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Interflag sandstone laminae, a novel sedimentary structure, with implications for Ediacaran paleoenvironments

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ABSTRACT

Interflag sandstone laminae are thin, silty to sandy, layers between thicker sandstone beds, and a new name for sedimentary structures recently called “shims”, and “microbial mat sandwiches”, from Ediacaran fossil localities of Nilpena, South Australia. They have been regarded as structures unique to Precambrian marine environments, but both the age and environmental associations are reinterpreted in this study. Interflag sandstone laminae from Eocene (Wasatch Formation, Colorado, U.S.A.) and Pennsylvanian (Mansfield Formation, Indiana, U.S.A.) fluvial levees and scroll bars were studied in the field, and by means of petrographic thin sections and granulometry. Climbing translatent ripples and distinct grain size distributions are evidence that interflag sandstone laminae were eolian, whereas intervening flagstones were deposited by fluvial traction currents. Other evidences of exposure to wind include microbial earth textures, shallow cracking structures, zibars, setulfs, root traces, and insect trackways. Other evidences of flagstone deposition in traction currents include intraformational claystone breccias, oscillation and current ripples, and microbial mat textures. Similarly distinct beds can be seen in modern sandy river levees, such as the Murchison River of Western Australia and Green River of Utah (U.S.A.). These observations reveal that interflag laminae are created by exposure and wind-drift, but flagstones are produced by floods. Quartzose flagstones of demonstrable marine origin, with fossil brachiopods and trilobites, have also been examined, but lack interflag sandstone laminae. Interflag sandstone laminae are evidence of alternating flood and wind, only known from fluvial environments, and are further support for the idea that Ediacaran vendobionts from South and central Australia, and Namibia lived on land.

1. Introduction

Sedimentary structures have been known for a long time (Allen, 1963; Middleton, 1965), so it is a surprise when a new kind of sedimentary structure is recognized, such as hummocky stratification (Dott and Bourgeois, 1982). Thus it was notable when yet another novel sedimentary structure was documented from the Ediacaran fossil locality of Nilpena in South Australia (Fig. 1) by Tarhan et al. (2017a). This structure is a strongly bimodal distribution of bed size: thick flagstones alternating with thin laminae. Tarhan et al. (2017a) called the lamina a “shim”, which is an engineering wedge used to adjust alignment of the overall structure. A shim is something inserted, so not appropriate for the alternating sedimentary bed sequence, so it is here termed “interflag sandstone lamina”. This new term comes from a classical bed thickness classification (McKee and Weir, 1953) of lamina (3–10 mm thick) versus flagstone or flaggy bedding (1–5 cm thick). Flagstone facies are widely recognized and quarried for paving stones (Donovan and Foster, 1972; Knight, 1994; Wignall and Best, 2004). What is unusual and distinctive about interflag sandstone laminae is the alternation of beds of very different thickness, texture, and color. Interflag sandstone laminae are generally lighter in color and finer in grain size than interbedded flagstones, and so appear similar to sheets of white paper between books bound in brown and red (Fig. 2A, B).

Tarhan et al. (2017a) also called these structures “microbial mat sandwiches” and “anactualistic sedimentary features”, because they considered them created by marine matgrounds unique to rocks older than the Cambrian Explosion of burrowing marine invertebrates. This paper documents a wider distribution in time and space for interflag sandstone laminae, and for various microbial fabrics (Schieber et al., 2007), microbially induced sedimentary structures (MISS of Noffke, 2010), or textured organic surfaces (TOS of Gehling and Droser, 2009). Microbial trace fossils and body fossils are clues to the nature of interflag sandstone laminae, and both are described here in terms of available ichnotaxonomy (Maples and Archer, 1987; Buatois and Mángano, 1993; Retallack, 2009a, 2011, 2012b, 2013; Knaust, 2015; Getty and Bush, 2017; Stimson et al., 2017), as well as by informal schemes such as “old elephant skin”(Gehling and Droser, 2009).

Interflag sandstone laminae are a distinctive sedimentary structure relevant to ongoing debate concerning whether enigmatic Ediacaran

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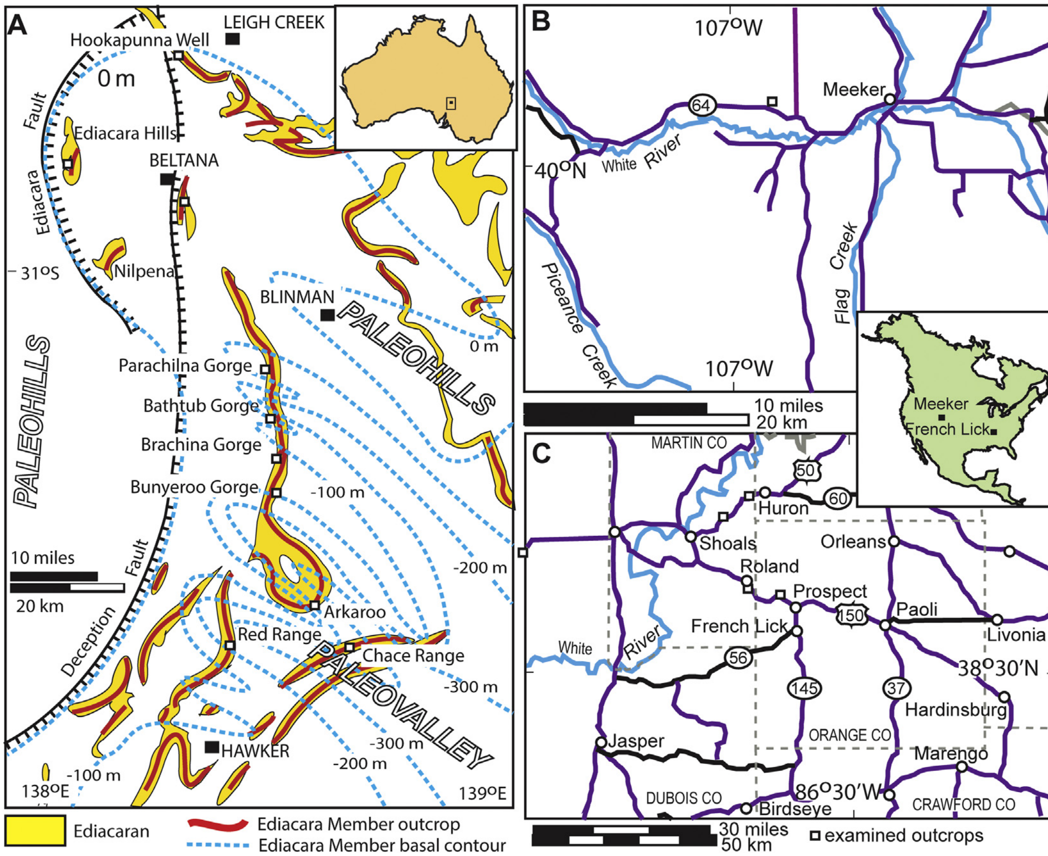

Fig. 1. Study locations in South Australia, Indiana and Colorado, U.S.A. Basal contours on the Ediacara Member define paleovalleys into the Gawler Craton source area to the west.

vendobiont fossils in interflag sandstone laminae are marine (Tarhan et al., 2015, 2016; Coutts et al., 2016) or terrestrial (Retallack, 2013, 2016a, 2016b, 2016c, 2017a). Field observations and measurements of the structures are combined with laboratory measurements of granulometry, and sizes of associated body and trace fossils to determine processes in their formation. Also included are observations of

