of sediment with solid, liquid and gaseous fluids are augmented by biotic interactions. A multitude of observations demonstrate the ways in which different lifeforms provide biomaterials and modify Earth surface processes and landforms at the present day (Table 1). By variously mediating fluid and sediment properties and rates and scales of erosion, weathering, deposition and transport, organisms can induce sedimentary or geomorphic signatures on scales that range from the shape of individual grains (e.g., Harvey et al., 2011) to the form of entire mountain belts (e.g., Istanbulluoglu and Bras, 2005; Fremier et al., 2017). Entire scientific subdisciplines, such as biogeomorphology, ecogeomorphology and zoogeomorphology, set out to address the importance of life as a controlling element within recent landscapes (e.g., Naylor et al., 2002; Murray et al., 2008; Phillips, 2009; Corenblit et al., 2011; Butler and Sawyer, 2012; Viles, 2019).

The variety and number of such influences is unsurprising because the mass of mobilized sediment is dwarfed by the mass of life: for example, the annual global continent-ocean flux of terrigenous sediment is c. 28.1 GT (Syvitski et al., 2004), in contrast to the 476 GT of planetary carbon that occurs as biomass (Bar-On et al., 2018). Yet, for over 90% of early Earth history, the majority of biomass existed only as microbial communities below the Earth surface (McMahon and Parnell, 2018), spatially divorced from contemporaneous sedimentary processes. Despite this, the origin and ancestry of life influences on Earth surface processes and sedimentation have only infrequently been considered, particularly with respect to clastic sediments.

We contend that, when exploring the heritage of the planetary surface, it is essential to consider how different biological agents (which have evolved through Earth history) influenced the type, frequency, and intensity of physical processes that operate at the Earth's surface, and how this compares to modern observations. In order to do this, we must consider the SSR as a single entity; the 3.8 Ga accrual of which has exceeded the evolutionary lineages of all domains of life, with the possible exception of certain microbiota (Knoll and Nowak, 2017). In this respect the SSR is a thin (< 20 km [Allen et al., 2002]) and partial (62.5-69.5% coverage [Blatt and Jones, 1975]) exogenic veneer of planet Earth: a sedimentary shell that (1) has been accumulating since Earth formed a crust; and (2) consists of fragments of strata from deep time that have fortuitously survived to the present, avoiding destructive recycling through erosion and subduction (Ronov et al 1980, Veizer and Mackenzie, 2014, Peters and Husson 2017).

### *1.1. Deep time biosphere signatures*

As we look back at successively older portions of the whole SSR, we can see that its older strata were formed on ‘alternative Earths’ (Beerling and Butterfield, 2012), in existence prior to the evolution of particular organisms, groups of organisms, and behaviours. These alternative Earths are recorded in the SSR as synchronous strata from different parts of the globe which, taken together at any common interval of geological time, could potentially harbour the same range of abiotic allogenic (e.g., tectonic, climatic and sea-level) sedimentary signatures as are known from the recent Earth (albeit at different rates and intensities). However, for any particular synchronous interval, only a finite selection of the full census of biologically-affected sedimentary materials and traits (as known to cumulatively exist within the global SSR) can be recognised, because some will not yet have arisen, and some will have ceased to operate, at the time of deposition. When the global SSR is considered as a single entity, escalation from its oldest to youngest strata reveals that some of its intrinsic materials and traits have first occurrences (or major shifts in frequency of occurrence), in stratigraphic synchrony with the fossil record of prospective life triggers (Figure 1).

In this paper, we explore what is already known about biosphere signatures, discuss the philosophical background, potential and practicalities for further investigation, provide a catalogue of selected signatures, and explain why there could be significant implications arising from an improved understanding of life signals in the SSR. We place extra emphasis on biosphere signatures in siliciclastic strata, which have traditionally been less well-investigated than those in biogenic or chemogenic strata.

## 2. Classes of biosphere signatures

We here distinguish two overarching classes of biosphere signatures, as preserved in the SSR (Figure 1): 1) Biologically-dependent signatures (BDS) which directly incorporate material or structure generated by life; and 2) Biologically-influenced signatures (BIS) which are favoured by life-induced parameter changes to the rates, frequency of occurrence, and spatial influence of sedimentary processes.

### *2.1. Biologically-dependent signatures (BDS)*

Lithologies, materials, structures and facies which could never occur without particular biogenic detritus, biochemical processes, or the manipulation of sediment by organism life habits are classed as biologically-dependent signatures. BDS can be directly recognised within the SSR, so the known historical record of such characteristics is relatively complete, well-documented, and well-accepted. Discussions of BDS can be found in analyses of secular trends in certain carbonate (e.g., Riding, 2000) or coal lithologies (e.g., Diessel, 2010), or trace fossils (e.g., Buatois and Mángano, 2018), throughout the SSR. The demonstrable role of life in forming these signatures mean that it is usually undisputed that they have defined stratigraphic onsets or durations in the SSR, in approximate evolutionary synchrony with their formative organisms.

### *2.2. Biologically-influenced signatures (BIS)*

Many of the life influences on Earth surface processes, listed in Table 1, do not involve the direct supply of matter or direct forces from life. Instead, they involve altering the magnitude, or frequency of occurrence, of contributive physical parameters within a system. For example, in alluvial sediments, certain signatures may reflect conditions of enhanced bank stability: in modern rivers, bank stability is greatly enhanced by a variety of binding and baffling effects of vegetation, however abiotic river bank stability can also be afforded by inorganic chemical precipitates, cohesive sediment, or ice (e.g., Matsubara et al., 2015; McMahon and Davies, 2018a; Kleinhans et al., 2018). Signatures such as these are here classed as biologically-influenced signatures. BIS have been less commonly discussed in previous literature than BDS, and many examples likely remain to be identified. This is because BIS require a holistic view of the SSR and are rarely detectable from any individual outcrop: since the resultant signature may occur without life, their positive identification is hindered by equifinality - the potential for different processes, or the same process with different drivers, to have resulted in similar sedimentary end-states (see Section 3.1.1.).

At present, the reported record of BIS is biased to organisms and behaviours that are voluminous and sessile (such as vegetation [Davies and Gibling, 2010a, McMahon and Davies, 2018b]), or involve direct interaction with accruing sediment (such as effects arising from bioturbation [Herringshaw et al., 2017; Mángano and Buatois, 2017]).

## 3. Time-length scales of biosphere signatures

There is a general correlation between the time and length scales of most Earth surface phenomena, both with and without biological influences (Figure 2; Kleinhans et al., 2005, 2009). For example, it is possible to contrast phenomena such as an instance of bioturbation (occurring over an interval of minutes to weeks, over an area approximately metres-squared), with the formation of a soil, peat or reef (over hundreds to thousands of years, over kilometres-squared), to the biological forcing of the evolution of the proto-atmosphere (up to a billion years or more, over the whole globe). The time-length scale of any particular phenomenon determines the frame of reference that needs to be accessed in order to understand its formative mechanisms. Using the examples given, an instance of modern bioturbation is best understood at the small scale over short time periods (e.g., Dorgan, 2015), whilst the evolution of the proto-atmosphere requires a global compendium of data, from a substantial interval of geological time (e.g., Holland, 2006). Conversely, applying an inappropriate time-length frame of reference risks producing meaningless or fallible conclusions (e.g., changes to the morphology of a single burrow over hundreds of years, or determining proto-atmospheric evolution from one datapoint).

When we seek to elucidate life influences on the whole SSR, we are often either searching for trends in a multitude of small- or medium- time-length scale phenomena, or singularities in long- time-length scale phenomena. A challenge in achieving this is presented by the fact that we cannot always choose the time-length scales at which we make observations from the ancient SSR, because of its inconsistent exposure and preservation. We here emphasise that BDS and BIS may be variably recognisable depending on whether we look at: 1) an individual outcrop (or core, etc.) or regional group of outcrops, revealing strata that are particular to the age and geological setting at a location; or 2) the holistic SSR, uniting reported instances of phenomena from the entire stratigraphic expanse of the geological timescale across the globe.

These distinct approaches offer two wholly-different focal lengths with which to interrogate the SSR, and either one may be more or less suited to identifying particular traits, depending on the time-length scales of the phenomena associated with those traits.

### *3.1. Biosphere signatures at outcrop*

Outcrops are present-day geomorphological features: exposures of rock that are finite in their extent and terminate against areas of non-exposure or erosion, and may be internally partitioned by faults and unconformities. Where they consist of sedimentary rock, they can provide high-resolution windows onto discretized fragments of the global SSR, the time-length scale of which dictates which phenomena may be identified (and the degree of confidence to which they may be identified) (Davies et al., 2019). Spatially, outcrops are small-scale: their area can be significantly less than many ancient geomorphological landforms (e.g., McMahon and Davies, 2018a), they may reveal only fragmentary records of spatially heterogeneous phenomena (e.g., Marenco and Hagadorn, 2019), and, in most instances, they record only a diminutive fraction of a total depositional environment (e.g., Runkel et al., 2008; Davies and Shillito, 2018; Davies et al., 2019). Temporally, outcrops consist of individual beds which formed on timescales ranging from minutes to days (e.g., in the case of those composed of hydrodynamic bedforms; Miall, 2015; Paola et al., 2018; Davies et al., 2019) to tens of thousands of years (e.g., in the case of palaeosols; e.g., Candy et al., 2004; Barnett and Wright, 2008). Within any given outcrop, beds representing these different time-durations can occur as a stochastically shuffled succession. Additionally, packages of individual beds, vertically-stacked to the dimensions of the outcrop, may record much longer time intervals than the sum of their parts, because the breaks between beds can record extensive sedimentary stasis or time lost to erosion (Paola et al., 2018).

The timescales represented by different outcrops, or within a single outcrop, can thus be highly variable. In general, however, outcrop-archived timescales are weighted towards enabling the direct recognition of BDS that arose from Earth surface phenomena on short- to moderate- time-length scales (Figure 2). This is particularly true of BDS which occur in direct association with fossil evidence for biological involvement, or where such an association can be inferred. Examples of such phenomena include trace fossils, or vegetation-induced sedimentary structures that reflect the modification of local hydrodynamic conditions by standing vegetation (Rygel et al., 2004) (Figure 3).

The limitation of outcrop studies is that they can be used to recognise only very localized examples of BDS, which can arguably have little significance beyond being geological curios. The recognition of any life signatures provides evidence only that that BDS could be formed at a particular place and time, and they are not implicit of any evolutionary context unless they are compared with a global compendium of outcrops (Section 3.2.). Furthermore, the direct recognition of most BIS and some BDS at outcrop is hampered by equifinality and underdetermination.

### *3.1.1. Outcrop: Problems of equifinality*

Equifinality refers to end-states that can potentially be explained by multiple different causes (Beven, 1996). In the SSR at outcrop, where every individual bed or sedimentary structure is effectively an end-state relative to depositional conditions, many sedimentary signatures can have plural plausible explanations, the most likely explanation for which can only be abduced by the observer (e.g., Kleinhans et al., 2005, 2009; Shillito and Davies, 2019a). This presents a particular problem for the recognition of BIS at outcrop. For example, none of the BIS illustrated in Figure 1 are wholly reliant on life for their formation: their occurrence may be promoted by particular lifeforms or behaviours, but they can also be generated by purely abiotic processes.

An example of equifinality between biotic and abiotic sedimentary signatures can be seen in marine dropstones. Whilst primarily associated with deposition from melting icebergs (e.g., Bischof, 1990), marine mammals, birds, driftwood, ship ballast release, and floating seaweed have all been documented as potential rafting agents (Figure 4; Emery, 1941, 1955; Flemming, 1951; Joliffe, 1989; Woodborne et al., 1989; Bennett et al., 1996; Frey and Dashtgard, 2012). These biotic explanations are arguably far less likely than a glaciogenic origin, but nonetheless they must be considered possible alternative explanations for specific dropstones on any ancient alternative Earths where they were possible. In such instances, accessory sedimentary features would be needed to weigh the balance of probability as to the exact cause (e.g., searching for signatures such as abundance, varves, striations, faceted clasts, or glendonites).

Generally, the simpler the form within the SSR, the more problematic it may be to ascribe a biological origin: many simple trace fossils, body fossils, stromatolites and microbial sedimentary structures can be hard to distinguish from sedimentary structures of inorganic origin (Jensen et al., 2006; McLoughlin et al., 2008; Ohmoto et al., 2008; Buatois and Mángano, 2016; Davies et al., 2016; Allwood et al., 2018; Brasier et al., 2019). In the case of microbial sedimentary structures, Davies et al. (2016) suggested that a practical first approach to circumvent this problem would be to classify sedimentary surface textures according to the perceived likelihood of a microbial origin, based on the weight of accessory evidence: Category B being definitively biotic (microbial) and Category A definitively abiotic; Category Ba is then assigned for structures with supporting evidence for a biotic origin, but where an abiotic origin cannot be ruled out (or Ab for the converse situation); Surface textures with a plausible biotic origin, but where there is no clear evidence are Category ab. Such an approach need not be limited to microbially-induced sedimentary structures and could be extended to suspected BIS during the initial stages of any investigation; thus mitigating against problems of equifinality (and acknowledging that some solutions are inescapably ambiguous).

### *3.1.2. Outcrop: Problems of underdetermination*

Equifinality can lead to the related problem of undetermination of biological influence. Underdetermination refers to the situation that arises when there is insufficient available or total evidence to ascertain which particular explanation, amongst plural potential explanations, is the true cause of an observed phenomenon (Kleinhans et al., 2005). Two examples illustrate this (Figure 4):

1) In modern environments, large herbivores such as cows and hippopotamuses are known to promote the formation of small fluvial channels. Herding trails are grazed of vegetation and compacted under the animals' weight, leading to decreased infiltration of meteoric water and increased surface runoff and erosion (Trimble and Mendel, 1995). During overbank flooding and avulsion, these conduits may become the preferred route for water in the landscape,

resulting in the abandonment of previously dominant fluvial channels (McCarthy et al., 1992). If such features were to be translated into the SSR, the sedimentary signature would be one of multiple small abandoned channels (i.e., discrete channel architectural elements, aggradationally filled with fine-grained sediment), but direct evidence for the organismal trigger (i.e., footprints organised within trackways) would have been obliterated by the physical processes of erosion which they promoted and which created the channels. This limitation of the SSR is borne out by examples of Mesozoic fluvial successions, such as the Early Cretaceous Wealden Group of southern England, which contains both abundant abandoned channel elements and discrete fossilized footprints of herbivorous herding dinosaurs (Shillito and Davies, 2019b). In similar successions, the possibility of dinosaur-induced avulsion has previously been suggested (Jones and Gustason, 2006). Yet while modern analogue can tell us that herding dinosaurs (heavier than extant large animals [e.g. Lockley et al., 2012]) likely promoted channel avulsion during the Mesozoic, and outcrops can contain evidence that both small channel avulsion processes and dinosaurs co-existed in ancient environments, underdetermination means that the SSR is unlikely to provide definitive evidence of specific instances of dinosaur-induced avulsion, because other non-dinosaur causes remain plausible (Shillito and Davies, 2019b).

2) Beavers are well-known ecosystem engineers in modern rivers, promoting the formation of wetlands through their damming of river channels with cut wood. The wood-cutting clade of beavers arose in the latest Oligocene (Rybczynski, 2008) and so they may be expected to have left facies signatures within the SSR. Pliocene strata in Arctic Canada contain both outcrop sedimentary evidence of wetlands, in the form of extensive peats, and beaver activity (fossil woody debris with characteristic bite marks) (Mitchell et al., 2016a). However, the peats represent deposition over a c. 49 Ka timescale, and so even in such instances of remarkable co-occurrence, the discrete outcrop signature cannot be directly attributed to a

specific beaver damming event, instead recording an amalgam of deposits that show the dominant sedimentary conditions, apparently under the influence of the presence of a particular organism (Mitchell et al., 2016a). The non-unique facies signatures arising from the effects of beaver dams means that the recognition of their effects at outcrop is hampered by underdetermination.

### ***3.2. Biosphere signatures in the whole SSR***

In a review article entitled "The search for a topographic signature of life", Dietrich and Perron (2006) asked the question: 'if life had not arisen on Earth, would landscapes be significantly different?' Using a variety of geomorphic transport laws, they concluded that there may be no unique geomorphic signature of life, but the influence that different organisms can have on the frequency distribution of landform properties can be highly significant. The question that they posed can be directly addressed when we consider Earth's SSR as a whole, the longevity of which means that parts of it did accrue on a planet where particular types of life had not yet arisen. By collecting and collating global outcrop and other geological observations (from original fieldwork and published records), it is possible to catalogue the disparity and diversity of sedimentary phenomena that are particular to time intervals in which different organisms, groups of organisms and behaviours were nascent, advanced, extinct, or had not yet evolved. Cross-comparison with similar catalogues of phenomena from antecedent and subsequent intervals makes it possible to identify hypotheses that life may have played a role in the observed patterns of BDS and suspected BIS. This is because first appearances and abundance shifts in sedimentary phenomena may become apparent that are stratigraphically synchronous with the evolutionary origins of life traits, and which (from modern analogue) are known to be potential causes of those phenomena. Holistic study of the SSR thus presents the opportunity to 1) understand trends within unequivocal BDS (e.g., Riding, 2000; Diessel, 2010; Buatois and Mángano, 2018), and 2) infer potential trends in BIS, when alternative explanations can be ruled out, or recognised as less likely explanations (e.g., Davies and Gibling, 2010a, 2013; McMahon and Davies, 2018b; Tarhan, 2018; Chen et al., 2019).

Trends in suspected BIS (Figure 1) before and after the evolution of particular life traits are expected to resemble the frequency distribution curve illustrated by Dietrich and Perron (2006; their fig. 5) for abiotic versus biotic settings. In other words, if one or more of the parameters that cause a particular phenomenon can be accentuated or dampened by a particular life trait, then it can be expected that the frequency distribution of that phenomenon within the SSR will differ in strata deposited before and after the evolution of that life trait. This is well-ascertained for particular sedimentary signatures within alluvial strata, which appear more or less abundant after the evolution of land plants (Figure 5). In modern systems, vegetation plays a fundamental role in affecting fluvial form and process (e.g., Corenblit et al., 2007, 2009; Wohl, 2013; Gurnell, 2014; Horton et al., 2017; Kleinhans et al., 2018), but it does so by changing particular physical parameters within the whole river system. As a result, many signatures in ancient alluvium will be BIS, even where they cannot be directly recognised as such at an individual outcrop. For example, Davies and Gibling (2010b) noted that published interpretations of meandering river planforms increased in stratigraphic alignment with the evolution of land plants, but emphasised that “the presence of Precambrian and extraterrestrial meandering systems indicates that vegetation is not essential for meandering” (Davies and Gibling, 2010b, p. 51) (e.g., Matsubara et al., 2015). In this instance, it is implicit that an individual outcrop of pre-vegetation alluvium that could be interpreted as the product of a meandering river would tell us little about the larger role of vegetation in producing BIS. However, trends in the frequency distribution of alluvial signatures before and after the evolution of land plants, across the whole SSR, begin to reveal patterns in suspected BIS, for which a vegetation cause appears the most probable explanation.