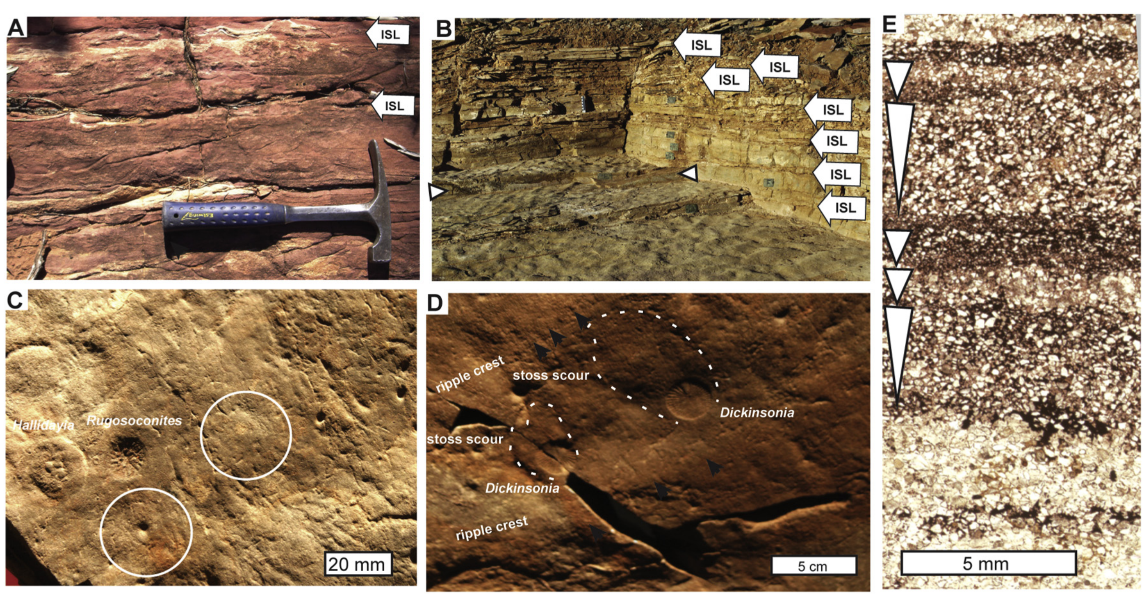

Fig. 2. Sedimentary structures in the Ediacara Member of the Rawnsley Quartzite in the Flinders Ranges, South Australia: (A–B), interflag sandstone laminae (ISL at arrows) in Bunyeroo Gorge (A) and Nilpena (B); (C), *Rivularites repertus* (old-elephant skin) showing sutured radial growth, crack fills and ridge impressions, effaced discoid fossils (white circles) and fossil impressions (*Hallidaya brueri* in positive relief to left, and *Rugoconites enigmaticus* in negative relief to right), on sole of sandstone slab from Crisp Gorge on display in South Australian Museum: (D), another area of slab from Crisp Gorge (above), showing fossil *Dickinsonia costata* with stoss scours, and ripples with linear scours (arrows); (E), coarsening-upward laminae in thin section scan of bedding above *Dickinsonia* fossil from Brachina Gorge (Condon Collection University of Oregon specimen R3223). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Table 1
Quartzose interflag sandstone laminae with trace fossils, plants, or vendobionts.

Formation	Age	Example taxon	Locality	UO loc.#	Coordinates
Wasatch Formation	Eocene	*Rugalichnus matthewii*	Meeker, Colorado	15783	N40.01544° W108.09080°
Dakota Formation	Cretaceous	*Araliopsoides cretacea*	Hoisington, Kansas	11664	N38.489071° E98.781912°
Mansfield Formation	Pennsylvanian	*Sphenophyllum angustifolium*	Huron, Indiana	15848	N38.71474° W86.53519°
Mansfield Formation	Pennsylvanian	*Rugalichnus matthewii*	Shoals, Indiana	15849	N38.68686° W86.73728°
Mansfield Formation	Pennsylvanian	*Rivularites repertus*	Roland, Indiana	15852	N38.59440° W86.68204°
Mansfield Formation	Pennsylvanian	*Treptichnus bifurcus*	Prospect, Indiana	15851	N38.59234° W86.64565°
Panther Mountain Form.	Devonian	*Haskinsia collophylla*	Summit, New York	15585	N42.60370° W74.56910°
Tumblagooda Sandstone	Silurian	*Daedalus archimedes*	Kalbarri, Western Australia	12497	S27.81570° E114.49106°
Grindstone Range Sandst.	Ordovician	*Farghera robusta*	Grindstone Range, S. Australia	12378	S31.253906° E138.97847°
Aar Member	Ediacaran	*Ernietta plateauensis*	Ernietta Hill, Namibia	15763	S26.758576° E16.466028°
Kliphoek Member	Ediacaran	*Rangea schneiderhoehni*	Aarhausen, Namibia	15756	S26.720574° E16.535195°
Kanies Member	Ediacaran	*Ernietta plateauensis*	Pockenbank, Namibia	15765	S27.47481° E16.693521°
Ediacara Member	Ediacaran	*Medusinites mawsoni*	Brachina Gorge, S. Australia	2810	S31.344718° E138.55722°
Arumbera Formation	Ediacaran	*Arumberia banksi*	Alice Springs, N. Territory	13168	S23.79483° E133.689947°
Central Mt. Stuart Beds	Ediacaran	*Arumberia banksi*	Central Mt. Stuart, N. Territory	15634	S21.9352° E133.4362°

Note: Numbers in the UO loc.# column are locality numbers in the Condon Collection, Museum of Natural and Cultural History, University of Oregon.

comparable sedimentary structures on modern fluvial levees as a guide to the distinct sedimentary processes that can produce alternating laminae and contrasting flagstones.

2. Materials and methods

This paper documents additional examples of interflag sandstone laminae in the Flinders Ranges of South Australia, as well as two especially well understood Phanerozoic examples from the Early Pennsylvanian, Mansfield Formation of southern Indiana, U.S.A., and from the early Eocene, Wasatch Formation of central Colorado, U.S.A. Field observations are also included of interflag sandstone laminae from a variety of other localities (Table 1), and shallow marine flagstone sequences that lack interflag sandstone laminae (Table 2). Thin sections were prepared from the Australian, Indiana, and Colorado examples. Granulometric distributions were compiled from long axis of 1000 grains measured in petrographic thin sections of both the interflag lamina and flagstone. These measurements were used to construct grain size histograms, and cumulative size distributions like those of Retallack (2008, 2012a). The intriguing suggestion of a correlation between maximum fossil size compared with both flagstone and interflag sandstone lamina thickness as a feature of the originally recognized interflag sandstone laminae (Tarhan et al., 2017a) was also examined at each of the four Indiana fossil localities (Table 1). Measurements were made in the field of the largest fossil at each of the four localities, and a representative set of 46 specimens of trace and other fossil samples (F120914–7, F121715–35, F121737–42) are catalogued in the Condon Collection of the Museum of Natural and Cultural History of the University of Oregon (online portal is at paleo.uoregon.edu).

3. Ediacaran of South Australia

3.1. Background

Interflag sandstone laminae are especially striking in quarries in the late Ediacaran, Ediacara Member of the Rawnsley Quartzite on Nilpena Station (Figs. 1, 2B), near Parachilna, South Australia (Tarhan et al., 2015, 2017a), but are widespread in the Ediacara Member throughout the Flinders Ranges (Fig. 2A). Tarhan et al. (2017a, p. 181) have itemized a suite of properties based on the Nilpena quarries useful for their wider recognition: "(1) extremely thin (sub-mm- to mm-scale) bed thickness; (2) lateral discontinuity; (3) textural uniformity, including lack of disparity in grain size, between adjacent beds; (4) lack of amalgamation; (5) lack of erosional bed junctions; (6) doubly rippled bedforms defined by rippled bed tops and bases which crisply cast the tops of underlying rippled beds; (7) ubiquity of textured organic surfaces (TOS); (8) positive correlation between body fossil size and abundance and bed thickness; and (9) texturally immature assemblages of sandstone rip-up clasts along bed tops." Criterion 3 was imprecisely determined and variable. As noted by Tarhan et al. (2017a, p. 185), "Grain size was determined through field observation…Of the 113 adjoining bed-pairs in this section for which grain size could be confidently determined for each bed, 53% were characterized by grain size homogeneity." Thin section and granulometric data presented here shows that some South Australian Ediacaran interflag laminae are finer grained than the enclosing flagstones. Criterion 8 is also problematic for definition of a sedimentary structure, because it requires extensive collections of fossils.

Table 2
Flaggy quartz sandstones indisputably marine (with *Cloudina*, trilobites, brachiopods, or ammonites), but lacking interflag laminae.

Formation	Age	Example taxon	Locality	UO loc.#	Coordinates
Grave Creek beds	Cretaceous	*Cyclothyris densleoni*	Placer, Oregon	12138	N42.646728° W123.21077°
Osburger Gulch Member	Cretaceous	*Canadoceras mysticum*	Ashland, Oregon	15697	N42.16372° W122.6538°
Snapper Point Formation	Permian	*Notospirifer hillae*	Point Upright, NSW	10629	S35.638678° E150.321529°
Lambie Quartzite	Devonian	*Cyrtospirifer inermis*	Tallator, NSW	10394	S34.081737° E150.132778°
Oriskany Sandstone	Devonian	*Acrospirifer murchisoni*	Wardensville, West Virginia	11774	N39.064698° W78.661705°
Crotty Quartzite	Silurian	*Camarotoechia synchoneua*	Queenstown, Tasmania	10617	S42.080151° E145.54946°
Tuscarora Sandstone	Silurian	*Arthrophycus allegheniensis*	Milroy, Pennsylvania	11558	N40.736329° W77.634019°
Second Bani Formation	Ordovician	*Destombesia abbesina*	Alnif, Morocco	15602	N31.04298° W5.15628°
Taddrist Formation	Ordovician	*Drabovia redux*	Zagora, Morocco	15592	N30.50873° W5.98045°
Pacoota Sandstone	Cambrian	*Rusophycus lata*	Ellery Creek, N. Territory	15645	S23.81012° E133.06506°
Gypsy Quartzite	Cambrian	*Kutorgina cingulata*	Addy, Washington	11397	N48.352514° W117.842668°
Ladoga Svita	Cambrian	*Obolus convexus*	Lava River, Russia	10963	N59.917019° E31.649609°
Spitzkopf Member	Ediacaran	*Streptichnus narbonnei*	Swartpunt, Namibia	15768	S27.476854° E16.69589°
Aar member	Ediacaran	*Beltanelliformis brunsae*	Aar farm, Namibia	15757	S26.701320° E16.476220°

Note: Numbers in the UO loc.# column are locality numbers in the Condon Collection, Museum of Natural and Cultural History, University of Oregon.