### *3.2.1. Whole SSR: Problems of equifinality*

Time-dependent frequency distribution trends in particular sedimentary phenomena are emergent patterns within the whole SSR, but such observed patterns are end-states that are potentially as prone to issues of equifinality as individual signatures are at outcrop (i.e., correlation is not causation). To be recognised as being contingent on biological evolution, other alternative explanations must be determined to be less likely. In the case of long term secular trends in the SSR, traditionally the three overarching explanations have been tectonics, climate and sea-level, and it remains true that many of these controls may leave non-unique signals that could be mistaken for biosphere signals. Critically, however, all three of these forcing mechanisms exhibit cyclicity or episodicity over geological timescales, albeit at different frequencies, from longest (tectonic cycles) to shortest (sea-level cycles) (e.g., Allen, 2008; Foreman and Straub, 2017). They are thus inadequate explanations for singular, non-recurrent shifts in the frequency distribution of sedimentary signatures in the whole SSR.

The unidirectional nature of evolutionary innovation means that biological signature shifts in the SSR may be more readily identifiable than those generated by cyclic phenomena. Unless they are of sufficient magnitude, cyclic signals can suffer from shredding at different scales, whereby components of the original cyclic record are reworked or removed by autogenic processes (Jerolmack and Paola, 2010). In order to leave a recognisable signal, the period of cyclic oscillation must be longer than the key timescales of internal autogenic dynamics in any sedimentary system that is contributing strata to the SSR (Hajek and Straub, 2017; Foreman and Straub, 2017). Expanding this concept, consideration of the whole SSR can best reveal those cyclic phenomena that occur at the largest time-length scales (e.g., supercontinent cycles: Bradley, 2011). In contrast, unidirectional signals arise from a binary system shift (i.e., absence/presence of an evolutionary component), thus while the timing onset of the signal may be only coarsely recognised, the shift should be globally apparent (Figure 6).

For example, in the case of alluvial signatures attributed to vegetation, the onset of major sedimentological change occurs towards the end of the Silurian. This is in stratigraphic correlation with the evolution of tracheophytes (e.g., Edwards et al., 2015; Wellman and Strother, 2015), but post-dates a multitude of tectonic and climatic cycles in the preceding 3.4 Ga of time recorded in the SSR (e.g., Weller and St-Onge, 2017), some of which would have harmonized to create abiotic global backdrops that were similar to the late Silurian world (Torsvik and Cocks, 2016). In the absence of earlier, comparable facies shifts, the evolution of vegetation appears the most likely trigger. Further support for this hypothesis is then seen in the persistence in abundance and occurrence of the signatures in the SSR, which do vary through subsequent intervals (likely due to tectonic and climatic cycles), but which never revert to pre-vegetation character (Davies and Gibling, 2010a, 2013; Davies et al., 2017). Additional testing is possible by comparing the distribution of signatures in pre- and syn-biotic worlds, across similar tectonic or climatic settings. For example, McMahon and Davies (2018b) showed a significant increase in the amount of mudrock in alluvium in stratigraphic correspondence with the rise of land plants. While mudrock abundance in alluvium may potentially be explained by proximity to an orogenic source, cross-comparison of mudrock abundance before and after the evolution of land plants, using the analogous Grenville and Caledonide orogenies as controls, suggests that tectonic controls are secondary to evolutionary controls (Figure 7).

### *3.2.2. Whole SSR: Problems of underdetermination*

Underdetermination affects whole SSR analyses in instances where 1) there are frequency distribution shifts in SSR signatures without synchronous fossil evidence, and 2) any suspected BIS cannot be identified as such due to a lack of predictive modern analogue.

In the first instance, Figure 1 omits a number of Precambrian secular changes in the SSR, which may be attributable to life, but occur where synchronous fossil evidence is lacking. The recognition of frequency distribution shifts in the SSR requires that strata dating from before and after the evolution of a particular organism or clade can be studied. This is possible for most metazoan and plant groups, which have a predominantly Phanerozoic record, but is considerably more problematic for life in the Precambrian – the fossil record of which is more poorly understood and which may, in part, have a greater temporal lineage than the SSR itself (Butterfield, 2015; Knoll and Nowak, 2017). For example, modern observations attest to ways in which microbiota generate biosignatures by altering bedform stability fields through biophysical sediment cohesion (Malarkey et al., 2015; Parsons et al., 2016). When preserved in the SSR, however, such bedforms are often erosionally truncated and the precise flow regimes that formed them are usually unknown: the same array of physical structures can be developed with or without microbial influence. Furthermore, since the SSR may not extend far enough back in time to observe any pre-microbial to microbial shift in the frequency distribution of bedform dimensions, and since the timing of the evolution of key microbial traits (e.g., the ability to generate extra-cellular polymeric substances) is wholly unknown, it is not possible to directly ascertain a microbial role in the formation of relict bedforms; even though such life-sediment interactions should be expected to have occurred regularly since the evolution of the first interstitial microbial life (Chen et al., 2017). Additionally, certain microbial controls on sedimentary environments and geomorphology have limited potential to enter the SSR. For example, at sub-bankfull flood stage in some modern rivers, microbial mats and biological soil crusts may be seen to colonize and stabilize sediment on bar tops and river margins (Dupraz et al., 2009). However, the dominant record of sedimentation in rivers scales towards seasonal maxima, meaning that deposits that get preserved in the SSR will often be those formed when sub-bankfull biosignatures are reworked (Rice et al., 2016) (in this instance, when microbial surfaces are undercut and destroyed by lateral channel migration). Thus the sedimentary signatures in the SSR may reveal end-state evidence of reworked channel margins colonized by matgrounds (e.g., intraformational clasts bearing microbially-induced sedimentary structures), but are unable to reveal the influence that microbial communities had on fluvial process during average flow conditions (McMahon et al., 2017).

Notwithstanding these issues, some trends in the SSR are so obvious and singular that they may be considered BIS even without a fully understood trigger. Precambrian chemical sediments, such as bedded phosphorites and sulphates, are suggested to have been influenced by the evolution of life, and are reviewed elsewhere: see, for example, Eriksson et al. (2013), Lepland et al. (2013), and Strauss et al. (2013).  Particularly prominent amongst such signatures are Banded Iron Formations , the disappearance of which has long been considered to have been influenced by biological evolution (Cloud, 1973; Erikkson et al., 2013). Recent studies have shown that Banded Iron Formations may occur near continuously between the Archean and early Palaeozoic (Canfield et al., 2018; Li et al., 2018), indicating pockets of ferruginous ocean conditions which became rare during the Phanerozoic. However, while the disappearance of Banded Iron Formations from the SSR is a strong secular signature, underdetermination means that we cannot directly point to tangible fossil evidence for the synchronous evolution of a particular organism or life strategy (e.g., photosynthesis). Additionally, any precise life trigger for the disappearance of Banded Iron Formations would have been twice-removed from the effect: the direct cause of their disappearance was a change in global ocean chemistry, which in turn was influenced by life.

Sedimentary structures that feasibly exhibit shifts in the Precambrian may include raindrop imprints, which have been posited to occur within a different range of sizes prior to the Great Oxidation Event because of a different air density at the time (Som et al., 2012). However, this shift in sedimentary signatures is at least thrice-removed from any life trigger (i.e., a different raindrop size due to different air density due to different atmospheric composition due to different life metabolism), so any link to biological evolution can only be very tenuously made. In addition, equifinality means there are non-unique explanations for the anomalously-sized raindrop impressions that Som et al. (2012) used to calculate atmospheric density: for example, the rate and duration of rainfall (Kavanagh and Goldblatt, 2015).

Underdetermination also limits the opportunity to recognise BIS in the whole SSR when there is limited understanding concerning what signatures should be sought as potential BIS. In some instances, new data may offer future opportunities to interrogate the SSR with respect to these signatures. Examples include the underexplored signatures arising from changes in ocean circulation and water displacement associated with the evolution of swimming metazoans (Huntley and Zhou, 2004; Butterfield, 2018); decoupling our understanding of the evolution of physical (churning) and chemical (gut evolution and sediment processing) aspects of bioturbation; or distinguishing between the impact of meiofaunal versus macrofaunal bioturbation.

### *3.3. Recognition of biosphere signatures*

BDS and BIS provide records of ancient phenomena that occurred on different time-length scales. These records can be accessed by studying the SSR at different time-length scales; from individual beds, through to outcrops, groups of outcrops, and the whole SSR as presently reported (Figure 2). While it is essential to consider the limitations imposed by equifinality and underdetermination, it should also be recognised that such problems are not unique to biosphere signatures: equivalent issues have always hampered interpretations of abiotic causal mechanisms (e.g., tectonics, climate, sea-level) drawn from end-state phenomena. If, in the SSR at outcrop, we cannot recognise those biological sedimentary phenomena that occur on time-length scales that are comparable to outcrop scales (Figure 2), then there are only two explanations: 1) they are indistinguishable due to equifinality and underdetermination (e.g., biogenic turbulence damping), or 2) they did not occur (e.g., Archean bioturbation).

The key to further recognition of hypotheses concerning biosphere signatures is a two-stage process: 1) finding a consensus between modern analogue and models that attests to a biological contribution to the formation of a particular signature (e.g., Table 1); and 2) surveying the whole SSR to see whether there is a sudden origin or abundance shift of that signature, in stratigraphic alignment with the fossil record of the evolution of the trigger organism/behaviour. Confirmation that any stratigraphic shift is unidirectional provides supporting evidence that the suspected biological trigger is more likely than repetitive tectonic, climatic or sea-level changes that would have continuously occurred before and after the change (e.g., see Davies et al., 2017). Once unidirectional shifts in presence/absence or abundance have been recognised that fulfil these criteria, they can be considered robust hypotheses for the presence of BDS and BIS.

## 4. Examples of biosphere signatures

Figure 1 shows the range, within the SSR, of certain BDS and BIS and the relationship of these ranges to the origins of certain taxa as evidenced in the fossil record. The purpose of this paper is to encourage further interrogation of the SSR for biosphere signatures, and therefore the trends and taxa depicted in Figure 1 should not be considered to be exhaustive. Alternative signatures could be illustrated: for example, different types of metazoan reefs, microbially-induced sedimentary structures, anthropogenic signatures other than plastic, or a more granular subdivision of features such as burrows. However, recent reviews of such information are available elsewhere (for example, respectively within Kiessling, 2002; Chen et al., 2019; Waters et al., 2016; Buatois and Mángano, 2018).

The trends shown in Figure 1 are simplified, particularly with respect to secondary organisms. For example, certain microbiota could be argued to have played a secondary role in almost all of the signatures listed. We have also shown only proactive instances where signatures have been directly induced or dampened by taxa: later interactions with other taxa clearly exist but are not illustrated (e.g., the influence of grazing metazoans on microbialites (Riding, 2006) or human modification of coal deposits, coral reefs, or river systems (Goudie and Viles, 2016; Williams et al., 2016; Gibling, 2018)).

With these caveats, the examples shown in Figure 1 are amongst the most often reported biosphere signatures, and this section provides a brief review and explanation of each of them.

### *4.1. Drivers of biosphere signatures*

The taxa shown in Figure 1 primarily follow the same groupings as those used in Bar-On et al. (2018), who reported that these groups comprise the most voluminous biomass at the present day. We have also included taxa omitted by Bar-On et al. (2018), namely: Porifera, because of their notable contribution to siliceous sedimentary rocks (e.g., Maliva et al., 1989; Kidder and Erwin, 2001); tetrapods and reptiles, because of their prominent body fossil records; and angiosperms, grasses and trees, as subdivisions of land plants with particular roles in the creation of the SSR.

Since the purpose of Figure 1 is to illustrate correlation between the tangible fossil record and the physical SSR, the apparent origins of the taxa included refer to the earliest unequivocal body fossil remains of total group representatives of such organisms, rather than origins inferred from indirect evidence (e.g., trace fossils; here considered a BDS component of the SSR) or phylogenetic predictions. Earliest occurrences have been determined from the papers listed in Table 2, which we consider to make the least equivocal and most widely-accepted claims, though we offer the following caveats: (1) the fossil record of microbial organisms is inherently opaque and a number of doubtful "earliest" claims have been made (e.g., see discussion in Allwood et al., 2018): to maintain a cautious estimate, we here use the earliest unequivocal stromatolites (Allwood et al., 2006; Knoll and Nowak, 2017) as a proxy for the origins of Archaea, Bacteria and viruses, but concede that this is extremely uncertain; (2) we have depicted the origin of fungi based on the earliest fossils of fungi-like filaments that have recently been reported from the Palaeoproterozoic (Bengtson et al., 2017; Loron et al., 2019), but note that confident identification of fungal fossils is problematic due to widespread convergence on a filamentous habit; if the recently reported instances were excluded, then the other oldest putative fungi would be Mesoproterozoic (Butterfield, 2005) or Silurian (Smith, 2016), and the earliest confidently identified crown group fungi would be Devonian (Peckmann et al., 2008); (3) the earliest known fossils of some taxa, such as protists and nematodes, likely post-date their true origins by a substantial interval, due to the poor preservation potential of these taxa; and (4) when reported fossils need to be attributed to groups with debatable (e.g. paraphyletic) definitions (e.g., bird, fish, mammal, reptile, tetrapod), we have made a judgement call based on how likely the reported fossil organism would have been to interact with Earth surface processes in a manner comparable to extant organisms of that group.

### *4.2. Examples of BDS: Lithologies*

Sediments that are all or partially formed from the dead tissues or detritus of once-living organisms, or which have been precipitated as a result of organism metabolism, are clearly recognisable as biogenic lithologies. Examples of BDS lithologies are shown in Figure 8, and discussed in the following section.

### *4.2.1. Microbialites and Microbialite limestones*

*Stratigraphic range:* Isolated stromatolites are known from the Palaeoarchean (3.45 Ga) Strelley Pool Chert of Western Australia (Allwood et al., 2006). Extensive microbial carbonates are known from Neoarchean (2.55 Ga) successions in South Africa (Riding, 2011). Microbialites and microbialite limestones thus have a range from the Archean to present (Riding, 2000) (Figure 8A-C).

*Primary Organisms and Role:* Various microbiota which induce the precipitation of minerals including carbonates (Riding, 2008). While Bacteria, Archaea and certain protists have long been identified as playing key roles in microbialite production, recent work also shows how viruses can act as loci for crystal nucleation (Perri et al., 2018) and rupture cyanobacterial cells to release bicarbonate (Lisle and Robbins, 2016).

*Further Information:* Microbiota may both contribute to and promote carbonate precipitation, so different microbialites and microbial limestones may variably be classed as both BDS and BIS. Extensive reviews of microbialites and microbial carbonates are presented by Riding (2000, 2006, 2008, 2011), who describes how microbialites have evolved through time. Riding (2000) notes that the time from the Neoarchean to the end of the Mesoproterozoic was the acme of stromatolite microbialites, with a decline in abundance beginning in the Neoproterozoic. Microbialite limestones are reported to have exhibited other abundance peaks in the Cambrian to Early Ordovician, Late Devonian to Early Carboniferous and Mid-Triassic to Early Cretaceous, and microbial contribution to 'metazoan' and 'abiotic' limestones remains significant throughout the Phanerozoic (Riding, 2000, 2011).

### *4.2.2. Bioclastic limestones*

*Stratigraphic Range:* The oldest bioclastic limestones known are formed from fragments of early biomineralizing organisms such as *Cloudina* and *Namacalathus* (Figure 8D), found in multiple latest Ediacaran fossil localities globally, including in Paraguay, China, Brazil and Namibia (e.g. Grant, 1990; Warren et al., 2013; Cai et al., 2019). After their first occurrence in the terminal Ediacaran, later occurrences throughout the Phanerozoic SSR fluctuate and evolve in their diversity and composition, coeval with evolutionary histories of different benthic calcareous organisms (Wilkinson, 1979).

*Primary Organisms and Role:* Shelly metazoans, calcareous algae and foraminifera, often boosted by biomineralizing micro-organisms (James and Jones, 2016).

*Further Information:* The formation of bioclastic limestones (comprising a significant proportion of clasts derived from skeletal material) first required the evolution of a calcareous shelly biota in the latest Ediacaran (Porter, 2007; Wood et al., 2017; Cai et al., 2019). The skeletal mineralogy of these organisms has fluctuated between calcite and aragonite with changes in ocean chemistry over geological time (e.g., Turchyn and DePaolo, 2019). There is a general increase in the diversity of calcareous organisms over time (Figure 8D-F), and modern carbonate-producers begin to come to prominence from the middle Mesozoic onwards (Stanley and Hardie, 1998; Veizer and Mackenzie, 2014).

#### *4.2.3. Coal and peat*

*Stratigraphic Range:* Coal appears worldwide in the Middle Devonian SSR (Kennedy et al., 2013). An apparent global absence of coal in the earliest Triassic has been ascribed to the mass extinction of terrestrial flora during the PT Event (Retallack et al., 1996; Benton and Newell, 2014), but the lithology recovered in the Middle Triassic (albeit with a different maceral composition), and coals (or their unlithified equivalent, peat), have persisted on Earth to the present day (Figure 8G-H).

*Primary Organisms and Role:* The accumulation of the first coal deposits required sufficient areal coverage and persistence of a lignin-bearing terrestrial flora (particularly woody trees). Since the earliest coal deposits, various fungi have played a role in the accumulation and partial decay of woody material, prior to its coalification (Nelsen et al., 2016).

*Further Information:* Coal is defined as a combustible rock resulting from the compaction of plant remains, containing over 50% by weight and over 70% by volume of carbonaceous material (Schopf 1966). Precursor lithologies of carbon-rich coaly shales, formed within incipient smaller-stature plant communities, first appear in Early Devonian strata (Kennedy et al., 2013). The subsequent global distribution of coal is tectonically and climatically controlled: Carboniferous coals are most common in regions that formed equatorial Euramerica, whilst the assembly of Pangea, and the Kasimovian collapse of equatorial rainforests (DiMichele, 2013), means that the location of Permian coal deposition can be tracked towards progressively higher palaeolatitudes during that period (Hilton and Cleal, 2007). Major evolutionary shifts in the dominant vegetation of ancient coal forests are also suggested to be reflected in the internal properties of coals. Collinson and Scott (1987) suggested that Carboniferous coals (dominantly formed from arborescent lycopsids) differ from Cretaceous and younger coals (dominantly formed by taxodiaceous conifers) in terms of their degree of compression, maceral composition, and number of coal splits (i.e., clastic layers within coal successions).

### *4.2.4. Chalk and calcareous ooze*

*Stratigraphic Range:* Jurassic chalk deposits are present (though uncommon), but the lithology has persisted in the SSR since that time (Bernoulli and Jenkyns, 2009).

*Primary Organisms and Role:* Chalk is a pelagic carbonate sedimentary rock predominantly formed from coccolithophore fragments; thus the Triassic evolution of calcifying haptophytes (De Vargas et al., 2007) was a prerequisite for its accumulation.