3.2. Field observations

Interflag sandstone laminae are associated with a distinctive suite of other sedimentary structures, which give clues to their paleoenvironment. Especially common with interflag sandstone laminae at Nilpena are symmetrical ripple marks of the kind called oscillation ripples (Tarhan et al., 2015), but others are short-wavelength, asymmetric current ripples, and both kinds are sometimes dissected by shallow scours at a high angle to the crest (Fig. 2D). Sometimes the interflag sandstone lamina itself is rippled (Tarhan et al., 2017a, their fig. 3A), but the laminae also mantle prior ripples, with greatest thickness in the ripple troughs (Tarhan et al., 2015, their fig. 3A). The sandstone laminae are non-adhesive, and separate easily on planes with a variety of unskeletonized fossils and microbially induced sedimentary structures (Tarhan et al., 2017a).

Other current structures associated with sandstone laminae are scours where sediment has been eroded around sessile fossils of *Dickinsonia* (small ridge in bed bottom of Fig. 2D). Strong unidirectional currents are also indicated by stalks of fossils which appear current aligned and partially pulled out of attachment to the surface (Tarhan et al., 2010). *Dickinsonia* fossils may have edges rolled over by currents as if they were pliable, or whole crescents ripped off as if they were brittle, and these currents also were unidirectional because many on the same slab are severed by currents from the same direction (Evans et al., 2015). *Dickinsonia* was thus a low obstacle, attached to the substrate by a force that exceeded internal body cohesion (Retallack, 2017b).

Mounded beds of the Ediacara Member have been regarded as hummocky stratification (Gehling, 2000; Tarhan et al., 2015), but are problematic for the following reasons. At Nilpena levels F and J of Figs. 2B and 3A are isolated bedforms only 4–6 cm high, with marginal reactivation surfaces, unlike the original hummocky stratification, which are uneroded cosets meters thick and many meters wide (Dott and Bourgeois, 1982). Hummocky stratification was subsequently recognized in a variety of sizes (Swift et al., 1983; Martel and Gibling, 1993), but none as small as the Nilpena structures. These are similar to megaripples (Boersma et al., 1968; Swift et al., 1983) and antidunes (Conaghan, 1980; Rust and Gibling, 1990). Another putative example of hummocky stratification from the Red Range (Gehling, 2000, his fig. 10d) has a conspicuous internal reactivation surface and coarsening-upwards laminae, like a zibar (Nielson and Kocurek, 1986; Chakraborty, 1991; Trewin, 1993; Biswas, 2005). Similar coarsening-upwards layers have been widely recognized in the Ediacara Member in the Flinders Ranges to the east of Nilpena (Fig. 2E).

3.3. Granulometry

Both Ediacaran and Cambrian red beds of South Australia show grain size and textural differences between interflag sandstone laminae and associated flagstones (Retallack, 2008, 2012a). Some interflag sandstone laminae are inverse graded, and separate along ferruginized planes (Fig. 2E), but others are rippled and normally graded, and separated by thin, red, clayey seams (Fig. 3A). Ediacaran sandstone laminae have mean and standard deviation of grain size 4.1 ± 1.3 phi respectively, and median grain size is 3.9 phi, whereas the flagstone mean and standard deviation are 2.2 ± 0.9 phi and median grain size is 2.1 phi (Retallack, 2012a). With these standard deviations, Ediacaran interflag laminae are moderately well sorted, but the flagstone beds are well sorted. Grains are subangular to angular in the laminae, but subrounded to rounded in the flagstones (Fig. 2E).

3.4. Microbial, plant and animal traces

At Nilpena, both interflag sandstone laminae and their associated flagstones preserve a variety of soft-bodied fossils and microbial trace fossils. The body fossils are mainly extinct vendobionts such as *Dickinsonia* (Evans et al., 2015; Coutts et al., 2016), which show increasing size in proportion to the thickness of the bed (Tarhan et al., 2017a).

Both flagstones and interflag laminae also have markings known as microbially induced sedimentary structures (MISS of Noffke, 2010), or textured organic surfaces (TOS of Gehling and Droser, 2009). A precise characterization of these structures is provided by names, diagnoses and holotypes of ichnotaxonomic classification (Retallack, 2009a, 2009b, 2009c, 2011, 2012b, 2013). The most common microbial ichnotaxon throughout the Flinders Ranges is complexly cracked-healed and ridged structures (*Rivularites repertus* Fliche, 1906), also informally known as “old elephant skin” (Fig. 2C).

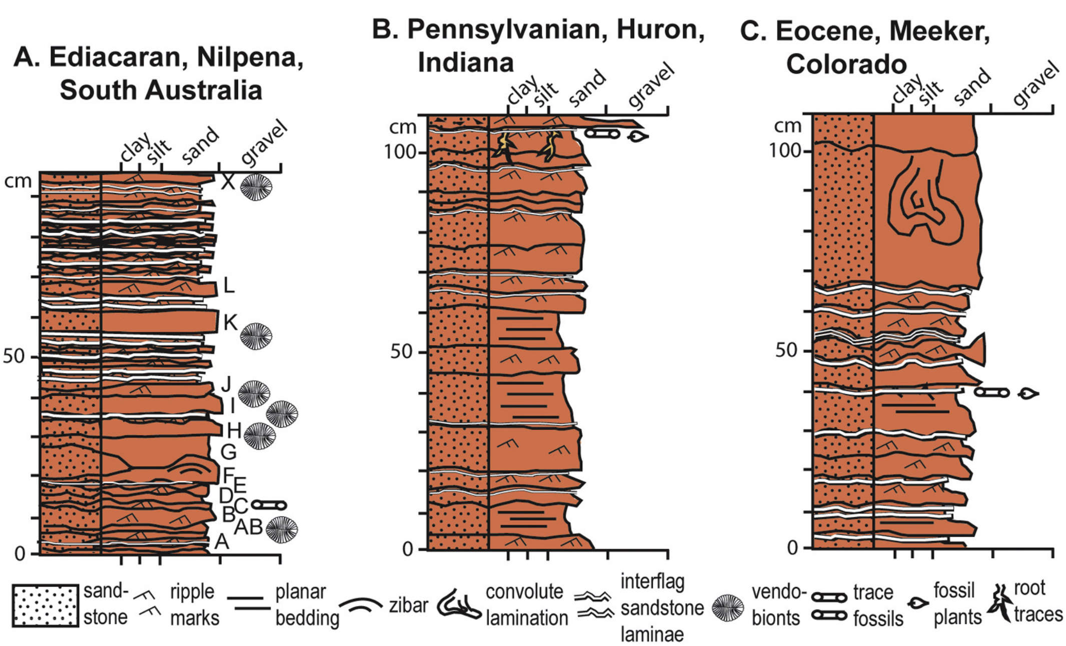

Fig. 3. Detailed measured sections with interflag sandstone laminae (white) alternating with red sandstone flagstones from South Australia, Indiana, and Colorado. Section A from Nilpena is redrafted from Tarhan et al. (2017a). Each section includes strongly bimodal beds: red-brown, sandy, flagstones (1–5 cm or thicker) alternating with white-gray, sandy-silty, non-erosive, unamalgamated interflag laminae (3–10 mm). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.5. Interpretation of the Ediacara Member

Five sedimentary facies have traditionally been recognized in the Ediacara Member (Fig. 4), but their interpretation has been controversial concerning whether they were marine or non-marine (Table 3). For example, the massive sandstone facies has been interpreted as mass-flow sands in a submarine canyon fill (Gehling and Droser, 2013), or as deposits of upper flow regime in a braided fluvial channel (Retallack, 2013), like comparable facies in the Triassic Hawkesbury Sandstone and modern Brahmaputra River (Conaghan, 1980). Nevertheless, the traditional five facies are recognized here with the following minor exception, of white sandstone facies rather than original "white concretionary sandstone facies" (Gehling, 2000). Later thin section studies have failed to show concentrically layered concretions, and found only internally massive nodules or sand crystal rosettes ("desert roses" Retallack, 2012a, 2013).

Paleosols of five distinct types in the Ediacara Member indicate intermittent exposure (Table 3; Fig. 4A–E). Paleosols with desert roses, for example, are unlike limpid evaporite crystals of marine or lacustrine beds, in which crystallization displaces saturated sandy and shaley matrix (Ziegenbalg et al., 2010). These paleosols have also been confirmed by petrographic evidence of mineral weathering within profiles, chemical tau analysis, isotopically light and highly correlated $\delta^{18}O$ and $\delta^{13}C$ of carbonate nodules, and high Ge/Si ratios (Retallack, 2012a, 2013, 2016b, 2017a).

Although the Nilpena flagstones continue to be interpreted as marine (Tarhan et al., 2016, 2017a; Reid et al., 2018), this is paleogeographically problematic. The Nilpena localities are at the head of paleovalleys (Fig. 1A), 20 km west onto the emergent Gawler Craton from the main belt of Ediacara Member outcrops with paleosols (Fig. 4A–E) in the Flinders Ranges (Retallack, 2012a, 2013; Tarhan et al., 2015). Nilpena was thus 60 km inland from the Ediacaran shoreline, as shown in the paleogeographic restoration of Jenkins et al. (1983).

Most sedimentary structures and facies in the Ediacara Member are ambiguous as to marine or non-marine paleoenvironments (Table 3), including oscillation ripples (Reineck and Singh, 1973; Dingler and Clifton, 1984), and putative hummocky stratification (Dott and Bourgeois, 1982; Martel and Gibling, 1993). Wind dissection of ripples are erosional features, but setulfs in the lee of obstacles (Sarkar et al., 2011) and zibars

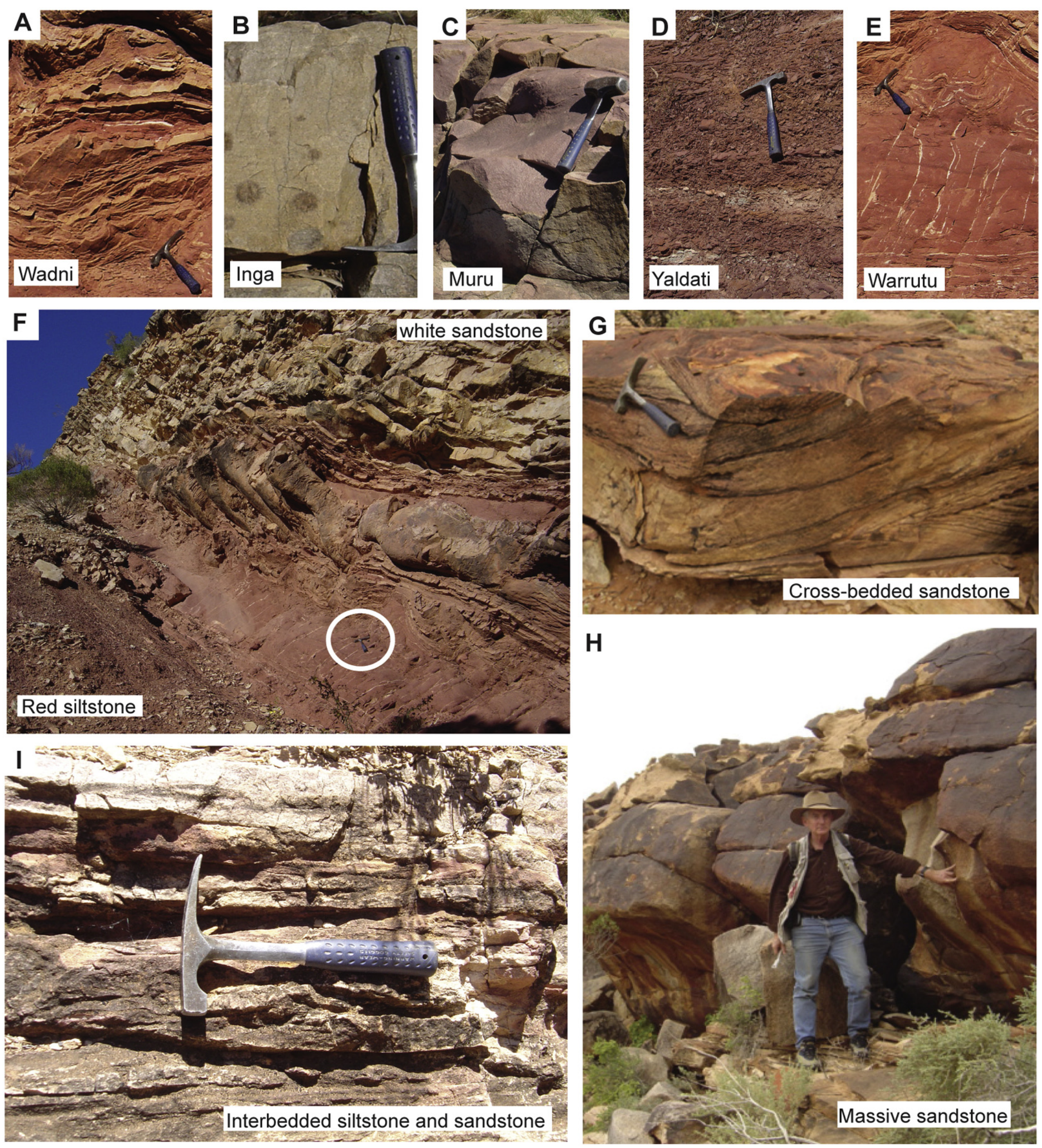

Fig. 4. Five different kinds of paleosols (A–E) and five sedimentary facies (F–I) in the Ediacara Member of the Rawnsley Quartzite, Flinders Ranges, South Australia (Table 3). Localities are Brachina Gorge (A–F), Ediacara Hills (G–H) and Bathtub Gorge (I). Waterlain and eolian interpretations are based on granulometry (Fig. 6).

Table 3
Description and alternative interpretations of sedimentary facies in the Ediacara Member of the Rawnsley Quartzite, in South Australia.

Facies description (Gehling, 2000)	Marine interpretation (Gehling and Droser, 2013, Reid et al., 2018)	Non-marine interpretation (Retallack, 2012a)	Paleosols (Retallack, 2012a, 2013)
Red laminated siltstone and fine-grained sandstone	Delta front sands	Silty floodplain with caliche	Wadni (Fluvent), Yaldati (Calcid) Warrutu (Anhyturbel)
White concretionary and cross-bedded sandstone	Subtidal shoreface sands	Sandy floodplain with desert roses	Muru (Gypsid), Inga (Gypsid), Wadni (Fluvent)
Interbedded siltstone and fossil-bearing sandstone (+**interflag sandstone laminae**)	Subtidal wave-base sands	Fluvial levee	Wadni (Fluvent)
Channelized cross bedded sandstone	Sheet-flow sands of submarine canyon fill	Lower flow regime fluvial channel	No paleosols
Massive amalgamated sandstone with deformed contacts	Mass-flow sands of submarine canyon fill	Upper flow regime fluvial channel	No paleosols

are constructional eolian bedforms with inverse grading from climbing translatent beds (Nielson and Kocurek, 1986; Qian et al., 2015). Additional evidence of deposition on dry land comes from v-shaped cracks (Fig. 4F), which cannot form in quartz sand under microbial mats or by syneresis, but only by desiccation of the whole depth bound by microbes as in a microbial earth soil (Prave, 2002; Retallack, 2012b). Polygonal networks of such cracks are illustrated for the Ediacara Member by Gehling (2000, his fig. 7d). A novel line of evidence for paleoenvironments at Nilpena is the Ge/Si content of early diagenetic silica cement in fossil holdfasts of vendobionts from Nilpena (Tarhan et al., 2016). The grains have Ge/Si of <1 μmol/mol inherited from parent granite, but the early diagenetic silica cement has 2–10 μmol/mol found only in soils and paleosols (Retallack, 2017a). These analyses are not compromised by authigenic clay inclusions in the cements, because clay inclusions are not visible in cathodoluminescence or energy dispersive spectroscopy of the analyzed silica cement (Tarhan et al., 2016). "Old-elephant skin" bedding textures (*Rivularites repertus* Fliche, 1906) at Nilpena, also have complex healed cracks, pressure ridges, and disruptions like microbial earth crusts (Fig. 2C), and are unlike stromatolites and other aquatic microbial textures (Prave, 2002; Retallack, 2012b, 2016b).

Previously published evidence of paleochannels, silty paleosols and granulometry (Retallack, 2012a, 2013) supports evidence presented here that Ediacaran interflag sandstone laminae were loess, or wind-redeposited alluvial sand and silt in floodplains of coastal valleys. Distinct eolian and alluvial grain size populations are found in the Ediacara Member (Figs. 5A, 6C). The Ediacara Member at Nilpena lacks red massive siltstones, evaporitic sand crystals, and isotopically distinctive calcite nodules of the Ediacara Member taken as evidence of paleosols elsewhere in the Flinders Ranges (Fig. 4A–E). Paleosols in these flagstone facies are poorly developed, and difficult to recognize because they lack root traces used to recognize very weakly developed Phanerozoic paleosols. Fortunately, zibars, setulfs, Ge/Si ratios, and "old elephant skin" now allow recognition of Precambrian Entisols.