*Further Information:* After the first appearance of chalk accumulations in the Jurassic, their abundance fluctuated in line with tectonic and climatic controls on the location of the calcium carbonate compensation depth within sediment-accumulating basins: the lithology is globally most common in Cretaceous North American and European successions (Figure 8I) where regional basin and sea-level conditions promoted its accumulation (Bernoulli and Jenkyns, 2009). Whilst chalk is a rock type and thus restricted to the lithified SSR, coccoliths remain a significant component of modern, deeper marine calcareous oozes (James and Jones, 2016).

## ***4.3. Examples of BDS: Materials***

Biogenic materials are dead tissue, waste product, or other matter that require direct manipulation by organisms. BDS materials are illustrated in Figure 9.

### *4.3.1. Fecal pellets and bromalites*

*Stratigraphic Range:* The earliest fecal pellets in the SSR are known from the earliest Cambrian (Fortunian) Lontova and Voosi formations of Estonia (Figure 9A; Slater et al., 2018): they diversify and persist for the remainder of the Phanerozoic (Figure 9B).

*Primary Organisms and Role:* Bilaterian metazoans with a through-gut, enabling alimentation and excretion of novel biomaterials.

*Further Information:* Material processed through the digestive systems of animals can enter the SSR in the form of faecal pellets or coprolites (or the more inclusive category of bromalites). In most instances, where these structures are recognisable they may form only a minor element of the host sediment, but on occasion their accumulation may reach rock-forming proportions. Examples of such include the huge volumes of primary carbonate mud produced within the intestines of teleost fish in the modern tropical carbonate factory (Perry et al., 2011; Salter et al., 2012), as well as many peloidal carbonates, phosphate deposits and some terrestrial soils. Even where cohesive gut-processed material cannot be identified in the form of recognisable coprolites, modern analogue indicates that all non-chemosynthetic ecosystems below the photic zone rely on the sedimentation of marine snow. Packaging of surface water organic materials by pelagic animals provides a fundamental link between the phytoplankton and the benthos. The rain of organic particles from surface waters to the seafloor is reliant on processing and clumping into larger particles by zooplankton, and particularly macrozooplankton (Turner, 2002), since the sinking rate of small particles is too slow for such material to reach a sedimentary sink before being dissolved or recycled in the water column. This enhanced export and basis of the modern biological-pump was essentially ‘invented’ by the evolution of zooplankton grazers in the Cambrian (Logan et al., 1995; Butterfield, 1997). The processing of material by planktonic metazoans is thus a critical step in the formation of many marine oozes and other deep sea sediments (e.g., Smayda 1971). None of these pathways, structures or processes could have formed on Earth prior to the evolution of the bilaterian through-gut. Identifiable coprolites first appear in marine facies in the Cambrian, post-dating the late Ediacaran or earlier evolution of total group bilaterians. This onset in the SSR possibly represents the first packaging of materials within a peritrophic membrane, and/or other forms of digestion that are more likely to produce cohesive coprolites. The earliest known vertebrate coprolites are Ordovician in age (Aldridge et al., 2006), the earliest terrestrial coprolites recorded are Silurian (Edwards et al., 1995), and recycling of fecal sediment by coprophages is known from at least the Late Cretaceous (Chin and Gill, 1996), each reflecting the Phanerozoic evolution of producers and their preferred habitats.

### 4.3.2. Inertinite and charcoal

*Stratigraphic Range:* The earliest instances of inertinite are known from the late Silurian of Estonia and Sweden (Diessel, 2010) and it persists in the SSR thereafter. The first accumulations of charcoal are known from the latest Silurian (Přídolí) Downton Castle Formation of England (Figure 9C; Glasspool et al., 2004).

*Primary Organisms and Role:* Land plants, both as a fuel source and by creating a fire-sustaining atmosphere.

*Further Information:* Inertinite is a common maceral within coal and forms a minor carbonaceous component of other lithologies. It records plant material that has undergone incomplete combustion during wildfires, and thus requires both vegetative matter as fuel and the requisite atmospheric oxygen to sustain combustion (the latter factor itself promoted by plant photosynthesis) (Diessel, 2010). The oldest late Silurian instances of inertinite correspond approximately with the origins of vascular plants, reflecting the ongoing evolution of land plants as both a combustible fuel and a source of fire-sustaining oxygen (Figure 9C-D). Subsequent stratigraphic variance in the abundance of the maceral is well-documented as resulting from tectonic and climatic changes (e.g., a global decline in inertinite abundance at the start of the Permian, reflecting Pangean aridification [Virgili, 2008; Diessel, 2010]).

### 4.3.3. Plastics

*Stratigraphic Range:* Plastics are considered here as biologically-dependent materials because they are absent from the rock record until their first creation by humans in the latest Holocene (19th century), but are now common particles of sediments across different environments (Figure 9E-F; Zalaciewicz et al., 2016).

*Primary Organisms and Role:* Humans as creators of plastic waste.

*Further Information*: Plastics are a novel component of the SSR (i.e., having a different range of densities and shapes in comparison to mineral grains), which were absent from the planet until a required threshold set of biological anthropogenic (technological) circumstances had been crossed. While a multitude of other anthropogenic materials and properties of the SSR exist (e.g., Waters et al., 2016), plastics are considered to be one of the most significant anthropogenic contributors to modern sediments (Zalaciewicz et al., 2016). Unique plastic-related lithologies include conglomerates formed by the melting of plastic on volcanic islands (Corcoran et al., 2014): while such instances are highly localized and may lack longevity in the SSR over geological timescales, the spread of particulate microplastic to rivers and marine basins suggests that some traces of the material may have long-term preservation potential (Zalaciewicz et al., 2016; Kane and Clare, 2019). Plastics are an example of a biologically-dependent material that have a delayed onset relative to the evolution of the organism that acted as the driver behind their existence (i.e., plastics appear c. 0.15 ka whereas *Homo sapiens* originated c. 315 ka (Hublin et al., 2017)), as they additionally required the origination of particular behaviours in their driver organism (i.e., hydrocarbon discovery, plastic invention, mass manufacture, and widespread indifferent disposal).

### *4.4. Examples of BDS: Structures*

Structures are patterns or constructions within sediment, sculpted or imparted either directly or indirectly by living or dead organisms, and with the potential to be preserved within sedimentary strata. Examples of BDS structures are shown in Figure 10.

#### *4.4.1. Burrows*

*Stratigraphic Range:* The oldest definitive infaunal burrows date from the late Ediacaran (reviewed in Buatois and Mángano, 2016). Burrows, as an umbrella grouping, are known from every subsequent stratigraphic interval of the SSR until the present day (Buatois and

Mángano, 2018), and show a progressive diversification of architectures (Buatois et al., 2017) and expansion into new environmental niches (e.g., their first appearance in non-marine strata in the latest Silurian; Minter et al., 2016, 2017; Shillito and Davies, 2017) (Figure 10A-D).

*Primary Organisms and Role:* Representatives of numerous metazoan phyla and some protists, excavating burrows for feeding, locomotion, or dwelling, through a variety of different mechanisms in different sediment types (e.g., Dorgan et al. 2006; Dorgan, 2015). Note that Figure 1 shows only organisms that have been inferred to create burrows in the SSR: for example, although both ornithopod dinosaurs (Varricchio et al., 2007) and modern birds (McGowan et al., 2018) are known burrowers, as yet there appears to be no recognised trace fossil record of bird burrows. Additionally, the types of organisms forming burrows, their methods of burrow excavation, and environmental impact vary immensely through geological time and 'burrows' is an extremely broad category: for example, meiofaunal burrows from the Ediacaran (Parry et al., 2017) are fundamentally different in their signature and effects to the traces of life in the SSR reflected by the earliest vertebrate burrows (e.g., suspected fish burrows in Devonian strata: Friedman and Daeschler, 2006) or anthropogenic tunnel systems (Zalasiewicz et al., 2014).

*Further Information:* Some cnidarians are capable of producing simple vertical burrows, while cnidarians and some protists can produce surficial trails (e.g. Matz et al., 2008; Liu et al., 2010). However, production of all other burrow types requires a hydrostatically manipulated body cavity (e.g. a coelom) and advanced sensory systems, meaning that their late Ediacaran appearance in the SSR is likely coincident with the evolution of total group Bilateria (Budd and Jensen 2000). The evolution of burrowing not only resulted in a new class of biologically-dependent structures in the SSR, but also had a profound effect on the nature of sedimentation and Earth surface processes. These impacts include the transformation of the marine sediment-water interface from an essentially 2D plane to a heterogeneous 3D construction (Herringshaw et al., 2017), the physical redistribution of nutrients and particulate matter (Budd and Jensen 2017), changing the carbon, phosphorus and sulfur cycles (Canfield and Farquhar, 2009; Boyle et al., 2014, 2018; Lenton and Daines, 2018), the modification of porewater chemistry, and a trophic escalation among the benthos (McIlroy and Logan, 1999; Mángano and Buatois, 2017). The precise timing and details of how intensified bioturbation caused these secondary effects is discussion topic of current investigation (e.g., determining an early [Mángano and Buatois, 2017; Gougeon et al., 2018] versus late [Tarhan et al., 2015] acceleration). Specific burrow structures can be seen to evolve in terms of their size, depth and environmental facies preferences within the SSR, subsequent to their initial evolution: for example, the increased depth of penetration and shifting (offshore) environmental preferences of *Zoophycos* burrows following their Cambrian evolution (Zhang et al., 2015).

### *4.4.2. Coral reefs*

*Stratigraphic Range:* The earliest reef-forming corals occur in the early Cambrian of South Australia (Fuller and Jenkins, 2007), and large-scale coral reefs are known intermittently throughout the SSR from the Middle Ordovician onwards (James and Wood, 2010), with particular abundance after the Mesozoic evolution of scleractinian corals (Lipps and Stanley, 2016).

*Primary Organisms and Role:* Cnidarians as reef constructors, extracting calcium and carbonate ions from seawater to construct their skeletons.

*Further Information:* Coral reefs are the largest biotic constructions that currently exist on Earth (Dietrich and Perron, 2006). Coral evolution since the first large-scale reefs in the Middle Ordovician has meant that the types of reef-forming coral have changed through geological time (for example the Mesozoic shift from tabulate and rugose corals to scleractinian corals) (Figure 8F, Figure 10E-F), and the abundance of such reefs has fluctuated due to biological, tectonic and climatic change, as well as competition from other reef-building organisms (e.g., Chen et al., 2019). Nonetheless, such structures (and associated environments such as storm-protected back reef environments) have a defined, biologically-dependent onset in the SSR. Although scleractinian corals are the principle reef-builders in modern oceans, as with bioclastic limestones, other metazoan and microbial reefs and reef mounds exist with their own trends within the SSR (for example, Cambrian Archaeocyatha or Jurassic–Cretaceous rudist bivalves (Wood, 1995, 2017; Zhuravlev, 2001)).

#### *4.4.3. Root structures*

*Stratigraphic Range:* Putative root-like structures exist in the latest Silurian (Figure 10G), and definitive root traces are known in earliest Devonian strata within the Old Red Sandstone of the Anglo-Welsh Basin, UK (Hillier et al., 2008). Root structures are subsequently persistent throughout younger non-marine and marginal marine strata (Figure 10H), with variable diversity of form and depth of penetration (Algeo and Scheckler, 1998).

*Primary Organisms and Role:* Land plants anchored with in-sediment roots, plus symbiotic mycorrhizal fungi.

*Further Information:* Root structures are sedimentary structures formed by the casting of decayed plant roots within heterolithic sediment (Hillier et al., 2008), or can occur as rhizoliths with associated calcrete (Brasier, 2011). Recorded fossil material of fully vascular plant roots (with meristems) are known as carbonaceous impressions from around the same time as the earliest root casts, from the Early Devonian of Scotland and Wyoming (Matsunaga and Tomescu, 2016; Hetherington and Dolan, 2018). After their first appearance, root structures vary in their diversity of form and depth of penetration, reflecting the continuation of botanic evolution (Algeo and Scheckler, 1998) as well as progressive tracheophyte co-evolution with symbiotic mycorrhizal fungi (Brundrett and Tedersoo, 2018). Related to roots, recent descriptions of surface trenching and penetrative tunnels, attributed to the actions of bacteria, fungi and exudates in cryptogamic ground covers (Mitchell et al., 2019) may also prove to be BDS in the SSR, although their simplicity of form would require careful consideration of issues of equifinality.

#### *4.4.4. Trample-grounds*

*Stratigraphic Range:* The earliest trample-grounds reported from the SSR occur within Late Triassic strata from at least two locations: (1) the Chinle Formation of Arizona, where they are associated with fossilized reptile nests (Hasiotis and Martin, 1999); and (2) the Flemming Fjord Formation of east Greenland, where they are associated with large theropod dinosaur trackways (Milan et al., 2004). They remain relatively common in non-marine sedimentary facies throughout the Mesozoic and Cenozoic.

*Primary Organisms and Role:* Large animals with sufficient weight to load unconsolidated sedimentary substrates and/or repeatedly congregate in large groups at the same place. Known examples in the SSR include trample-grounds associated with nesting reptiles (Hasiotis and Martin, 1999), extremely large terrestrial animals such as dinosaurs (Figure 10I) and mammoths (McNeil et al., 2007; Milan, 2011), and herding, predator avoidance and congregational feeding activity of large birds (Scott et al., 2012) and mammals (Bromley et al., 2009).

*Further Information:* Trample-grounds form when the integrity of shallow subsurface sediment layers is disturbed by the weight of large organisms congregating and moving across a substrate. They are preserved in the rock record as localized patches of soft-sediment deformation and mixing of heterolithic strata, extending up to a metre beneath a former substrate. Sometimes these are preserved immediately below discrete footfall impressions (for the largest trample-ground makers, such as dinosaurs: Milan et al., 2004; Shillito and Davies, 2019b). Their formation requires both overburden pressure from heavy organisms, plus waterlogged sediment that can behave thixotropically when deformed under the weight of the animal. Large terrestrial tetrapods have existed since at least the Carboniferous but the largest trackways associated with these animals do not appear to have left a definitive trample-ground record: large animals such as *Dimetrodon* are known to have left ‘ploughed’ furrows (Van Allen et al., 2005) but do not appear to have had the critical mass to deform substrates at depth.

## *4.5. Examples of BDS: Facies*

Sedimentary facies are groupings of sedimentary signatures that are seen to recur in multiple sedimentary successions. Facies assemblages are ascribed to particular depositional environments, because those environments are known to promote the co-occurrence of particular sedimentary signatures. Of all the biosphere signatures listed, these are most prone to potential error in their ranges because they first must be abductively interpreted and defined by geological observers. Nonetheless, instances of sedimentary facies that have defined stratigraphic ranges, or which, by definition of their formative environment, required particular life-forms, have been reported. Examples of BDS are discussed and defined in the following section, and illustrated in Figure 11.

### *4.5.1. Anastomosing fluvial facies*

*Stratigraphic Range:* The earliest reported anastomosing fluvial facies occur in the early Carboniferous (Kekiktuk Formation, Alaska; Melvin, 1993), and persist as a potential facies style thereafter.

*Primary Organisms and Role:* Anastomosing rivers are a geomorphic sub-category of anabranching rivers, defined as consisting of multiple channels with vegetated semipermanent alluvial islands that have either been excised from an existing floodplain or formed within channels (Nanson and Knighton, 1996). Their appearance in the rock record required adaptations within trees and other large land plants which enabled them to colonize well-drained levees, stabilize islands, and provide large-woody debris to encourage channel switching through avulsion (Davies and Gibling, 2011, 2013).

*Further Information:* Anastomosing river facies are identified by a combination of features including multiple fixed-channel ribbon sand bodies along common stratigraphic horizons, a high mudrock to sandstone ratio, evidence for vertical accretion of channels, evidence for 3D channel networks, and crevasse splay and levee deposits (Davies and Gibling, 2011). They are absent from the SSR prior to the Mississippian, suggesting a stratigraphic lag after the evolution of the first (Devonian) trees (Stein et al., 2012), possibly due to the protracted adaptation of traits such as increased arborescence, mechanically-complex wood or the capacity to colonize well-drained substrates: all of which conspire to force the development of anastomosing river landscapes (Davies and Gibling, 2013).

### 4.5.2. *Salt marsh facies*

*Stratigraphic Range:* The earliest reported salt marsh facies in the SSR occur within the Late Cretaceous (latest Cenomanian, c. 94 Ma) Peruc-Korycany Formation, Czech Republic (Uličny and Špičáková, 1997; Martinius and Van den Berg, 2011). As salt marshes are geologically-ephemeral environments, with ‘life-spans’ of only a few thousand years (Fagherazzi, 2013), the oldest extant salt marshes are Holocene.

*Primary Organisms and Role:* By definition, the earliest salt marshes could not have formed until after the evolution of halophytic vegetation. Halophily may independently have arisen multiple times since the evolution of the first land plants (Flowers et al., 2010; Cheeseman, 2015), and exceptionally preserved fossils from the Rhynie Chert suggest that salt-tolerance was already present within some Early Devonian flora (Channing and Edwards, 2009). Almost all modern halophytes (and all of Earth's extant salt marsh flora) are angiosperms (Flowers et al., 2010; Cheeseman, 2015)that have physiological characters that promote sediment accretion– for example, adventitious roots that promote stability, and flexible above-ground plant parts that induce dampening of fluid flow and sediment accretion (Mudd et al., 2010; Moor et al., 2017; Schwarz et al., 2018; Corenblit, 2018). Salt marsh angiosperms also concentrate drainage into tidal creeks and channels, and sustain topography and stratal accumulation on salt marshes (Temmerman et al., 2007; Da Lio et al., 2013).

*Further Information:* Presently, the earliest SSR evidence for salt marshes post-dates the evolution of halophyte angiosperms  (Uličny and Špičáková, 1997; Martinius and Van den Berg, 2011), but further investigation may reveal analogous environments created by earlier halophytic plant life. Interpreting salt marsh sedimentary facies from the rock record can be hindered by issues of equifinality, and is reliant on multiple strands of evidence: dark coloured mudrocks, with a high total organic carbon content, which may yield compacted halophyte leaf litter fossils, rootlets and marine microfossils, and which occur in association with transgressive surfaces (Uličny and Špičáková, 1997). The Late Cretaceous rise of salt marshes appears to mirror that of mangroves (Ellison et al., 1999): however, in that instance there is limited interaction with sediment, so the biogeomorphic environment is primarily recorded by certain mangrove fossil species.

## *4.6. Examples of BIS: Lithologies*

Examples of BIS lithologies (chert) are shown in Figure 12.

### *4.6.1. Chert (non-detrital and non-hydrothermal) and siliceous ooze*

*Stratigraphic Range:* Cherts of all kinds are known throughout the SSR from the Archean, and occur with variable abundance throughout the rest of the Precambrian and Phanerozoic, in part because of strong biological influence on non-detrital and non-hydrothermal cherts(Kidder and Erwin, 2001; Maliva et al., 2005).

*Primary Organisms and Role:* Various silica-biomineralizing organisms. In modern ocean environments, seawater is bereft of dissolved silica principally because of its removal by silica-secreting diatoms, but other silica-biomineralizing taxa include radiolaria, silicoflagellates, sponges and grasses. The biogenic silica produced by these organisms can become deposited as opal, cherts (bedded and nodular), and siliceous mudstones. The spatiotemporal distribution and abundance of non-detrital and non-hydrothermal siliceous marine-deposited sediments throughout the SSR has been perturbed by the evolution of silica biomineralizers (Maliva et al. 1989, 2005; Siever 1992; Kidder and Erwin, 2001).

*Further Information:* Cherts can be either abiogenic or biogenic, so are classed here as a biologically-influenced lithology. Prior to the evolution of the major Phanerozoic silica-secreting groups of organisms, the oceans are predicted to have exhibited much higher levels of dissolved silica, and consequently the Precambrian silica cycle was fundamentally different to that of today (Siever 1992). Pre-Phanerozoic silica-saturated ocean surface waters could become concentrated further in shallow, restricted environments, as is evident in the SSR from the prevalence of diagenetic cherts in ‘sabkha’-like supratidal, peritidal or shallow water environments from this time (Kidder and Erwin 2001). Arguably the first biotically-driven change in the spatiotemporal concentration of siliceous sediments that can be detected in the SSR is roughly coincident with the Ediacaran–Cambrian boundary: the early diagenetic silica that was more abundant in late Proterozoic shallow marine facies largely migrates towards deeper shelf environments during the earliest Palaeozoic. This retreat of shallow-water siliceous deposition has been widely associated with the drawdown of marine silica concentrations following the evolution of siliceous demosponges (Siever 1992; Kidder and Erwin 2001; Butterfield 2003), later followed by the Ordovician radiation of radiolarians.

During the Palaeozoic, radiolarians were the dominant silica-secreting plankton, and a substantial sediment-forming clade in their own right (i.e., radiolarite, a form of biogenic bedded chert composed of radiolarian tests). These were later joined by other silica-secreting phytoplankton forms (e.g., *Dictyochales*) before diatoms became the dominant siliceous plankton during the Cretaceous and Cenozoic. The major Oligocene–Miocene radiation of diatoms is itself closely tied to the expansion of grasslands and the resulting increased silicate weathering on the continents, triggered by the incorporation of opal phytoliths by grasses (Falkowski et al. 2004). The evolution of these major silica biomineralizing clades has left a statistically detectable signal in the SSR which can be split into four phases; 1) Precambrian dominantly abiogenic cherts, deposited primarily in silica-saturated peritidal shallow marine, or hydrothermal, environments; 2) a Cambrian to Ordovician transitional phase, with a mixed distribution (shallow and deep marine) of cherts; 3) Silurian to Cretaceous cherts, where bedded cherts are largely controlled by deposits of radiolarian skeletons and sponges, and abundant nodular cherts form in platform sediments and shallow-water carbonates; 4) a Cenozoic phase largely dominated by deep sea bedded cherts and controlled primarily by diatoms (Maliva et al. 1989). The progressive desaturation of seawater during the Phanerozoic with respect to silica could not have happened in the absence of the evolution of silica biomineralizers. The evolution of these clades not only provided the raw materials for the formation of biogenic siliceous sediments, but also altered the environment of deposition, diagenesis, and the distribution of non-detrital silica deposition.

## ***4.7. Examples of BIS: Materials***

Examples of BIS materials are shown in Figure 13.

### *4.7.1. Pedogenic clay minerals*

*Stratigraphic Range:* Pedogenic clay minerals are present throughout the SSR, but diversify in conjunction with biological evolution (Hazen et al., 2008, 2013).

*Primary Organisms and Role:* While the evolution of life in general, and photosynthesis, are thought to have influenced clay mineral diversity (Hazen et al., 2013), there is limited fossil evidence to demonstrate direct linkages. However, the role of plants and mycorrhizal fungi in expanding the critical zone of chemical weathering (Knoll and James, 1987; Moulton et al., 2000; Pate et al., 2001; Verboom et al., 2010) is thought to explain at least 60 clay minerals that are known today, but which are absent in pre-Silurian strata.

*Further Information:* The diversity of phyllosilicate clay mineral species changes throughout the SSR. Hazen et al. (2013) related stages of clay mineral evolution to ten different stages of Earth evolution, some biological (e.g., the evolution of life), some tectonic (e.g., the initiation of plate tectonics) and some atmospheric (e.g., the Great Oxidation Event). Clay minerals are suspected to have existed on Earth even before the oldest preserved sedimentary rock in the SSR (Hazen et al., 2013), and have thus been a component of pedogenic (soil) successions since the Archean (Figure 13A).

### *4.7.2. Calcrete*

*Stratigraphic Range:* The oldest purportedly pedogenic calcretes have been reported from 2.6 Ga palaeosols from South Africa (Watanabe et al., 2000; Brasier, 2011). They occur throughout the global Precambrian and Phanerozoic SSR, with an increased abundance after the Silurian (Davies and Gibling, 2010a).

*Primary Organisms and Role:* Vascular plants, from the Silurian onwards, and vascular plants with roots and associated mycorrhizal fungi, are thought to have released significant amounts of calcium ions from silicate rocks, promoting calcrete formation (Brasier, 2011). Brasier (2011) suggested that other organisms to play a role include arthropods (e.g., calcified cocoons and fecal pellets), from the Silurian onwards (Esteban and Klappa, 1983), as well as bacteria, algae and fungi, which may have contributed to calcite precipitation in pre-Silurian strata.

*Further Information:* Calcretes are mineral accumulations of calcium carbonate which form at the near-surface of sediment accumulations in non-marine settings (Wright and Tucker, 1991) and precipitate both in soils and from subterranean groundwaters (Brasier, 2011). Oversaturation of groundwater with calcium carbonate is not a wholly biologically-dependent scenario, but it is biologically-influenced. The occurrence of calcretes in the SSR increases dramatically in line with tracheophytic vegetation because of the enhanced chemical weathering of calcium silicates and increased atmosphere-substrate connectivity provided by plant roots (Davies and Gibling, 2010a; Brasier, 2011) (Figure 13B-C).

Plant and microbial bioengineering is also strong contributive factor for other soil duricrusts (e.g., silcretes, ferricretes) in modern semi-arid environments (Verboom and Pate, 2006). Further investigation of such features in the SSR is needed to see if their stratigraphic distribution mirrors that of calcretes.

## *4.8. Examples of BIS: Structures*

Examples of BIS structures are shown in Figure 14.

### *4.8.1. Sole marks*

*Stratigraphic Range:* Sole marks occur in strata as old as the Archean (Figure 14A; e.g., the Witwatersrand Group, South Africa; Beukes, 1996) and are present throughout the rest of the geological time scale, but apparently diminish in abundance after the early Palaeozoic (Figure 14B; Tarhan, 2018).

*Primary Organisms and Role:* Bioturbating organisms reduce the cohesiveness and sediment stability of substrates (de Deckere et al., 2001) and force the amalgamation of surface contacts between sedimentary strata (Tarhan, 2018). Accordingly, the evolution of bioturbation is argued to have reduced the frequency of both the production of sole marks (which require a hydroplastic substrate) and the preservation of sole marks (due to mixing of heterolithic sediments and reduced preservation of bed-junctions) (Tarhan, 2018).

*Further Information:* Sole marks include a variety of tool and prod marks, as well as flute and groove casts created by fluids. Tarhan (2018) compiled a dataset of global reports of such features and showed that they diminished drastically after the Cambrian. This was attributed to the explosion of bioturbating behaviour in the shallow marine realm. However, sole marks continued to be created and preserved throughout the rest of the Phanerozoic, albeit appearing in the SSR with reduced frequency.

#### *4.8.2. Flat-pebble conglomerates*

*Stratigraphic Range:* Palaeoproterozoic flat-pebble conglomerates have been reported from the 1.8 Ga Changcheng System in China (Hofmann and Jinbiao, 1981). Wright and Cherns (2016a) reported that the youngest flat-pebble conglomerate in the SSR is found in the Early Jurassic (Toarcian) of Portugal: Kullberg et al. (2001) ascribed those particular flat-pebble conglomerates to have formed by syn-sedimentary seismic activity and the slumping of incipiently cemented thin carbonate layers.

*Primary Organisms and Role:* Wright and Cherns (2015a,b) attributed the Phanerozoic diminishment of flat-pebble conglomerate abundance to the increasing depth of penetration by evolving burrowing animals, which increased the depth of oxygenation and early carbonate diagenesis. Prior to this, when diagenetic cementation was concentrated into a thin upper layer in shallow marine carbonate sediment, any storm activity would have been likely to exhume flat-pebble clasts from the thin cap of cemented carbonate sediment on the seafloor, providing the means to create flat-pebble conglomerates (Figure 14C).

*Further Information:* Flat-pebble conglomerates are matrix or clast supported conglomerates within carbonate strata that contain tabular-shaped and thin (<20 mm) pebble to cobble sized clasts comprised of fine grainstone to calcimudstone (Myrow et al., 2004). They are most common in late Cambrian and Early Ordovician strata and rare in post-Middle Ordovician strata (Wright and Cherns, 2015a,b). The rare existence of younger flat-pebble conglomerates (i.e., isolated reports from Silurian, Devonian, Triassic and Jurassic rocks) attests that they reflect an instance where the evolution of a certain behavioural repertoire among living organisms made a signature in the SSR less likely. However, as flat-pebble conglomerates may have multiple origins (Myrow et al., 2004), biological evolution did not totally preclude later special scenarios that promoted their generation (e.g., seismic reworking of shallow-cemented carbonates: Kullberg et al., 2001).

Other potential BIS related to carbonate weathering and erosion may also exist. For example, the dissolution of carbonate rocks in modern karst landscapes is strongly contributed to by organic acids and biogenic $CO_2$ (Phillips, 2016a). As such, there may be as yet unrecognised shifts in the frequency of palaeokarst surfaces within the SSR. However, the fact that dissolution can also occur abiotically, and that the stratigraphic range of palaeokarst extends throughout the Precambrian and Phanerozoic (e.g., Cherns, 1982; Kerans and Donaldson, 1988; Vanstone, 1998; Smith et al., 1999), means that such a possibility requires further investigation.

### 4.8.3. *Drip impressions*

*Stratigraphic Range:* The earliest reported occurrence of drip impressions is within late Carboniferous units including the Bashkirian Tynemouth Creek Formation, New Brunswick, Canada (Figure 14D; Davies et al., 2016) and the Kasimovian Stranger Formation, Kansas, USA (Lanier et al., 1993; Buatois et al., 1997).

*Primary Organisms and Role:* Trees are implicit in the earliest known examples (Davies et al., 2016), but earlier elevated drip-nucleating organisms (e.g., large tetrapods) may have left impressions.

*Further Information:* Drip impressions are circular or ovate impact craters with a raised central mound (Twenhofel, 1921), distinguished from rain drop impressions by a lower population density, greater dimensions, and a greater variety of sizes within an individual population. They develop in subaerial settings when water droplets nucleate at an elevated static point source, pinch off due to gravity, and then fall onto an unconsolidated substrate (Figure 14E). Ancient *depositional* sedimentary environments had markedly fewer elevated objects for water to drip from. Modern observations attest that elevated sources of dripping may include features such as overhanging cliff ledges or rocky outcrops, but since such features are erosional aspects of the landscape these have negligible preservation potential in the SSR. It was not until the Devonian evolution of trees and larger animals that elevated objects with potential drip nucleation points appeared within depositional sedimentary environments. The SSR bears evidence for this since the oldest known drip marks, so far reported, occur in Carboniferous strata, suggesting that they may be loosely considered to be a ‘vegetation-induced sedimentary structure’ (sensu Rygel et al., 2004) when witnessed in the SSR. Examples such as this attest to the fact that signatures of life in the SSR are not always directly analogous to life signatures in modern landscapes: at the present day, drip marks may be seen to develop from abiotic or biotic point sources, but when witnessed through the lens of the SSR they can very rarely have abiotic origins.

Related to drip marks, other rare sedimentary structures such as splash marks may also be BIS (Figure 14F). Splash marks record instances where wet sediment has been kicked up by moving animals: such features first require the Cambrian evolution of large tracemakers with the capacity to spend at least short intervals on damp subaerial substrates (MacNaughton et al., 2002).

### *4.9. Examples of BIS: Facies*

Examples of BIS facies are shown in Figure 15.

#### *4.9.1. Alluvial mudrock*

*Stratigraphic Range:* Mudrock occurs as a negligible lithology within alluvial strata from the Palaeoarchean to Cambrian (Figure 15A; McMahon and Davies, 2018b). The earliest alluvial successions to contain greater than 50% mudrock relative to coarser lithologies are latest Silurian (Přídolí) in age (Figure 15B) and occur across Euramerica: the Bloomsburg Formation, New York, USA (Driese et al., 1992), the Clam Bank Formation, Newfoundland, Canada (Quinn et al., 1998), and the Moor Cliffs Formation, Wales (Marriott and Wright, 2004). Similarly muddy units are found worldwide by the earliest Devonian: for example, the Xujiachong Formation, China (Xue et al., 2016).

*Primary Organisms and Role:* Land plants: (a) by promoting the retention of muds in the alluvial realm through above-ground baffling and below-ground stabilization, and (b) by promoting chemical weathering and mud production, in concert with mycorrhizal fungi (Davies et al., 2017; McMahon and Davies, 2018b; Fischer, 2018).

*Further Information:* Mudrocks are siliciclastic sedimentary rocks comprised of grains smaller than 0.063 mm diameter (silt: Ilgen et al., 2017). Alluvial mudrocks are those which achieved final resting, before their interment into the SSR, within continental waterlain deposits, and are rare in pre-vegetation strata (e.g., Long, 2004). Using data from 704 reported Archean-Carboniferous alluvial sedimentary formations, McMahon and Davies (2018b) showed a strong stratigraphic positive correlation between the abundance of mudrock within alluvial facies and the rise and evolution of land plants. The initial onset of this trend appears to occur coevally with the very first record of land plants in the Ordovician, and rises in conjunction with the increasing depth of rooting seen throughout the later Palaeozoic. The existence of alluvial mudrock that pre-dates the oldest land plants demonstrates that land plants did not ‘invent’ alluvial mudrock, but nonetheless, the 1.4 order of magnitude rise in alluvial mudrock abundance in syn-vegetation strata (when compared with alluvium deposited during the preceding 90% of Earth history) attests that land plants played a major role in promoting this environment-specific lithology.

### *4.9.2. ‘Sheet-braided’ alluvium*

*Stratigraphic Range:* Globally common in units older than and including the early Silurian Tuscarora Sandstone, Pennsylvania, USA (Cotter, 1978; Davies et al., 2011), but globally rare in younger strata.

*Primary Organisms and Role*: Land plants colonizing riparian corridors and subsequently inducing an increase in geomorphic complexity and decrease in channel dimensions, leading to a dramatic decrease in the frequency of deposition of sheet-braided alluvium (Davies et al., 2011).

*Further Information*: ‘Sheet-braided’ alluvium is a facies style that refers to alluvial sedimentary successions that are almost uniformly composed of repeated sandstone bodies with an aspect ratio greater than 20:1 (Figure 15C-D; Cotter, 1978; Davies and Gibling, 2010a; Davies et al., 2011; McMahon and Davies, 2018c). The term refers only to rock outcrop architecture and not depositional geomorphology (see McMahon and Davies, 2018c). Early Silurian and older alluvial units are almost always composed (dominantly or entirely) of sandstone beds of width:thickness ratio 20:1 or more (Long, 2004, 2006, 2011, 2018; Davies et al., 2011; McMahon and Davies, 2018c). In contrast, the 'sheet-braided' facies style is anomalous globally in late Silurian and younger alluvium (Davies and Gibling, 2010a; Gibling and Davies, 2012).

### *4.9.3. Fluvial IHS-LA sets*

*Stratigraphic Range:* The earliest reported occurrence of inclined heterolithic stratification – lateral accretion sets (IHS-LA; McMahon and Davies, 2018a) is within the Neoproterozoic Allt-Na-Béiste Member of the Diabaig Formation, Scotland (Figure 15E; Santos and Owen, 2016; McMahon and Davies, 2018a). Globally they are very rare in fluvial strata prior to the latest Silurian, but very common thereafter (Figure 15F).

*Primary Organisms and Role:* Land plants, encouraging small- to medium-sized fluvial channels to adopt a meandering planform through bank stabilization (rooting plus cohesive-sediment retention) (Davies and Gibling, 2010b; McMahon and Davies, 2018a).

*Further Information:* Inclined heterolithic stratification, organised into lateral accretion sets, is a diagnostic facies signature of meandering channels within fluvial facies (although, conversely, not all meandering channels create IHS-LA: Long, 2011; McMahon and Davies, 2018a). In order to form self-sustaining meanders, small–moderate sized river channels require bank stability (Lazarus and Constantine, 2013). While factors such as cohesive sediment or ice could provide such stability on pre-vegetation Earth (Davies and Gibling, 2010a,b), the advent of land plants introduced a new form of biological stability, both directly (through rooting) and indirectly (through retaining/producing cohesive sediment). The SSR contains very few instances of fluvial IHS-LA sets from before the Siluro-Devonian evolution of tracheophyte vegetation, but such facies signatures are extremely common in fluvial facies of the SSR in Devonian and younger strata (Davies and Gibling, 2010b).

## 5. Implications of viewing the SSR as a part-biological construct

The recognition that incremental stages of biosphere evolution in Earth history have acted as unidirectional allogenic sedimentary controls of a higher-order to, and independent of, abiotic controls, should not be controversial, but it is presently under-acknowledged. A greater understanding of the biosphere's role in constructing the SSR will inform predictions regarding a number of topical concerns in Earth Sciences, as follows:

### *5.1. The singularity of Earth amongst known rocky planets*

Rover missions on Mars are increasingly returning information regarding the Martian SSR (e.g., Stein et al., 2018), enabling direct analogy with that of Earth. Under the present null hypothesis that the planet has always been abiotic, Martian sedimentary signatures are assumed to provide useful insights into the range of sedimentary attributes that may be attained in the absence of life (even having been deposited with other variable parameters to Earth; McLennan et al., 2019). Conversely, when considered a target of astrobiological interest, the recognition that equifinality hampers the identification of genuine terrestrial biological signatures indicates that it is extremely unlikely that diagnostic visual geological signals of life will be identified within isolated outcrops of the Martian SSR, such as those so far imaged by rovers (Davies et al., 2018; McMahon et al., 2018; Chan et al., 2019; Corenblit et al., 2019). In the longer term, an improved understanding of those sedimentary traits that can be BIS on Earth, combined with a more refined stratigraphy for Mars and the identification of any unidirectional secular trends in the Martian SSR, will open robust avenues of exploration for ancient life on the planet.