An important clue to environment of the Nilpena "shims" is their fossils (Tarhan et al., 2017a, 2017b). The increased size of fossils such as *Dickinsonia* with increased thickness of the beds from laminae to flagstones does indeed appear to represent ecological succession, described taxonomically for these fossils by Reid et al. (2017). Tarhan et al. (2017a) argue that thinner beds represent disturbances at shorter intervals of time, allowing only early ecological succession, than depositional events leaving thicker flaggy beds with late successional communities. Ediacaran ecological succession is compatible with demonstration that the largest *Dickinsonia* are atop paleosols with the most and largest gypsum sand crystals (Retallack, 2013). This explanation of ecological succession applies equally to marine and non-marine habitats, especially in communities such as these dominated by sessile organisms (Tarhan et al., 2010; Coutts et al., 2016; Reid et al., 2017). Folds and mutilation of *Dickinsonia* have been interpreted as evidence of *Dickinsonia* motility (Evans et al., 2015), but instead demonstrate firm attachment (Retallack, 2017b). Faint impressions of *Dickinsonia* and comparable vendobionts interpreted as intermittent feeding trails (Ivantsov and Malakhovskaya, 2002), are now considered more likely rotted specimens

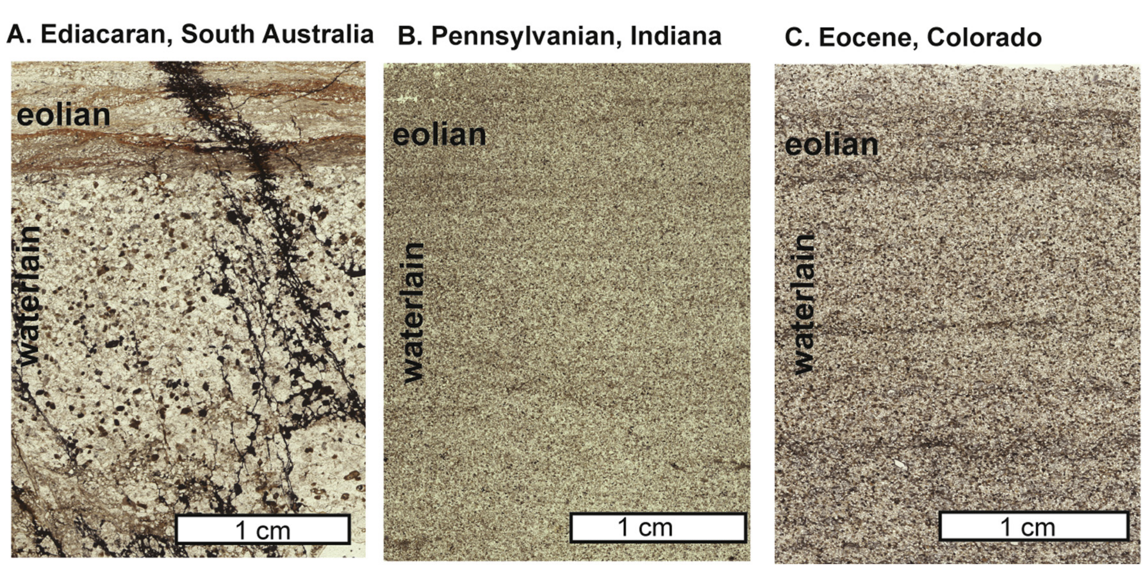

Fig. 5. Interflag sandstone laminae in thin section scans of the Ediacara Member of the Rawnsley Quartzite of South Australia, of the Mansfield Sandstone of Indiana and of the Wasatch Formation of Colorado, showing differences in grain size and angularity of grains. Specimen numbers in the Condon Collection of the Museum of Natural and Cultural History are R3214 (A), F121716B (B), F120914 (C).

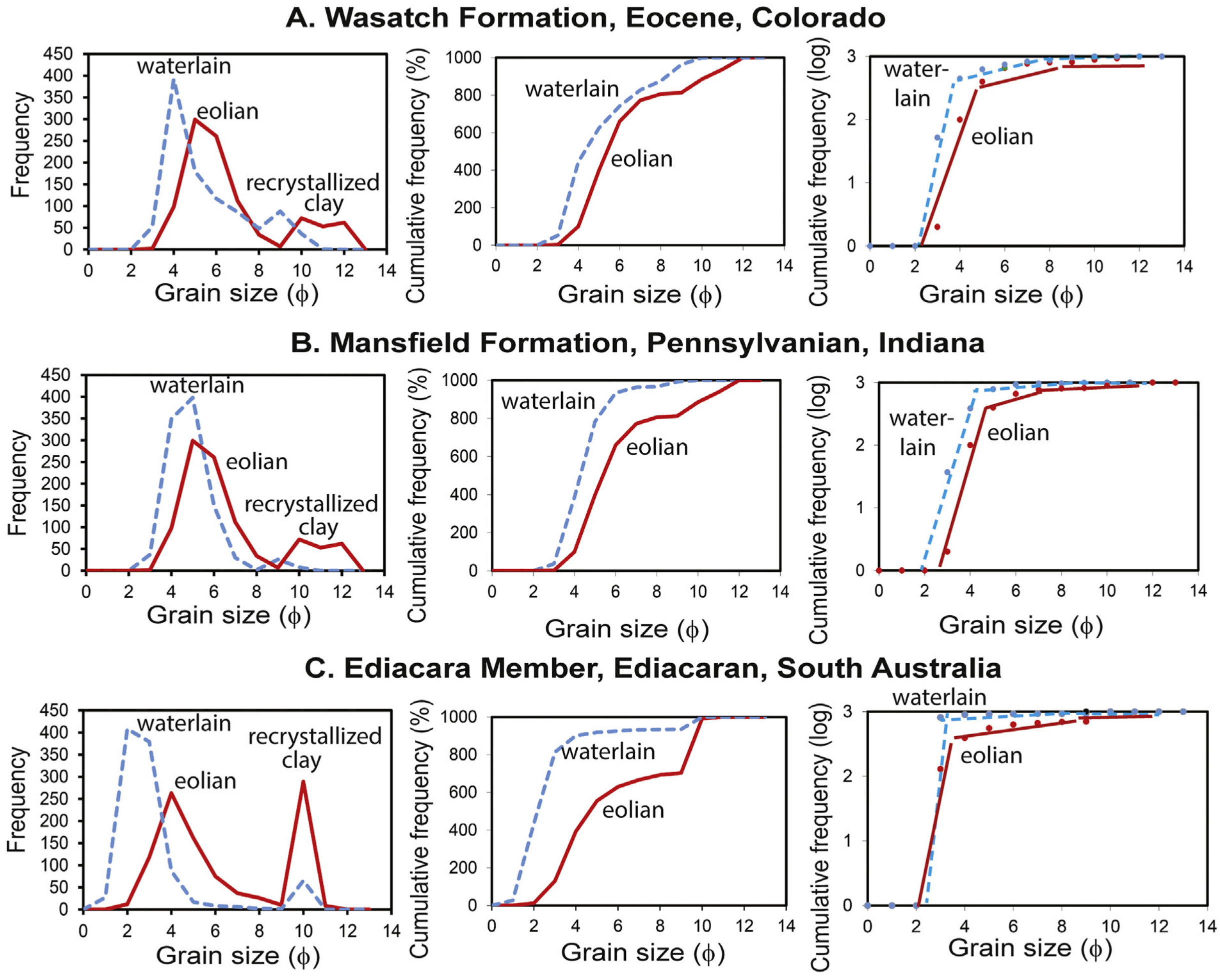

Fig. 6. Grain size distribution of interflag laminae (eolian) and interbedded flagstones (waterlain) from South Australia, Indiana, and Colorado, determined by point counting the thin sections shown in Fig. 4. Other Ediacaran grain size distributions also show distinct eolian and waterlain populations (Retallack, 2012a).

displaced by frost boils confined to one prominent level of periglacial involutions in the Ediacara Member (Retallack, 2016b). Thin sections of *Dickinsonia* show a well formed, segmented upper surface, but a lower surface dissolving into rhizine-like structures extending downward to attach firmly into the matrix (Retallack, 2016c). Most vendobionts were sessile organisms which grew in place slowly enough to track differences in their substrate exposure times, and interflag sandstone laminae represent short exposure times. Recent discovery of steroids in *Dickinsonia* (Bobrovskiy et al., 2018) does not necessarily mean that it was an animal, because Glomeromycotan fungi also have cholesterol (Weete et al., 2010). Glomeromycotan permineralized lichens (Yuan et al., 2005) and dispersed spores (Retallack, 2015) are already known in Ediacaran rocks. In addition the greater proportion of cholesterol over the algal biomarker stigmasterol with increasing size in *Dickinsonia* (Bobrovskiy et al., 2018) is more like building of fungal biomass from controlled algal photobionts, than fouling or random grazing by an animal.

4. The Pennsylvanian of Indiana, U.S.A.

4.1. Background

The Mansfield Sandstone of southern Indiana, U.S.A., crops out in ridges east of the Mitchell Plain in Orange and Martin Counties, and was examined at four localities near villages of Huron, Shoals, Prospect, and Roland (Fig. 1C; Table 1). The Mansfield Formation includes the "Hindostan whetstones" used widely for knife-sharpening and tombstones (Kvale et al., 2000). The whetstones are also famous for beautifully preserved fossil lycopsid plants (White, 1895; Jackson, 1916; Hoskins and Cross, 1940), of Early Pennsylvanian age (Morrowan or Westphalian A of Phillips and Peppers, 1984). The "whetstone facies" (Kvale et al., 2000; Kvale and Archer, 1991) and "massive sandstone facies" are distinct from the "thin bedded facies" of this study (Fig. 7, Table 4), which has a diverse trace fossil assemblage (Fig. 8) that is entirely non-marine (Maples and Archer, 1987; Getty and Bush, 2017). The massive sandstones have been interpreted as deltaic paleochannels, whetstones as lakes or bayous, and the thin-bedded facies as fluvial levees and scroll bars (Maples and Archer, 1987).