### *5.2. The historical context of the Anthropocene*

The evolution of *Homo sapiens* and their subsequent technological advances has induced a multitude of physico-chemical changes to the Earth surface system, some of which will leave signatures in the future SSR (Waters et al., 2016). Yet from a stratigraphic standpoint, the development of novel materials or an induced shift in the frequency distribution of signatures of the SSR (Waters et al 2016) does not intrinsically distinguish the Anthropocene from earlier intervals of biological innovation (such as those characterised by bioturbation or vegetation; Table 3 [Davies and Gibling, 2010; Williams et al., 2014; Mángano and Buatois, 2017]). Comparable ancient biologically-induced revolutions revealed in the SSR can help to frame and inform Anthropocene debate because they are profoundly rare singularities (typical $>10^8$ year recurrence interval) that often act as irreversible tipping points for Earth surface processes. At the same time, the conflation of the concept of a 'pre-human' world with that of an 'abiotic' one (i.e., considering human activity to be the only biological component of Earth's internal dynamics that is a discrete factor alongside astronomical and geophysical forcings, e.g., Gaffney and Steffen, 2017), should be avoided, because multiple lifeforms were affecting the operation of the Earth system long before human evolution. Further investigation and evidence from the SSR will provide informed predictions for the consequences of anthropogenic accentuation or reversal of previously-emplaced biologically-influenced processes (e.g., deforestation or livestock grazing; Goudie and Viles, 2016; Horton et al., 2017). A refined understanding of the rates and magnitudes of ancient biologically-induced changes will highlight the range and severity of changes to the Earth surface system that have the potential to be inflicted on timescales of critical societal relevance (Kemp et al., 2015).

### *5.3. The timescales of biological evolution*

The recognition of BDS and BIS shifts in the SSR can potentially calibrate evolutionary timescales where uncertainty about these has arisen from a suspected incomplete fossil record. The body fossil record is less complete than the SSR because it is a 'record within a record': its incompleteness arises from discovery biases and taphonomic issues of preservation (Holland 2016), as well as requiring preserved SSR to host it. Conversely, one of the primary reasons that the SSR is time-incomplete at any given locality is that, during intervals of non-deposition or erosion, sediment was being deposited elsewhere on the Earth surface (Runkel et al., 2008; Gani, 2017; Paola et al., 2018; Davies and Shillito, 2018; Davies et al., 2019). Accordingly, if SSR deposition were being affected by life at a given time interval, it is likely that, somewhere, this will have been recorded as an intensive property of its constituent strata. This is especially pertinent for the Phanerozoic SSR because (1) this encompasses the transition from dominantly subsurface to surface biomass (McMahon and Parnell 2018), (2) its fossil record of life is less contentious than in the Precambrian (Brasier, 2009), so before-and-after SSR traits are readily identifiable, (3) at least 30% of ancient global surface area (continental crust) from any one geological period is preserved (Domeier and Torsvik, 2017), and (4) its global rock outcrop volume does not exponentially decrease with increasing age (Ronov et al., 1980; Husson and Peters, 2018), meaning that its internal synchronous increments are broadly comparable.

An example of how this understanding may assist in the calibration of evolutionary timescales is found in the case of total group land plants, which, on the basis of proxy evidence, have been asserted to have originated at a variety of mutually-exclusive dates (see discussion in Boyce and Lee, 2017). Early molecular timetree models suggested at least a Cryogenian origin for land plants (Clarke et al., 2011). More recent improved soft maxima suggest that they originated between the middle Cambrian to Early Ordovician (Morris et al., 2018), whereas chemical weathering proxies have been used to infer a Neoproterozoic origin (Kennedy et al., 2006). Evidence from the SSR suggests that many of these estimated ages are unlikely, because plants have left a variety of sedimentary signatures in the alluvium of the fluvial environments that they inhabited. Abundant Cryogenian to Cambrian alluvial successions exist worldwide yet none contain sedimentary signals associated with younger syn-vegetation strata (Davies and Gibling, 2010a): if plants evolved during this interval they apparently did so impassively within their environment, leaving no record of physical interaction with ancient watercourses (or any palynomorphs). Conversely, evidence from the SSR confidently recognises major facies shifts beginning in the Ordovician (McMahon and Davies, 2018b), which can be explained – through modern analogue (Gurnell, 2014; Mitchell et al., 2016b) – by the evolution of land plants, and which are stratigraphically synchronous with the earliest palynological record (Wellman and Gray, 2000; Edwards et al., 2014). That the SSR provides a synchronous and tangible dual physical record of fossils and strata is its primary strength. In the example of the Ordovician origin of land plants, the SSR-supported null hypothesis is not easily dispelled by molecular timetrees or geochemical proxies, especially as such model-driven and indirect approaches can be compromised, respectively, by unforeseen survivorship biases (Budd and Mann, 2018) and non-unique explanations (geochemical equifinality) (Tosca et al., 2010).

### *5.4. Other speculative implications*

Present day heterogeneity of abiotic surface processes and landforms is known to promote biodiversity (Ward et al., 2002; Antonelli et al., 2018). Selection pressures induced by the evolution of novel surface processes and physical environments could conceivably have functioned as an evolutionary boost to biodiversity (Laland et al., 2017). In this way, BDS and BIS could implicate particular taxa as ecosystem engineers (Jones et al., 1994) over geological timescales (Erwin, 2008). A robust measure of biodiversity through time, when measured against innovations in the SSR, may shed new light on the co-evolution of life and the planet, and potentially reveal instances of ancient sedimentary environments that could be viewed as 'extended phenotypes' (*sensu lato,* Phillips, 2016b) of the fossil organism that inhabited them. In order to assess this, further efforts are needed to unite observations from modern ecological and biogeomorphological studies with long-term geological and palaeontological trends (e.g., Corenblit et al., 2015).

A further, highly speculative, implication may transcend palaeoecological considerations and concern the nature of the SSR itself. The volume of the SSR generally diminishes further back in time, due to accumulated effects of attrition and subduction. However, there is not (as was once modelled), an exponential decrease in sedimentary rock volume: rather, there is a major contrast in the diminished rock volume of the Precambrian relative to the Phanerozoic (Husson and Peters, 2018). Explanations for this have been sought with respect to Neoproterozoic glacial erosion (Keller et al., 2019), but this cannot explain why the volume of Ediacaran strata is comparable with diminished Cryogenian strata, but not more voluminous Cambrian strata. Intriguingly, the shift in rock volume itself seems to correspond with the rapid expansion of biomineralized life (Porter, 2007; Wood et al., 2017; Cai et al., 2019). Here there are open (and possibly intractable) questions: What if the Cambrian increase in the preserved volume of rock is a direct result of life evolution? There is certainly a rapid increase in the proportion of carbonate rock strata at this time (e.g., Peters and Husson, 2018, their Fig. 2) and the sequestration of calcium carbonate onto continental crust, by life, could have marked a shift in the locus of a mineral precipitate that was previously distributed more evenly (i.e., shared with subductable oceanic crust). At the same time, the expansion of rock volume by life-induced interstitial cements or clay minerals, or even the additional volume provided by biogenic detritus itself, may have trapped more strata on continental crust. We strongly emphasise the speculative nature of this particular avenue of thought, but note that the role of life in creating the SSR has so many facets and emergent effects that such a potential explanation should not be considered irrational.

## 6. Conclusions

The SSR is a tangible planetary characteristic that exhibits sequential variability in its lithological character, reflecting its formation, over geological time, in a shared space with the evolving biosphere. It plays a dual role in our understanding of the Earth surface: its nature is both a direct result of, and an historic archive of, the co-evolution of the biosphere and planet through geological time. As it is, at least in part, a residual product of life and life-induced processes, it should no longer be regarded as a passive repository of geochemical and fossil clues to ancient biospheres, but as an integral component of a dynamic archive. Life controls may sometimes be intractable, and their variety of manifestations are not always easily modelled or generalized, but their influence on the signatures of the SSR must be considered at least as consequential as traditionally-invoked controls such as tectonics, climate and sea-level; with all of which they are inseparably intertwined (Dietrich and Perron, 2006; Perron, 2017).

Individually (Table 1) or at outcrop the effects of life may seem esoteric, but cumulatively the geological record proves that they can be profound (Figure 1). As long as the we choose the correct focal length to interrogate the SSR for life signals (Figure 2), there is promise for recognising further trends that will promote new hypotheses and help lead us towards a mechanistic understanding of how Earth has co-evolved with life. Such trends must be expected because ancient alternative Earths, with different biospheres, would have operated under different physical conditions to the present day. Organisms did not change the laws of physics that underpin surface processes such as fluid flow, or fluid-grain interactions, but their successive evolution involved progressive, fundamental and irreversible alterations to the theatre in which these physical processes played out.

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## Figure and Table Captions

Figure 1. Stratigraphic range and shifts in abundance and diversity of selected sedimentary signatures within the SSR, showing correlation with trigger organisms and the earliest unequivocal body fossil remains of total group representatives of such organisms. See main text for details.

Figure 2. Illustrative plots showing the importance of time-length scales in searching for biosphere signatures. A) The different time-length scales at which the SSR can be approached using individual specimens, outcrops, groups of outcrops, or compendia of information from the whole SSR. B) Approximate most common ranges of time-length scales of different Earth surface processes and phenomena in which life plays a role, superimposed on plot from (A), showing how different approaches to the SSR may be more or less suitable for recognising ancient biosphere signatures (modified after Kleinhans et al., 2006). It should be noted that, with the exception of atmospheric evolution, all the illustrated phenomena operate at time-length scales far smaller than that recorded by the whole SSR. As such the whole SSR may additionally be utilized to identify secular trends in holistic

populations of these phenomena (e.g., long term changes in animal bioturbation). Additionally, the crossing of threshold values in some of these process may result in more rapid effects, which could potentially be recognised at a smaller scale (e.g., the catastrophic failure of a reef system, or the tipping point reached after cumulative atmospheric evolution).

Figure 3. Examples of vegetation-induced sedimentary structures resulting from sediment and water diversion around standing sessile plants. A) Recent scour crescent in front of fallen tree, Murchison River, Western Australia. B) Undulose sediment surface armoured by dense stand of *Protolepidodendron*, Middle Devonian (c. 385 Ma) Planteryggen Formation, Munindalen, Svalbard. C) Mudrock-filled hollow (arrowed) overlain by downturned strata, formed by infilling and decay of standing vegetation and subsequent subsidence of overburden sediment, Pennsylvanian (c. 320 Ma) Tynemouth Creek Formation, Gardner Creek, New Brunswick. D) Scour-and-mound bedding (white arrows) surrounding standing *Lepidodendron*, revealed by stigmarian roots (black arrow), Pennsylvanian (c. 320 Ma) Tynemouth Creek Formation, Gardner Creek, New Brunswick. E) Undulose bedding surface with multiple stigmaria and rootlets, showing irregular surface of sediment laid down between stand of trees, Mississippian (c. 330 Ma) Alston Formation, Lindisfarne, Northumberland, England. F) Downturning of beds of Siberian Traps volcanic ash, surrounding charcoalified remains of standing tree (arrowed), Early Triassic (c. 252 Ma) Abinskaya Series, River Tom, Kuznetsk Basin, Russia. Scale bar is 1 metre in A, D, E, F. Scale bar is 10 centimetres in B, C.

Figure 4. Examples showing problem of equifinality in the SSR (see text for full details). 1. Dinosaur footprints (A) in the Early Cretaceous Wealden Group (c. 130 Ma) of southern England are associated with two mud-filled abandoned channels (bases arrowed) indicative of channel avulsion (B).  The former could be a trigger for the latter, but no causality can be recognised at outcrop. 2. Beaver-cut wood accumulations are associated with peat

accumulations in the Pliocene (c. 5 Ma) Beaufort Formation of Arctic Canada, but ascertaining causality between beaver damming and wetland flooding is hindered by underdetermination: (C) beaver-cut woody debris showing chewing mark (arrow), Ellesmere Island; (D) peat accumulation with woody debris, Meighen Island (Davies et al., 2014). 3. Dropstones in the late Permian (c. 255 Ma) Broughton Formation, Wollongong Lighthouse, New South Wales, Australia (E), are associated with glendonites, attesting to their likely glacial origin. However, other means of transmitting cobbles to the marine realm are present – for example, seaweed buoyancy (F, Caol Ila, Islay, Scotland). Scale bar is 1 cm in C. Scale bar is 10 centimetres in A, D, E, F. Scale bar is 1 metre in B.

Figure 5. Conceptual plots showing the shift in frequency distribution of facies signatures in alluvium between pre-vegetation strata (red; Archean to Ordovician) versus syn-vegetation strata (green; Silurian to recent). Horizontal axis shows a quantitative measure of rock formation properties: the measured proportion of any individual alluvial succession that contains the named phenomena (comparable to the ‘quantitative measure of topographic features’ in Dietrich and Perron (2006), their Fig. 5). Vertical axis shows the frequency of occurrence of rock formations worldwide that exhibit the measured traits in the horizontal axis.

Figure 6. Cartoon diagram illustrating the heightened potential for recognising unidirectional shifts, such as signatures pertaining to life evolution, from the SSR. Three rock successions are shown, which accumulated over the same time interval, against a backdrop of two different allogenic influences; one unidirectional (red), one cyclic (blue). Both allogenic influences are assumed to have the potential to leave an indirect but readable signature in the accumulated sediment pile. None of the three successions are time-complete, but are comprised of preserved sediment (dark yellow) at stochastic intervals. In this instance, because the period of cyclic oscillation is at a greater frequency than the

sampling/preservation of sediment, the preserved signals of the cyclic influence will be readable only as a distortion of the true cycle and not easily comparable between the different sections. By contrast, all three successions show a defined off/on shift from the unidirectional influence, despite the fact that none of the successions preserve strata that are precisely contemporaneous with its onset.

Figure 7. Histograms comparing mudrock percentage in worldwide alluvial formations deposited during intervals of orogenic events. A) Formations whose deposition was affected (deposited neighbouring orogeny) and not affected (deposited away from orogeny) by the Grenvillian Orogeny (1100-900 Ma); B) Formations whose deposition was affected and not affected by the Caledonian/Acadian Orogeny (440-390 Ma). Data compiled from a compendium of whole SSR data (available in McMahon and Davies 2018b). While in both instances a tectonic influence can be recognised (because formations deposited adjacent to orogenic uplift contain more mudrock), the heightened abundance of mudrock in all formations deposited after the evolution of land plants (B) implies that the age of deposition relative to the evolution of vegetation is a more significant predictor of alluvial mudrock abundance than proximity to orogenies.

Figure 8. Examples of BDS lithologies. 1. Microbial carbonates: A) Side view of Archean stromatolitic microbial carbonate, Neoarchean (c. 2.6 Ga) Yellowknife Supergroup, Walsh Lake, Northwest Teritories, Canada; B) Plan view of Palaeoproterozoic (c. 1.9 Ga) stromatolitic carbonate, Gunflint Chert, Flint Island, Ontario, Canada; C) Large thrombolite domes in microbial carbonate, late Cambrian (c. 0.5 Ga) Petit Jardin Formation, Flowers Cove, Newfoundland, Canada. 2. Bioclastic carbonates: D) *Cloudina* limestone, late Ediacaran (c. 550 Ma) Nama Group, Namibia; E) Bioclastic limestone containing shelly debris of crinoids, spiriferid and rhynconellid brachiopods, Mississippian (c. 346 Ma) Ballyshannon Limestone Formation, Bundoran, County Donegal, Ireland; F) Bioclastic

limestone of scleractinian corals and bivalves, Pleistocene (c. 0.125 Ma) Wallabi Limestone, East Wallabi Island, Houtman-Albrohos Islands, Western Australia. 3. Coals: G) Vertically-bedded coal seams deposited as overbank facies between fluvial sandstone bodies, late Permian (c. 254 Ma) Kol'chuginskaya Series, Bachat, Kuznetsk Basin, Siberia, Russia; H) Uppermost coal seam preceding the Permian-Triassic extinction and subsequent 'coal gap', late Permian (c. 252 Ma) Bulli Coal, overlain by fluvial sandstones of the latest Permian Eckersley Formation, Clifton, New South Wales, Australia. 4. Chalk: I) Two chalk units, the lower one red in colour, in mid-Cretaceous (Albian-Cenomanian, c. 100 Ma) strata, Hunstanton Red Chalk Formation and Ferriby Chalk Formation, overlying ferruginous oolitic sandstone of the Carstone Formation, Hunstanton, Norfolk, England. Scale bar is 1 centimetre in A, D, E, F. Scale bar is 1 metre in B, C. Scale bar is 10 metres in G, H, I.

Figure 9. Examples of BDS materials. 1. Coprolites. A) Example of suspected earliest known occurrence of micro-coprolites, lower Cambrian (Terreneuvian, c. 529 Ma) Lontova and Voosi Formations, Estonia. B) Flattened mammal fecal pellets, Pliocene (c. 3.5 Ma) Beaufort Formation, Ellesmere Island, Nunavut, Canada. 2. Charcoal. C) Some of the earliest charcoal in the SSR: charcoalified remains of *Pachytheca*, late Silurian (Ludlow, c. 423 Ma) Lower Leintwardine Formation, Stoke Edith, Herefordshire, England. D) Cross-section view of fallen and partly compressed trunk of the giant fungi *Prototaxites*.  Charcoalified trunk is entrained with coarse basal lag sediments in the bottom of a fluvial channel body, Early Devonian (Emsian, c. 400 Ma) Battery Point Formation, Petit Gaspé, Québec, Canada. 3. Plastics. E-F) Examples of different sizes of plastics exhibiting sorting on beaches.  These plastics (and human-cut wood) have been transported substantial distances from human settlement into unpopulated areas of the High Arctic by ocean currents. Wijdefjorden, Svalbard. Scale bar is 0.1 millimetres in A. Scale bar is 1 millimetre in C. Scale bar is 1 centimetre in B. Scale bar is 10 centimetres in D, E. Scale bar is 1 metre in F.

Figure 10. Examples of BDS structures. 1. Burrows. A) Earliest evidence for metazoan locomotion: suspected cnidarian surface trail, Ediacaran (c. 565 Ma) Mistaken Point Formation, Mistaken Point, Newfoundland, Canada. B) Vertical invertebrate burrows (*Skolithos* and *Daedalus*) penetrating multiple beds of shallow marine dune cross-bedded sandstones, Silurian (c. 430 Ma) Tumblagooda Sandstone, Red Bluff, Kalbarri National Park, Western Australia. C) Horizontal network of suspected crustacean burrows (*Thalassinoides*) in marine limestone, Early Jurassic (c. 180 Ma) Beacon Limestone Formation, Eype, Dorset, England. D) Cross-sectional view of vertebrate burrow consisting of tunnel (black arrow) leading to terminal chamber (white arrow), probably made by a rhyncosaur, Middle Triassic (c. 240 Ma) Otter Sandstone Formation, Sidmouth, Devon, England. 2. Coral reefs. E) Cross-section view of coral and algal bioherms within coral reef, late Silurian (c. 420 Ma) Barlow Inlet Formation, Cornwallis Island, Nunavut, Canada; F) Reef knoll limestone with bedding of coral reef apron illustrated, Mississippian (c. 330 Ma) Low Limestones Formation, Chrome Hill, Derbyshire, England. 3. Roots. G) Putative root like structures, exhibiting downwards branching and penetrating for up to 3 cm within palaeosol, latest Silurian (c. 420 Ma) Silverband Formation, Lake Bellfield, Victoria, Australia. H) Stigmarian lycopsid rhizome showing rootlets, Mississippian (c. 330 Ma) Alston Formation, Lindisfarne, Northumberland, England. 4. Trample-grounds. I) Brittle and ductile soft-sediment deformation penetrating through heterolithic strata (yellow box) as a result of focussed trampling, most likely by a large sauropod dinosaur, Early Cretaceous (c. 120 Ma) Vectis Formation, Cowleaze Chine, Isle of Wight, England. Scale bar is 1 centimetre in A, G. Scale bar is 10 centimetres in C, E, H. Scale bar is 1 metre in B, D, F, I.