4.2. Field observations

Interflag sandstone laminae of the Mansfield Formation are thin (1–9 mm), and lighter colored (Munsell light olive gray, 5Y6/2) than the intervening flagstones (Munsell grayish brown 2.5Y6/2). Both the flagstones and the interflag laminae weather out and separate distinctly, and are not amalgamated (Fig. 7A–C). Flagstone bases are not discernably erosional, like the sandstone laminae, which also drape over pre-existing structures, and so pinch and swell in thickness to weather out like protruding tongues (Fig. 7A, B). They are completely within sandstone, with little or no clay (Fig. 5B), unlike flaser and lenticular bedding (Reineck and Singh, 1973). Some of the laminae mantle underlying ripple marks and are rippled on top (Fig. 7C). Thick (9 mm) laminae on planar surfaces may include highly asymmetrical climbing ripple marks with long wavelength and inverse grading

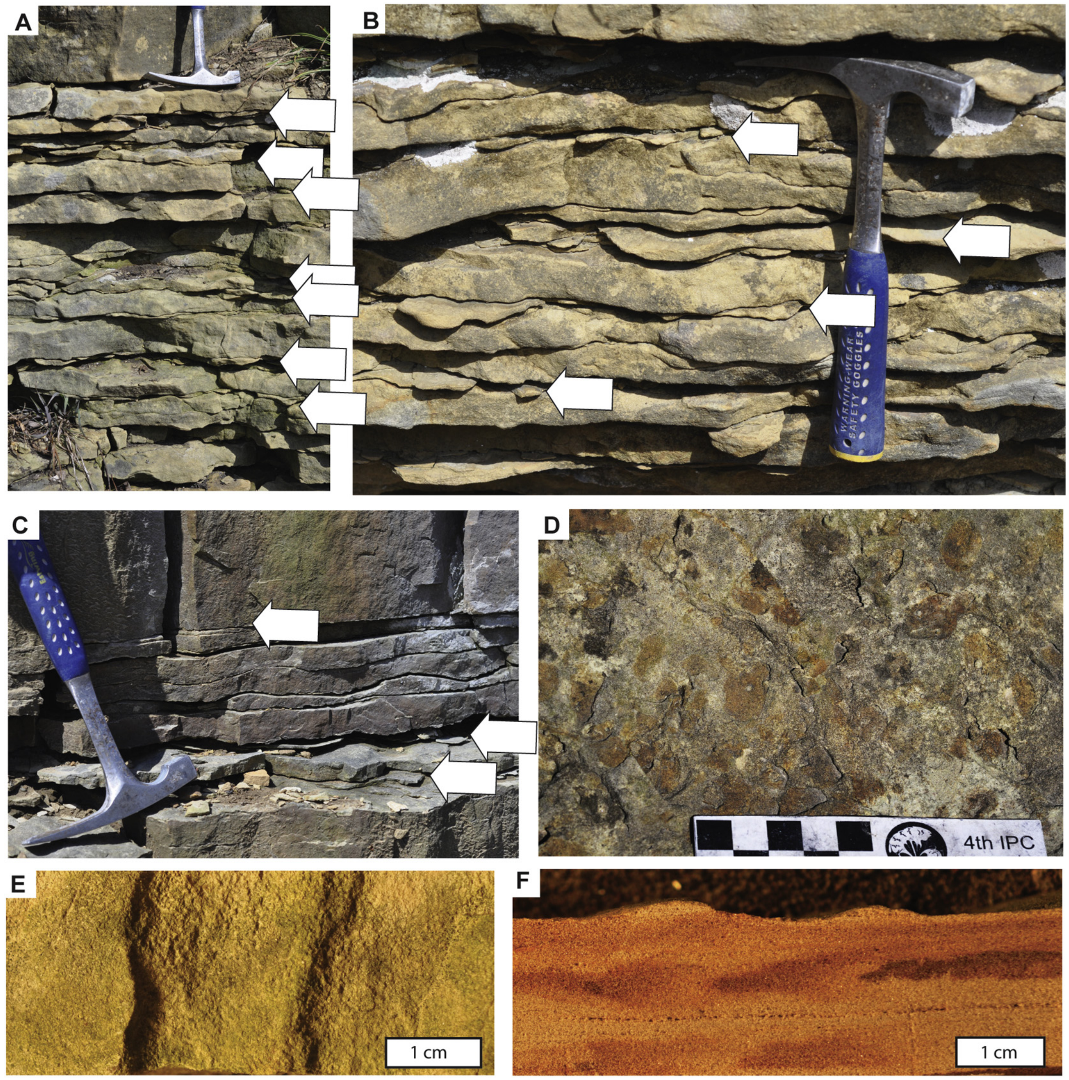

Fig. 7. Interflag sandstone laminae from the Early Pennsylvanian Mansfield Formation of southern Indiana: (A–B), light-colored, medium-grained, interflag sandstone laminae (at arrows) in Roland; (C), light-colored, medium-grained interflag, sandstone laminae (at arrows), near Shoals; (D), claystone breccia bedding plane near Huron; (E–F), climbing translatent strata (wind ripple) with surface marking of *Rugalichnus matthewii* from near Shoals in plan (E) and section (F). Hammers for scale (A–C), and cm square scale (D). Specimen E–F is F121730 in Condon Collection, Museum of Natural and Cultural History, University of Oregon.

(Fig. 7E, F). Some of the interflag laminae also include v-shaped cracks (Fig. 8G). The azimuth of current direction perpendicular to the step slipface of the climbing ripples (Fig. 7E, F) was east (112°), which is orthogonal to the azimuth of paleochannel trough cross-bedding of 220° determined for the Mansfield Formation by Bieber (1954) and Potter and Olson (1954). Interflag laminae are laterally discontinuous within an outcrop, as if filling broad swales (Fig. 7A, B). Nevertheless flagstones with interflag sandstone laminae of the Mansfield Formation (Fig. 3B) were found over an area of some 30 × 10 km, or 300 km^2 (Fig. 1C).

Table 4
Description and interpretations of sedimentary facies in Mansfield Formation, Indiana.

Facies description (Maples and Archer, 1987)	Interpretation (Maples and Archer, 1987)	Paleosols (new observations)
Whetstone	Lakes and bayous	Fibrists, Aquepts
Thin bedded (+**interflag sandstone laminae**)	Levee and scroll bar	Psamments, Fluvents
Massive sandstone	Deltaic paleochannel	No paleosols

4.3. Granulometry

Interflag sandstone laminae have a grain size distribution overlapping that of flagstones, but are mostly smaller in grain size than the intervening flagstones (Figs. 5B, 6B). For the sandstone laminae, mean and standard deviation of grain size are 4.4 ± 1.1 phi respectively and median grain size is 4.2 phi (coarse silt), whereas the flagstone mean and standard deviation are 4.0 ± 1.3 phi and median grain size is 3.6 phi (very fine sand). Both the laminae and the flagstones have grains that are angular and moderately well sorted according to the scale of Stewart et al. (1959).

4.4. Microbial, plant and animal traces

Both flagstones and interflag laminae have microbially induced sedimentary structures (Noffke, 2010). Ichnotaxonomic classification of microbial markings in the Mansfield Formation includes sinuous wrinkle structures (*Rugalichnus matthewii*: Fig. 8D) of aquatic origin, and cracked-healed and ridged structures (*Rivularites repertus*: Fig. 8B, C) of likely soil crust origin. *Rugalichnus matthewii* is a new name of Stimson

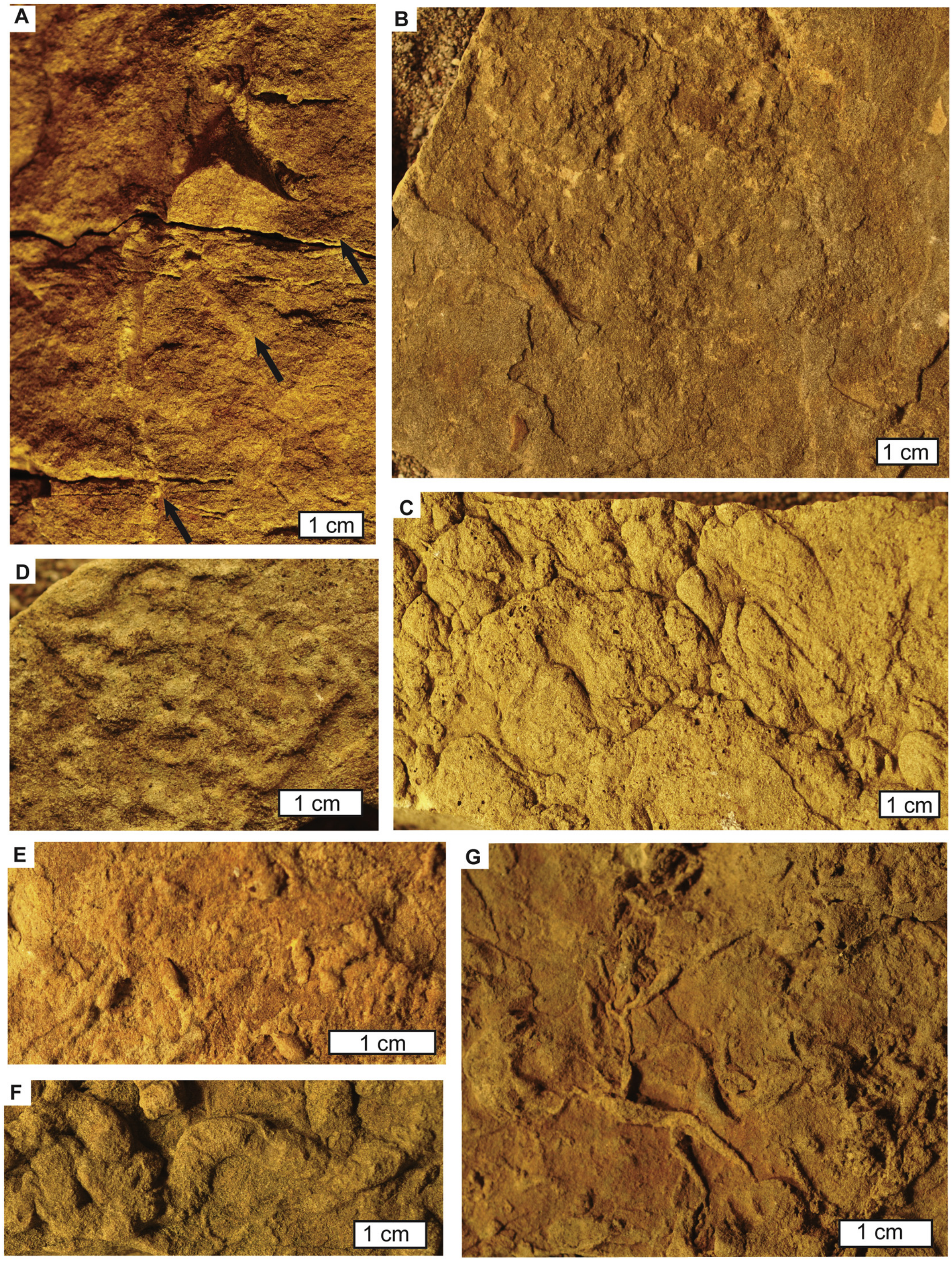

Fig. 8. Trace fossils from interflag sandstone laminae, Early Pennsylvanian Mansfield Formation of southern Indiana: (A), root traces vertical to bedding; (B–C), old elephant skin structure (*Rivularites repertus*) on sandstone, showing polycyclic cracking and healing; (D), microbial textures (*Rugalichnus matthewii*); (E), insect burrows (*Treptichnus bifurcus*); (F), insect burrow (*Scoyenia gracilis*); (G), shallow mud cracks. Specimens are from Huron (A–B, E, G), and Roland (C, F). *Rugalichnus* and *Rivularites* are both known from the Ediacaran, but the other trace fossils are not. Specimens in Condon Collection, Museum of Natural and Cultural History, University of Oregon are F121725A (A), F121718 (B), F121735 (C), F121728 (D), F121724 (E), F121734 (F), F121725 (G).

et al. (2017) for what has been widely known as "*Kinneyia*" (Thomas et al., 2013), or "wrinkle structures" (Noffke et al., 2002; Schieber et al., 2007). Comparable revision and more comprehensive study are also needed for *Rivularites repertus* (Fliche, 1906), better known as "old elephant skin" (Retallack, 2012b). Thick old elephant skin associated with desiccation cracks (Fig. 8G) is a microbial earth fabric, with massive internal structure and diffuse lower surface below sharp upper surface, unlike the laminated sharp lower contact of aquatic *Rugalichnus* microbial mats (Retallack, 2012b).

Also found were root traces in place of growth (Fig. 8A) and plant fragments, including *Sphenophyllum angustifolium* (Table 1). Of the diverse trace fossil assemblage known from the Mansfield Formation (Maples and Archer, 1987; Buatois and Mángano, 1993; Knaust, 2015), the following were collected for this work: *Laevicyclus parvus*, *Cochlichnus anguineus*, *Palaeophycus tubularis*, *Tonganoxichnus buildexensis*, *Treptichnus bifurcus* (Fig. 8E), and *Scoyenia gracilis* (Fig. 8F). Shallow undermat miners in this assemblage include *Palaeophycus* and *Treptichnus* (Maples and Archer, 1987).

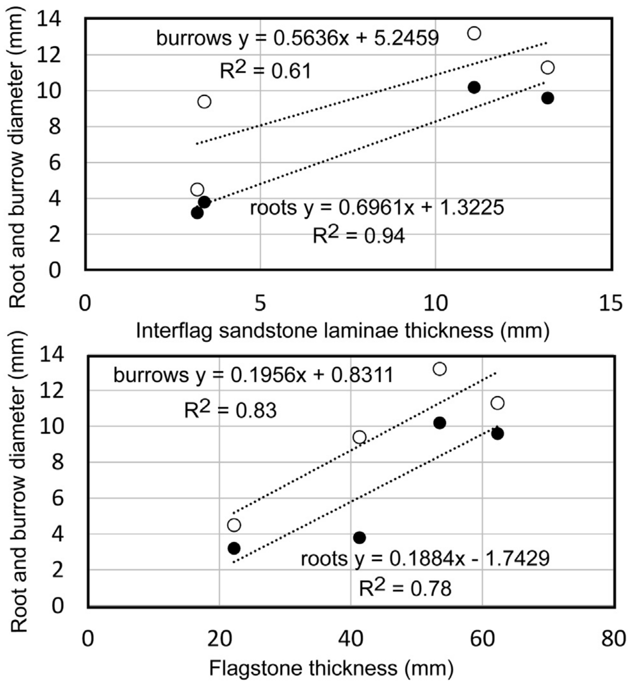

Fig. 9. Correlations between the largest root traces and burrows and interflag sandstone lamina thickness (A), or flagstone thickness (B) in the Early Pennsylvanian Mansfield Formation of southern Indiana. The four data points in each series correspond to largest trace fossil found at each of four localities of Table 1. Large burrows and roots within the laminae penetrate also into the flagstone immediately below.

The measured diameters of burrows and root traces in four especially fossiliferous beds at four different localities in Indiana (Table 1) show a correlation with thickness of both flagstone and interflag sandstone laminae (Fig. 9). The largest burrows found at the four localities were *Laevicyclus* (near Huron and Prospect), *Scoyenia* (at Roland) and *Palaeophycus* (near Shoals). The root traces are all slender and woody (Fig. 8A), like roots of cordaites or seed ferns. No stigmarian roots were found in the flagstones, although these, along with stumps and trunks of large tree lycopsids, are known from the whetstone facies of the Mansfield Formation (White, 1895; Jackson, 1916; Hoskins and Cross, 1940).

4.5. Interpretation of the Mansfield Formation

These Pennsylvanian interflag sandstone laminae from Indiana agree in all respects except for criterion 3 with the checklist for Ediacaran examples from Nilpena, South Australia: (1) thin; (2) laterally discontinuous; (3) texturally uniform; (4) unamalgamated; (5) nonerosional; (6) doubly rippled; (7) textured organic surfaces; (8) fossils larger and more abundant in thicker beds; and (9) rip-up clasts. Ediacaran interflag sandstone laminae do have Phanerozoic counterparts.

Primary sedimentary structures and granulometry reveal different processes of deposition for the interflag laminae and the flagstones of the Mansfield Formation. Interflag laminae pinch and swell in thickness where they filled preexisting ripples or swales (Fig. 7A–C). Asymmetric ripples in one bed (Fig. 7E, F) are climbing, long wavelength, and inverse graded, like climbing translatent stratification of wind deposition (Hunter, 1977). However their crests are not straight and are also steeper than wind ripples (Rubin, 2012), so they may have been modified by later slumping or erosion. In contrast, short-wavelength, ripple-drift cross lamination, scour-and-fill, and trough cross bedding of the flagstones and thicker beds are diagnostic of shallow water flow of levees and floodplains (McGowen and Garner, 1970; Collinson, 1970; Singh and Kumar, 1974). The flaggy facies of the Mansfield Formation have been interpreted as fluvial levees and scroll bars (Maples and Archer, 1987). The distinction between eolian and alluvial deposition is supported by granulometry, because of the slightly finer grain-size and better sorting of the interflag laminae, compared with the flagstones (Fig. 6B). Overlap in sizes of eolian and waterlain populations (Fig. 6B) may be due to local wind redeposition of waterlain sediment. The grain size distributions of sandstone laminae in the Mansfield Formation are comparable with those of the Quaternary, Peoria Loess of Kansas (median grain size 4.3 to 5.6 phi (silt), standard deviation 0.9 to 1.7 phi; Swineford and Frye, 1951). This is not to say that the Peoria Loess is similar to the Mansfield Formation in sedimentology, because it has eolian beds modified by paleosols, without fluvial interbeds (Wang et al., 2000). The prevailing wind direction orthogonal to steep crested climbing ripples in the Mansfield Formation is to the east (Fig. 7E, F), whereas fluvial paleocurrents in the Mansfield Formation were to the southwest (Bieber, 1954; Potter and Olson, 1954).