Figure 11. Example of fixed-channel alluvial style associated with anastomosing river facies, showing diagnostic criteria and contrast with braided river facies (after Davies and Gibling,

2011). Pennsylvanian-Permian (c. 298 Ma) Cutler Group, Mesa Montosa, New Mexico, United States.

Figure 12. Examples of abiogenic and biogenic cherts. A) Abiogenic cherty grainstones interbedded within a banded iron formation: chert precipitated due to silica-saturated waters. Palaeoproterozoic (c. 1.88 Ga) Ironwood Iron Formation, Mount Whittlesey, Wisconsin, United States. B-C) Cycles of biogenic chert, probably representing precipitation during local hiatuses in sedimentation, within chalk (rich in siliceous demosponge spicules, most notably *Rhaxella*). The “wood-grain” texture shown probably relates to fluctuating concentrations of silica-rich pore fluids and changing rates of precipitation (Maliva et al., 1999). Late Jurassic (c. 150 Ma) Portland Chert Member, Portland Bill, Dorset, England. Scale bar is 10 centimetres in A, C. Scale bar is 1 metre in B.

Figure 13. Examples of BIS materials. Pedogenic clay minerals and calcrete. A) Nodular calcrete forming vertic features within pedogenic clay-rich palaeosol, formed coevally with the early evolution of tracheophytes, late Silurian (Přídolí, c. 420 Ma) Moor Cliffs Formation, Rook’s Cave, Pembrokeshire, Wales. B) Calcretized rhizoliths along layer that also yields recognisable stigmarian root structures, late Pennsylvanian (c. 300 Ma) Fountain Formation, Manitou Springs, Colorado, United States. C) Micritic calcrete forming pinnacles due to the exposure of large rhizoliths, Pleistocene (c. 0.5 Ma) Tamala Limestone, Nambung National Park, Western Australia. Scale bar is 1 metre in all images.

Figure 14. Examples of BIS structures. 1. Sole marks. A) Sole marks on base of turbidite sandstone deposited before evolution of bioturbation, Neoarchean (c. 2.6 Ga) Burwash Formation, Yellowknife, Northwest Territories, Canada. B) Sole marks on base of lacustrine turbidite sandstone, deposited contemporaneously with the evolution of deep lake burrowing, Pennsylvanian (c. 315 Ma) Bude Formation, Maer Cliff, Cornwall, England. 2. Flat pebble

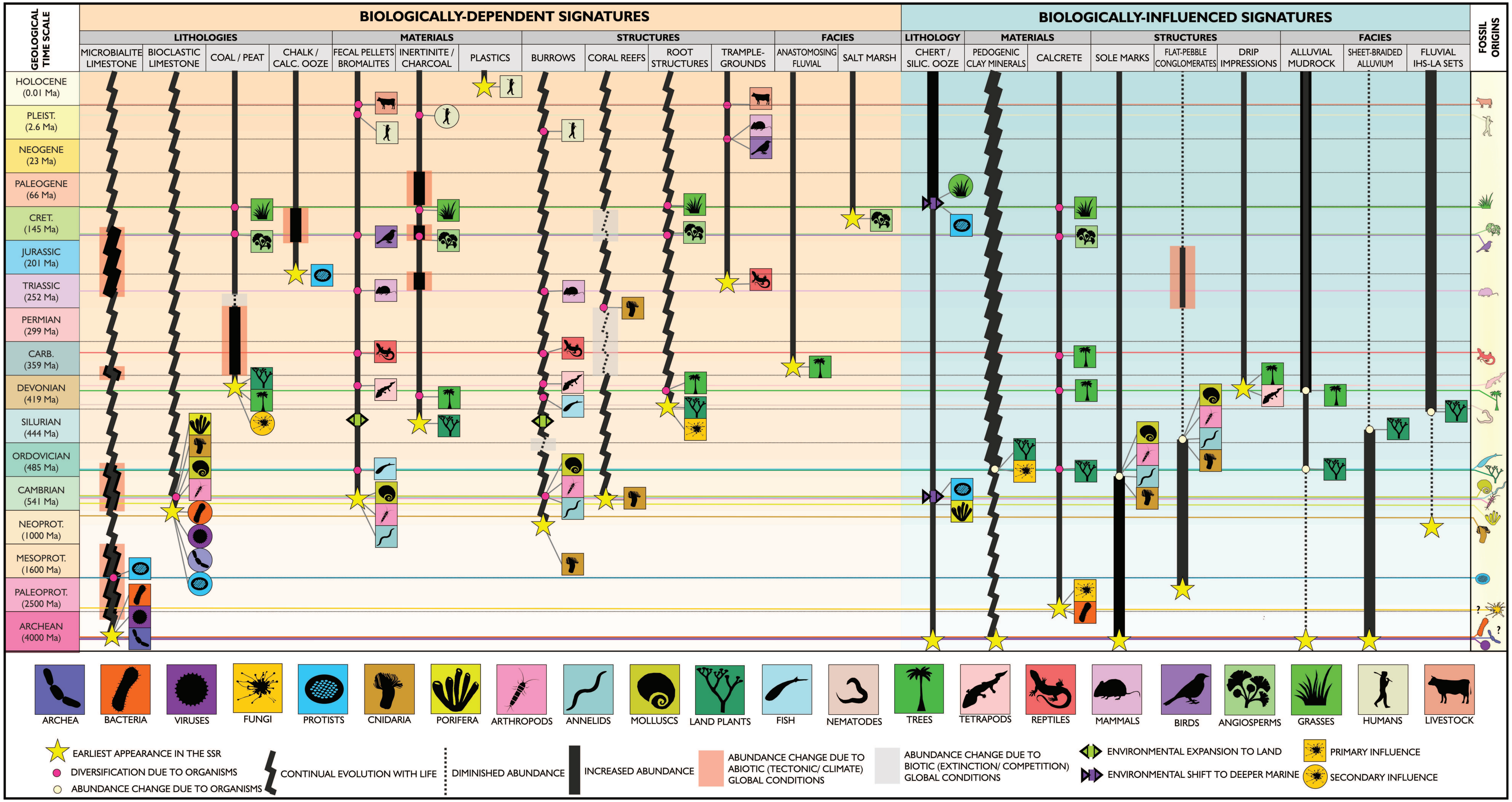
conglomerate. C) Flat pebble conglomerate within dolomite, Cryogenian (c. 720 Ma) Lossit Limestone Formation, Beannan Buidhe, Islay, Scotland. D) Flat pebble conglomerate within limestone, Middle Cambrian (c. 500 Ma) Cow Head Group, Beachy Cove, Newfoundland, Canada. 3. Drip impressions and splash marks. E) Casts of drip impressions in abandoned fluvial channel facies, seen in association with cordaitalean frond debris, Pennsylvanian (c. 320 Ma) Tynemouth Creek Formation, New Brunswick, Canada. F) Elongate splash marks (black arrows) resulting from the displacement of damp sand as an arthropod tracemaker traversed a wet subaerial substrate (seen in conjunction with other arthropod trackways; white arrows), Silurian (c. 430 Ma) Tumblagooda Sandstone, Z-Bend, Kalbarri National Park, Western Australia. Scale bar is 1 metre in A, B. Scale bar is 10 centimetres in D, F. Scale bar is 5 centimetres inC. Scale bar is 1 cm in E.

Figure 15. Examples of BIS facies. 1. Alluvial mudrock. A) Single thin mudrock layer (arrowed; c. 15 cm) within 200 metre succession of alluvial sandstones, early Cambrian (c. 540 Ma) Fréhel Formation, Cap du Chevre, Brittany, France. B) Dominance of alluvial mudrock relative to crevasse splay sandstones in syn-vegetation alluvium, Pennsylvanian (c. 300 Ma) Sangre de Cristo Formation, Durango, Colorado, United States. 2. ‘Sheet-braided’ alluvium. C) Archetypal ‘sheet braided’ alluvium, Neoproterozoic (c. 1 Ga) Applecross Formation, Cape Wrath, Scotland. D) Detail of ‘sheet-braided’ alluvium, Ediacaran-Cambrian (c. 541 Ma) Series Rouge, Pleherel, Brittany, France. 3. IHS-LA sets. E) Oldest known example of IHS-LA sets (yellow box), recording 41 cm deep sinuous creek draining into lake, Neoproterozoic (c. 1 Ga) Diabaig Formation, Diabaig, Scotland. F) Large scale LA-IHS with internal erosion surface (yellow box), recording deposition within tidally-influenced meandering point bar. Late Cretaceous (c. 80 Ma) Horseshoe Canyon Formation, Willow Creek, Alberta, Canada. Scale bar is 1 metre in A, B, D, E. Scale bar is 10 metres in C, F.

Table 1 – Table showing examples of influences of modern organisms to sediments, geomorphology and Earth surface processes.

Table 2 – Examples of the earliest fossil evidence for the life triggers shown in Figure 1.

Table 3 – Comparison of the potential effects, recordable as sedimentary signatures, of three of the most significant life influences on the properties of the SSR; bioturbation, vegetation and humans.


BIOLOGICALLY-DEPENDENT SIGNATURES
BIOLOGICALLY-INFLUENCED SIGNATURES
GEOLOGICAL TIME SCALE
LITHOLOGIES
MATERIALS
STRUCTURES
FACIES
LITHOLOGY
MATERIALS
STRUCTURES
FACIES
FOSSIL ORIGINS
MICROBIALITE LIMESTONE
BIOCLASTIC LIMESTONE
COAL / PEAT
CHALK / CALC. OOZE
FECAL PELLETS BROMALITES
INERTINITE / CHARCOAL
PLASTICS
BURROWS
CORAL REEFS
ROOT STRUCTURES
TRAMPLE-GROUNDS
ANASTOMOSING FLUVIAL
SALT MARSH
CHERT / SILIC. OOZE
PEDOGENIC CLAY MINERALS
CALCRETE
SOLE MARKS
FLAT-PEBBLE CONGLOMERATES
DRIP IMPRESSIONS
ALLUVIAL MUDROCK
SHEET-BRAIDED ALLUVIUM
FLUVIAL IHS-LA SETS
HOLOCENE (0.01 Ma)
PLEIST. (2.6 Ma)
NEOGENE (23 Ma)
PALEOGENE (66 Ma)
CRET. (145 Ma)
JURASSIC (201 Ma)
TRIASSIC (252 Ma)
PERMIAN (299 Ma)
CARB. (359 Ma)
DEVONIAN (419 Ma)
SILURIAN (444 Ma)
ORDOVICIAN (485 Ma)
CAMBRIAN (541 Ma)
NEOPROT. (1000 Ma)
MESOPROT. (1600 Ma)
PALEOPROT. (2500 Ma)
ARCHEAN (4000 Ma)
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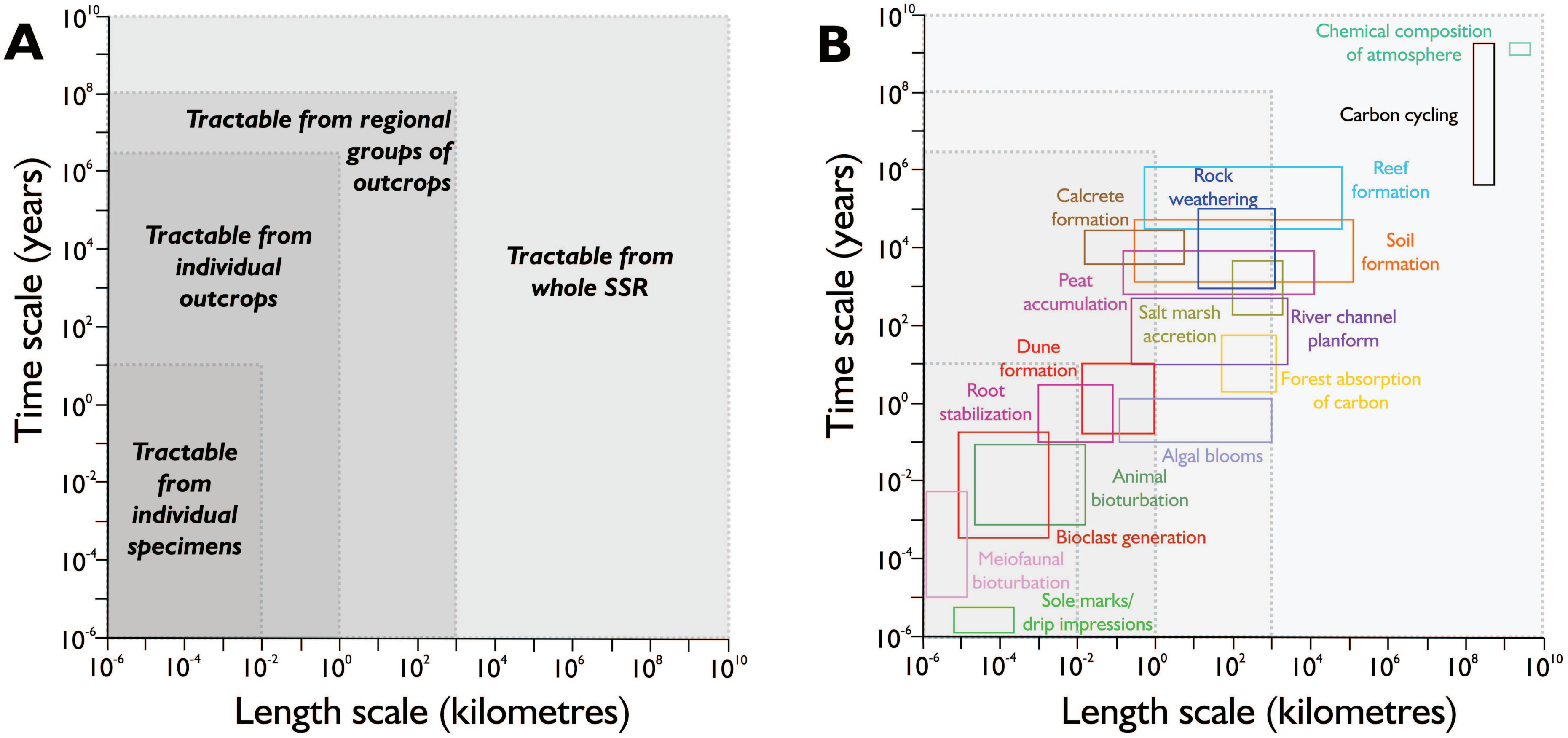
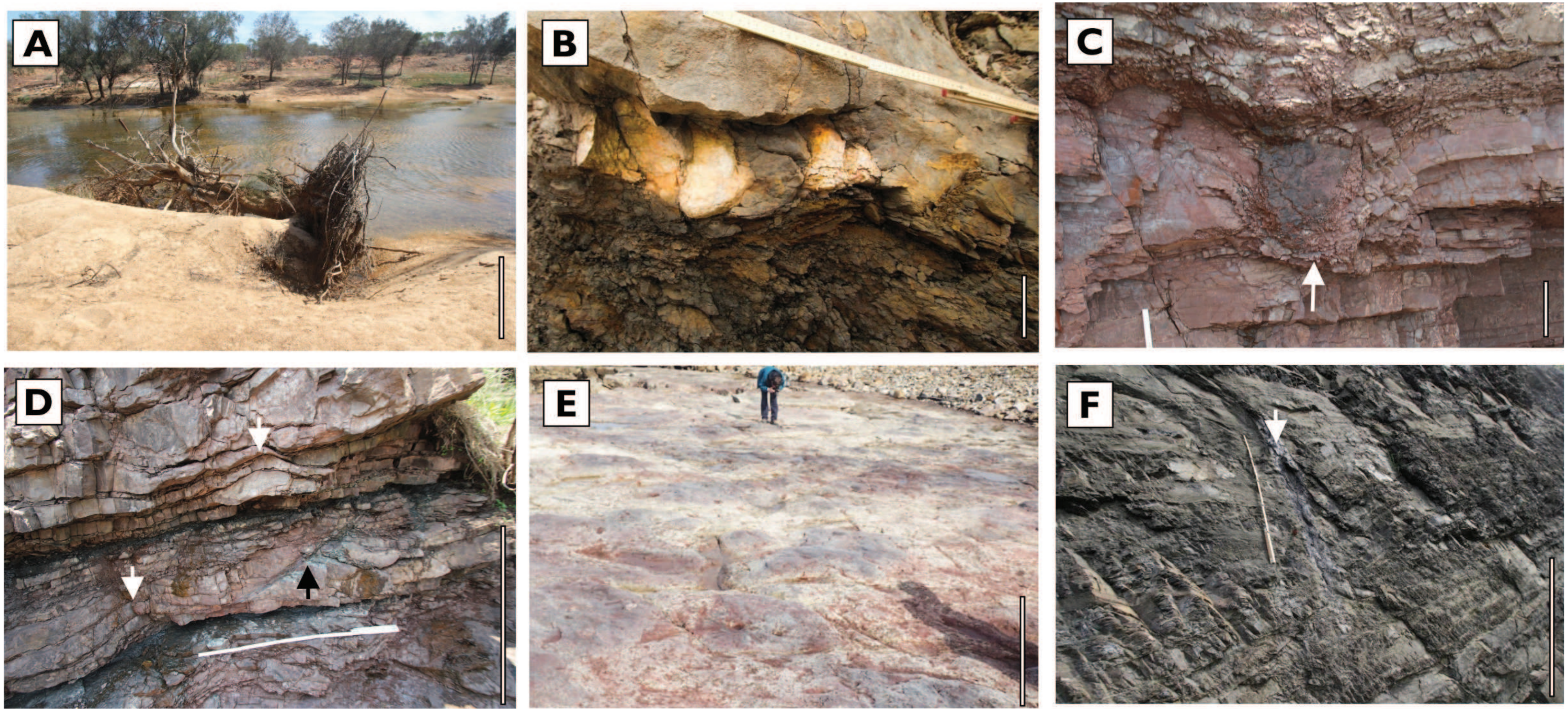
ARCHEA
BACTERIA
VIRUSES
FUNGI
PROTISTS
CNIDARIA
PORIFERA
ARTHROPODS
ANNELIDS
MOLLUSCS
LAND PLANTS
FISH
NEMATODES
TREES
TETRAPODS
REPTILES
MAMMALS
BIRDS
ANGIOSPERMS
GRASSES
HUMANS
LIVESTOCK
EARLIEST APPEARANCE IN THE SSR
DIVERSIFICATION DUE TO ORGANISMS
ABUNDANCE CHANGE DUE TO ORGANISMS
CONTINUAL EVOLUTION WITH LIFE
DIMINISHED ABUNDANCE
INCREASED ABUNDANCE
ABUNDANCE CHANGE DUE TO ABIOTIC (TECTONIC/ CLIMATE) GLOBAL CONDITIONS
ABUNDANCE CHANGE DUE TO BIOTIC (EXTINCTION/ COMPETITION) GLOBAL CONDITIONS
ENVIRONMENTAL EXPANSION TO LAND
ENVIRONMENTAL SHIFT TO DEEPER MARINE
PRIMARY INFLUENCE
SECONDARY INFLUENCE


A
Time scale (years)
Length scale (kilometres)
10^10
10^8
10^6
10^4
10^2
10^0
10^-2
10^-4
10^-6
Tractable from regional groups of outcrops
Tractable from individual outcrops
Tractable from individual specimens
Tractable from whole SSR
B
Time scale (years)
Length scale (kilometres)
Chemical composition of atmosphere
Carbon cycling
Reef formation
Rock weathering
Calcrete formation
Soil formation
Peat accumulation
Salt marsh accretion
River channel planform
Dune formation
Forest absorption of carbon
Root stabilization
Algal blooms
Animal bioturbation
Bioclast generation
Meiofaunal bioturbation
Sole marks/ drip impressions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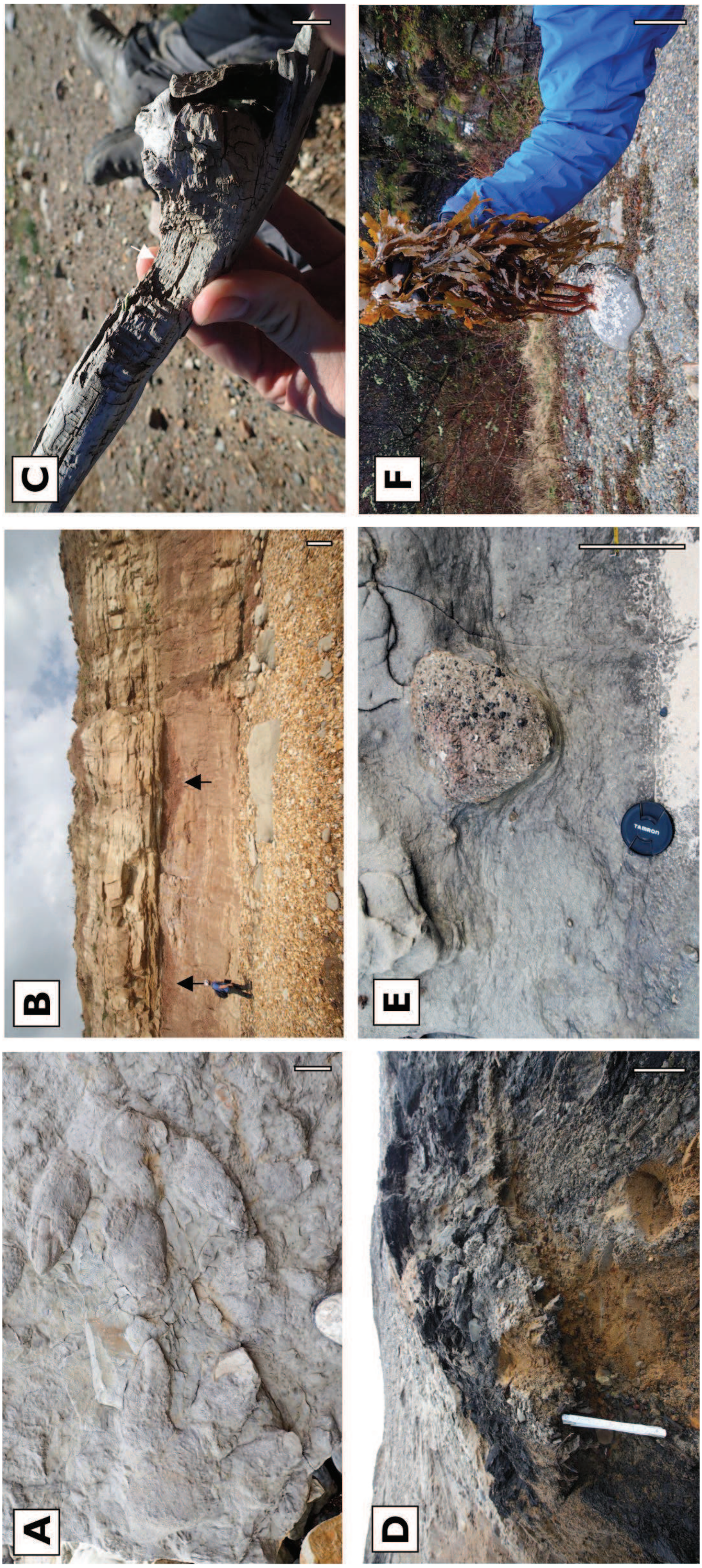
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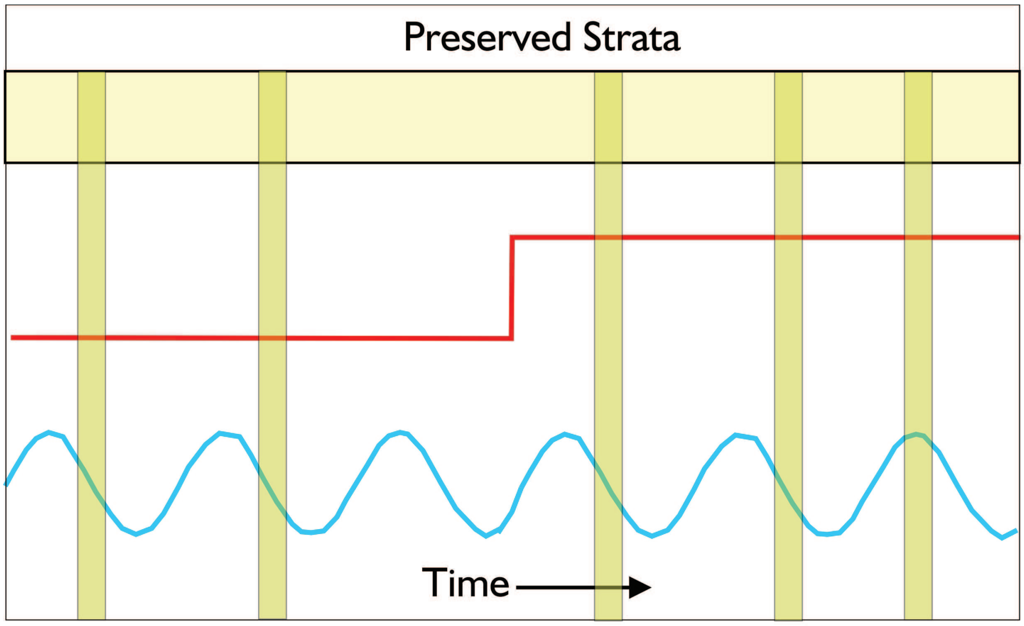
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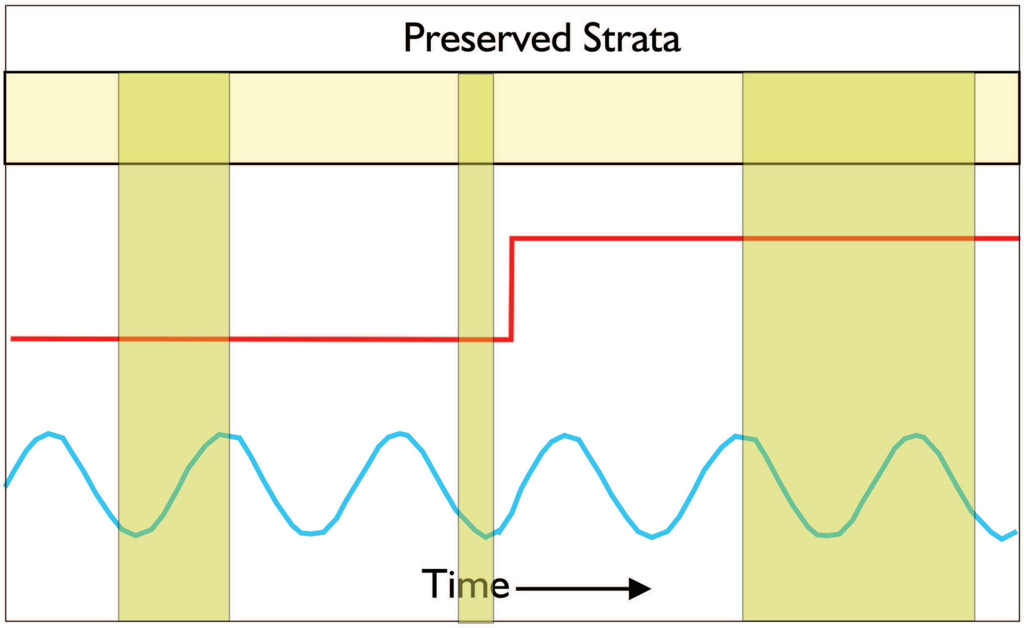
Time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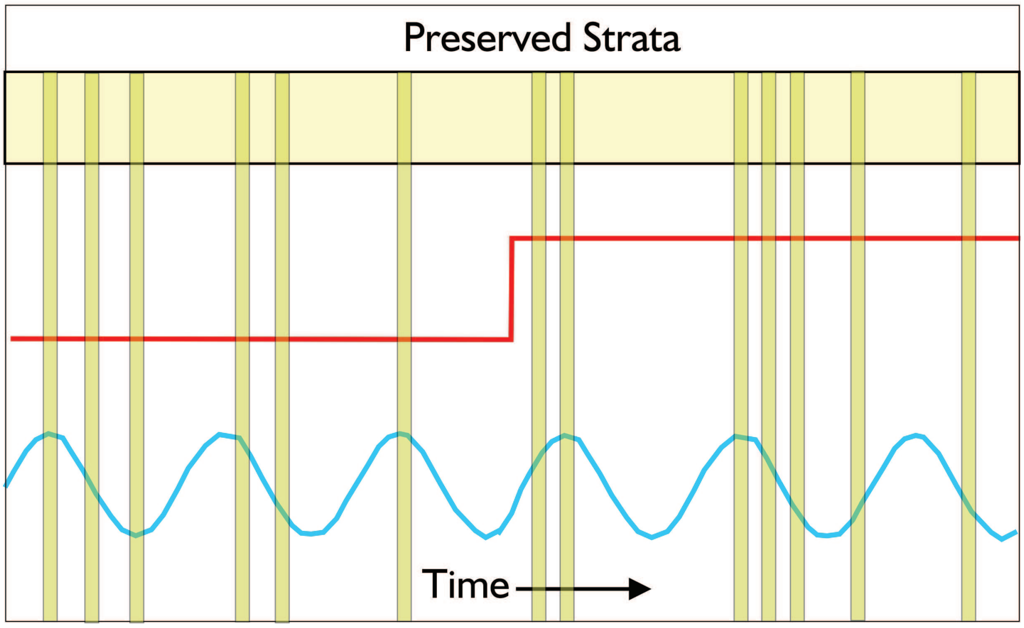
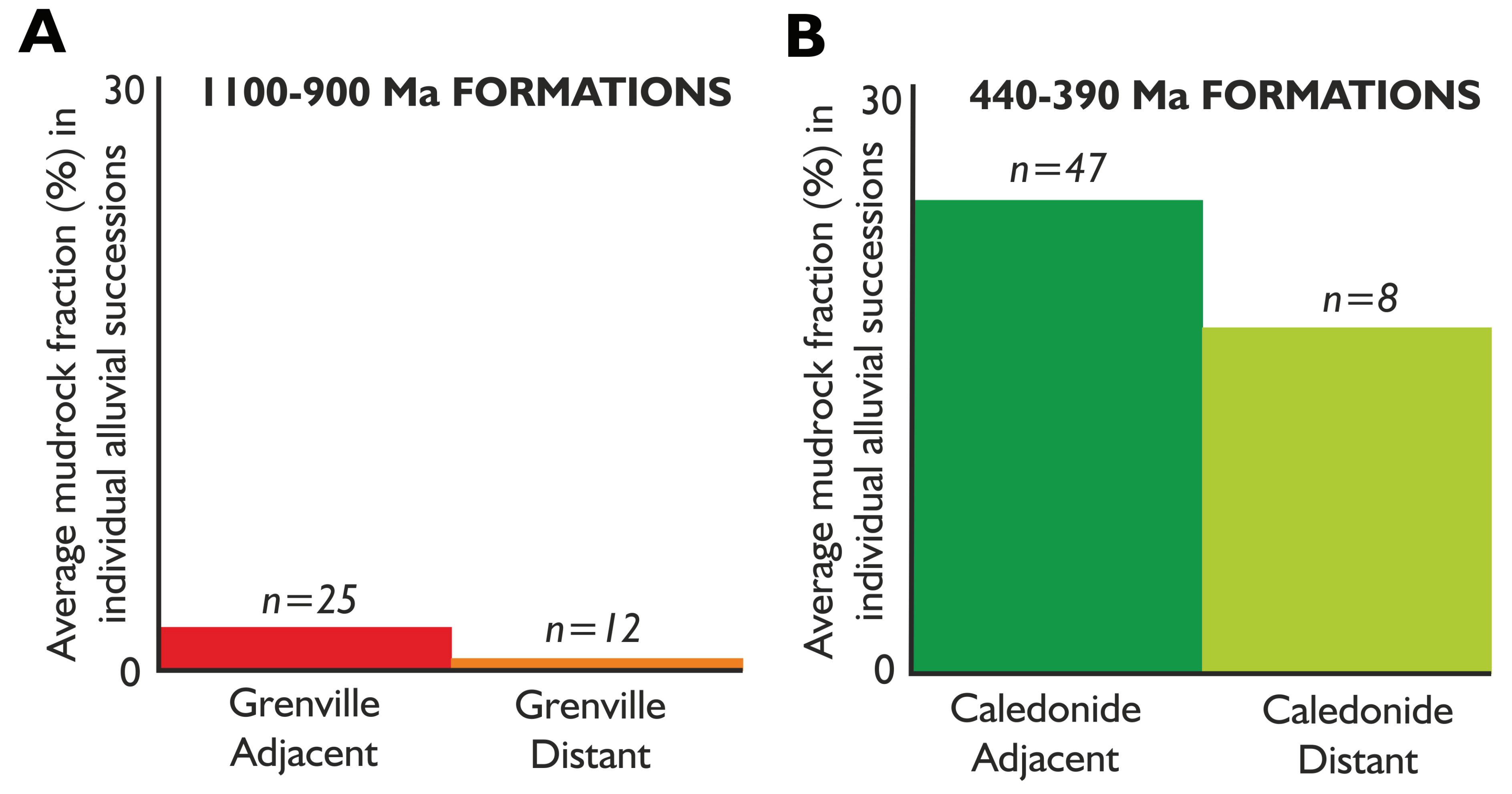

Preserved Strata
Time


A
1100-900 Ma FORMATIONS
Average mudrock fraction (%) in individual alluvial successions
30
0
n=25
n=12
Grenville Adjacent
Grenville Distant
B
440-390 Ma FORMATIONS
Average mudrock fraction (%) in individual alluvial successions
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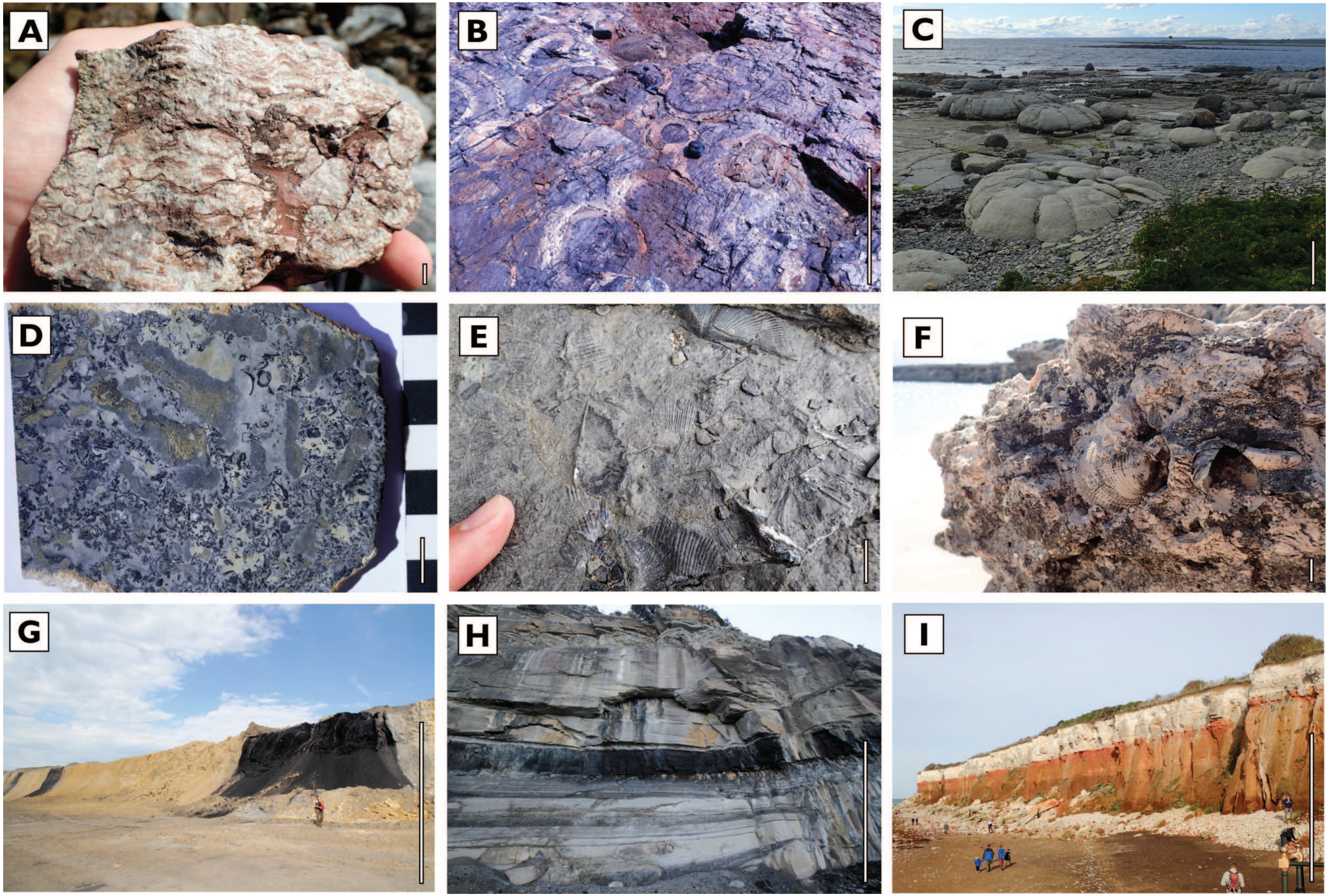
0
n=47
n=8
Caledonide Adjacent
Caledonide Distant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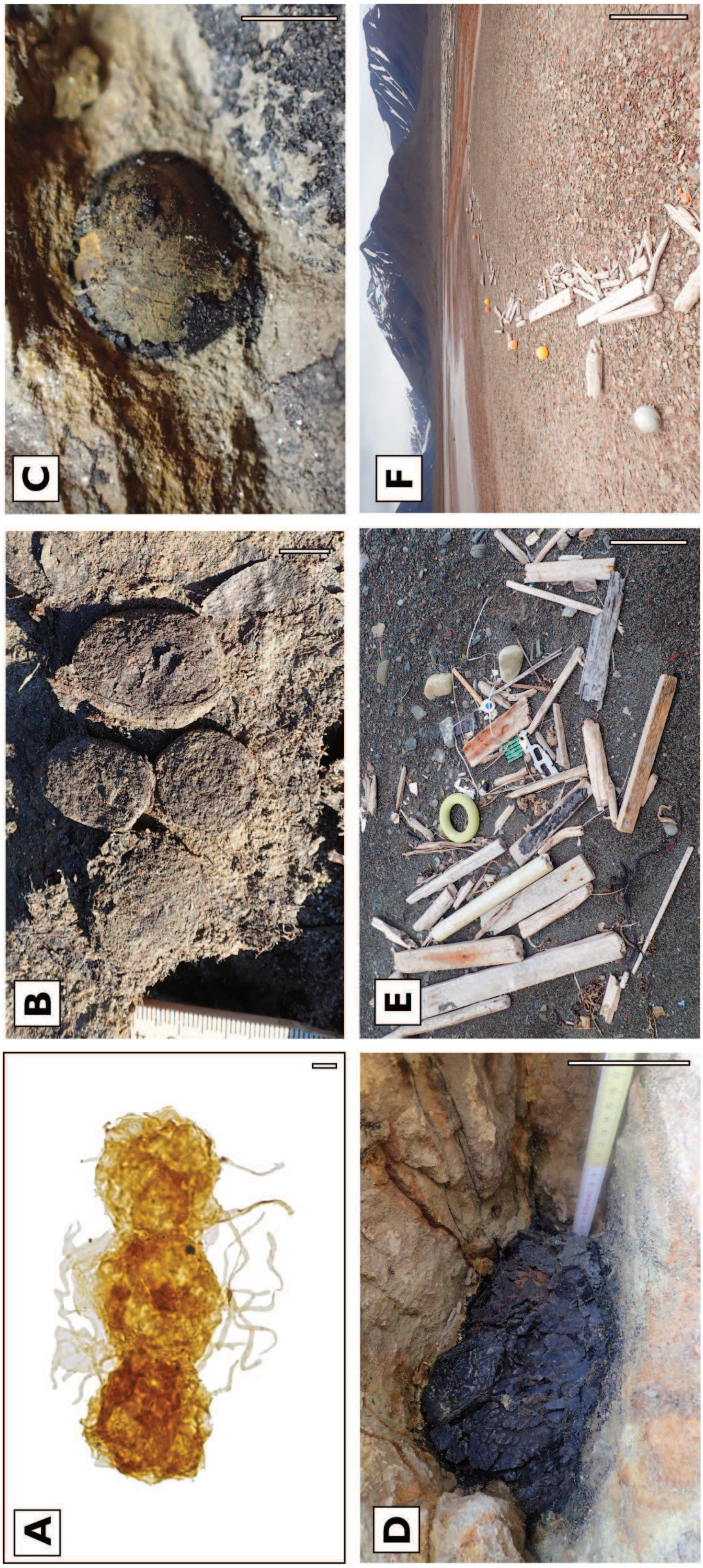
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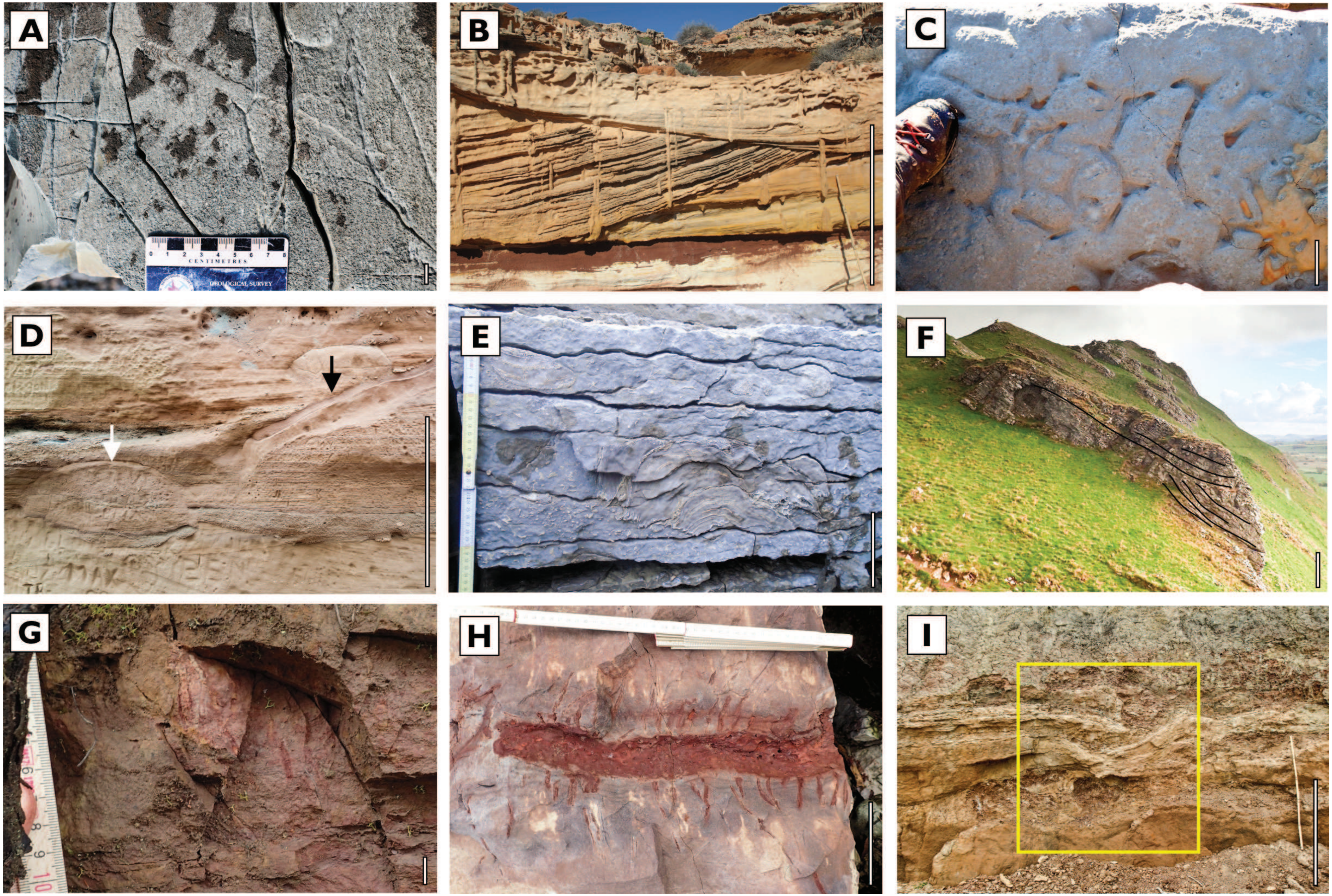
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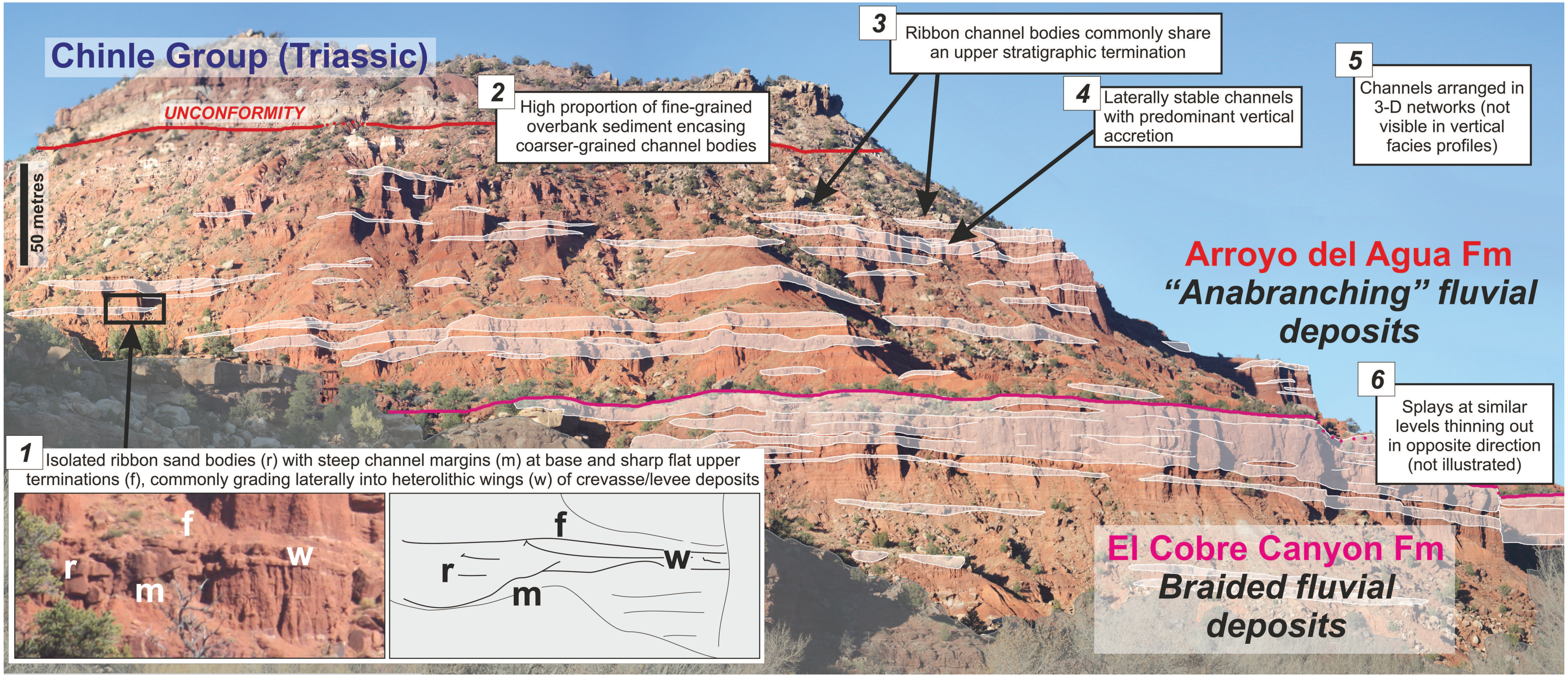


1 Isolated ribbon sand bodies (r) with steep channel margins (m) at base and sharp flat upper terminations (f), commonly grading laterally into heterolithic wings (w) of crevasse/levee deposits

2 High proportion of fine-grained overbank sediment encasing coarser-grained channel bodies

3 Ribbon channel bodies commonly share an upper stratigraphic termination

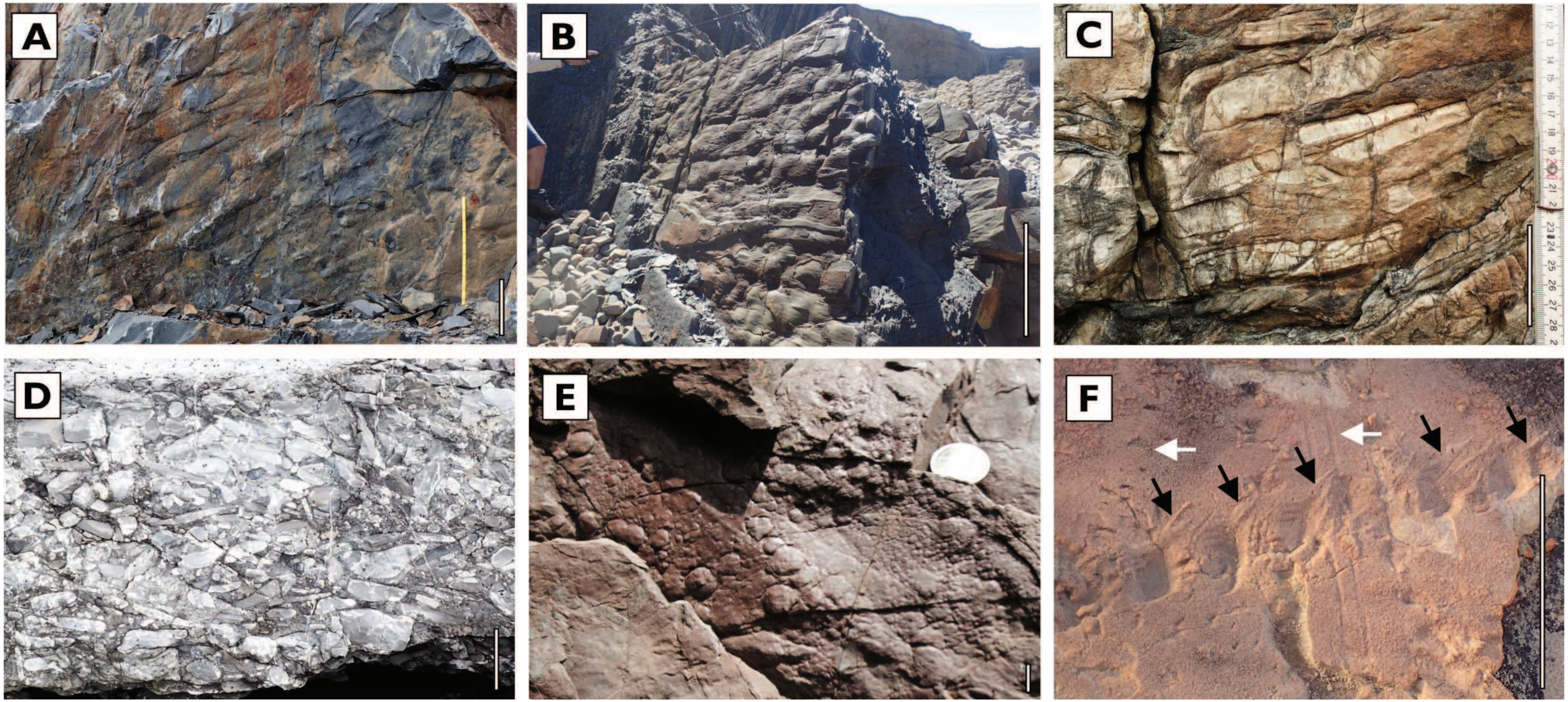
4 Laterally stable channels with predominant vertical accretion

5 Channels arranged in 3-D networks (not visible in vertical facies profiles)

6 Splays at similar levels thinning out in opposite direction (not illustrated)


A
B
C


A
B
C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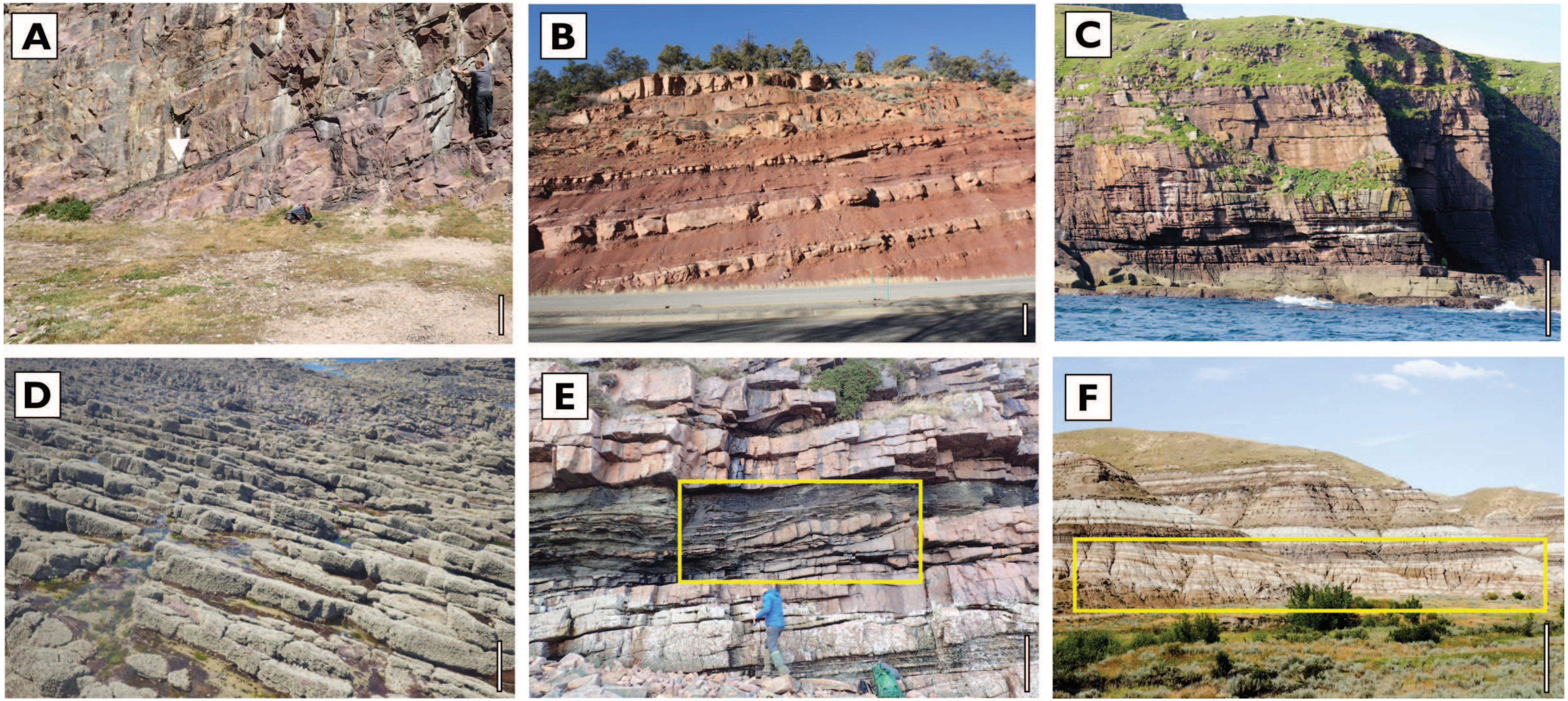
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