There are multiple lines of evidence that both the interflag laminae and the flagstones are very weakly developed paleosols. Both are penetrated by root traces in growth position (Fig. 8A). There are no definitively marine trace fossils in the Mansfield Formation (Maples and Archer, 1987). *Treptichnus* and *Tonganoxichnus* are considered trace fossils of insects (Mángano et al., 1997; Uchman, 2005; Genise, 2016). *Cochlichnus* and *Palaeophycus* may be traces of worms, *Laevicyclus* of molluscs or worms (Seilacher, 2007; McIlroy and Garton, 2010), and *Scoyenia* created by millipedes or insects (Retallack, 2001). Other evidence of exposure comes from desiccation cracks in sandstone (Fig. 8G), common in mudstones, but a puzzle for sandstones unless it is acting like mud because of microbial binding (Prave, 2002). Furthermore, both sandstone clasts (orange in Fig. 7D) and claystone clasts (dark brown in Fig. 7D) are found on some horizons. Evidence for microbial binding comes from the microbial trace fossils *Rivularites* and *Rugalichnus* (Fig. 8B, C). Some surfaces with trace fossils and adhering sandstone laminae, also show scour marks and fossil plants knocked down by strong unidirectional currents, like felled fronds in Ediacaran interflag sandstone laminae (Tarhan et al., 2010). Scouring around plant debris (Fig. 8A) demonstrates that some plant material was firmly rooted to the substrate. Occasional strong water currents are also in evidence from beds of claystone breccia with clasts as large as 4 cm (Fig. 7D).

The correlation between size of fossils and thickness of beds (Fig. 9) also can be explained by interpretation as paleosols. Microbial colonization is the earliest stage of ecological succession before germination of plants, and microbes bestow characteristic sedimentary fabrics (Fig. 8D), erosion-resistance, and binding (Noffke et al., 2002; Prave, 2002), allowing formation of desiccation cracks and more complex microbial markings in quartz sand (Fig. 8G). Root and burrow size in interflag laminae are measures of the very earliest stages of ecological succession on wind-drifted sedimentary surfaces, whereas the larger organisms of the flagstones represent more advanced ecological succession between floods.

5. The Eocene of Colorado, U.S.A.

5.1. Background

A cliff of Wasatch Formation north of county highway 64, 9 miles west of Meeker, Rio Blanco County, Colorado (Fig. 1B), exposes flagstones (Fig. 10A) in the Molina Member of the middle Wasatch Formation, above clayey Atwell Gulch, and below clayey Shire Members (Hancock and Eby, 1930; White and Hodge, 2013). The Molina Member has been interpreted as levee and paleochannel deposits of braided streams (Mohrig et al., 2000; Lorenz and Nadon, 2002), based on facies analysis (Table 5). Fossil mammals in the poorly fossiliferous Molina Member are basal Wasatchian (Wa0–Wa1) North American Land Mammal Age, which correlates with the early Eocene and ca. 54 Ma (Ypresian international stage: Kihm, 1984; Robinson et al., 2004).

Fig. 10. Interflag sandstone laminae (at arrows) from the early Eocene, Wasatch Formation of central Colorado. Hammers for scale.

5.2. Field observations

Directly above the talus slope near Meeker are 5 m of flaggy sandstones (Fig. 10A), with some intervals of more massive sandstone including convolute lamination and trough cross bedding, but only the basal 1 m of section is shown in Fig. 3C. Outcrop is poor above the sandstone cliff, and consists of green gray claystones and lignites of the Shire Member of the Wasatch Formation. Interflag medium-grained, sandstone laminae are 2–5 mm thick, and some are ripple trains that pinch out along strike. Intervening flagstones are 5–7 cm thick, and many show short-wavelength current ripples, and graded bedding to basal coarse sandstone. The sandstone laminae are very pale brown (10YR8/2) in cross section, but lamina surfaces and intervening flagstones are yellowish brown (10YR5/8). The basal contact of the flagstones is not discernably erosional, but mantle ripples and other features of the bed below. Both contacts of the interflag laminae are unamalgamated and weather out like thin tongues (Fig. 10B, C). Ripple marks indicate transport direction to the east, whereas trough cross beds in the Molina Member were formed by north-flowing rivers (Lorenz and Nadon, 2000). Other outcrops of the Molina Member have intraformational claystone breccias (Lorenz and Nadon, 2000).

Table 5
Description and interpretations of sedimentary facies in the Wasatch Formation, Colorado.

Facies description (Lorenz and Nadon, 2002)	Interpretation (Lorenz and Nadon, 2002)	Paleosols (new observations)
Mottled claystones	Floodplain	Saprist, Aquept, Fluvent
Flagstone (+**interflag sandstone laminae**)	Levee and scroll bar	Psamment, Fluvent
Massive to cross-bedded sandstone	Fluvial paleochannel	No paleosols

5.3. Granulometry

Grain size of the sandstone laminae and flagstone overlap, with the laminae finer grained than flagstones (Figs. 5C, 6A). For the sandstone laminae, mean and standard deviation of grain size is 5.5 ± 1.8 phi respectively, and median grain size is 5.2 phi, whereas the flagstone mean and standard deviation is 4.9 ± 1.8 phi and median grain size is

4.2 phi. Unlike the Indiana sandstone laminae (Fig. 6B), the Colorado laminae contain some large volcanic shards, which account for some of the overlap. Both the laminae and the flagstones have angular and moderately well sorted grains according to the scale of Stewart et al. (1959).

5.4. Microbial, plant and animal fossils

Interflag sandstone laminae of the Wasatch Formation are clearly defined, top and bottom by microbial textures that are smooth to dimpled, like ichnotaxon *Rugalichnus matthewii* (Fig. 10C). Also found were undermat miner burrows of the form species *Palaeophycus tubularis*, fine root traces, and fragments of twigs and leaves. The Wasatch Formation was too poorly fossiliferous to investigate the scaling of fossil size to bed thickness (Fig. 9).

5.5. Interpretation of the Wasatch Formation

The Molina Member fulfills 8 of the 9 modified criteria for recognizing interflag sandstone laminae: (1) thin; (2) laterally discontinuous; (3) texturally finer grained; (4) unamalgamated; (5) nonerosional; (6) doubly rippled; (7) textured organic surfaces; and (8) rip-up clasts. Like comparable facies in the Ediacara Member and Mansfield Formation, the non-marine Wasatch Formation flaggy beds represent fluvial levees, with wind ripples tending toward the east, but fluvial paleocurrents toward the north (Lorenz and Nadon, 2000). The interflag sandstone laminae have finer grain size and better sorting than the flagstones, more like loess than alluvium (Swineford and Frye, 1951). This may be an example of wind-drifted interflag sandstone laminae, between flagstones produced by floods.

6. Other examples of interflag sandstone laminae in deep time

Interflag sandstone laminae appear to be widespread in both Phanerozoic and Ediacaran rocks (Figs. 10, 11; Table 1). The geological context of Ordovician and Cretaceous examples in Fig. 11 is given by Retallack (2009a, 2009b) and Retallack and Dilcher (2012). Individual exposure surfaces of very weakly developed paleosols can also be recognized by a suite of structures, including wind dissected ripples (Figs. 2D, 11E), setulfs, and raindrop prints (Sarkar et al., 2011; Som et al., 2012). Thus interflag sandstone laminae are not “anactualistic facies” confined to the Ediacaran.

No examples of interflag sandstone laminae are yet known from any genuinely marine flaggy sandstones, based on my observations of localities with marine fossils in quartz sandstones at localities in the Condon Collection of the Museum of Natural and Cultural History of the University of Oregon (Table 2), or by published studies of those localities (Carey, 1978; Nilsen, 1984; Lindsey and Gaylord, 1992). Quartz sandstones can be recognized as marine by lags of abundant marine fossil shells, or Ediacaran trace fossils such as *Streptichnus* or discoids such as *Beltanelliformis* (Table 2). Marine fossiliferous quartzites differ fundamentally from the Ediacara Member of Nilpena in lacking unamalgamated interflag sandstone laminae. Marine flagstones have strong bedding, including parting lineation, so that their amalgamation is not entirely due to burrowing. Rather it is due to lack of lithologically distinct partings.

Interflag sandstone laminae in the Kanies, Kliphoef and Aar Members of the Dabis Formation of Namibia, and Arumbera Formation and Central Mount Stuart beds of central Australia (Fig. 12; Table 1) are in need of further examination. Grazhdankin and Seilacher (2002) describe “underground Vendobionta” from Namibia, but meant buried beneath the seafloor, as envisaged for other Namibian Ediacaran fossils (Ivantsov et al., 2016). Apparent interflag sandstone laminae associated

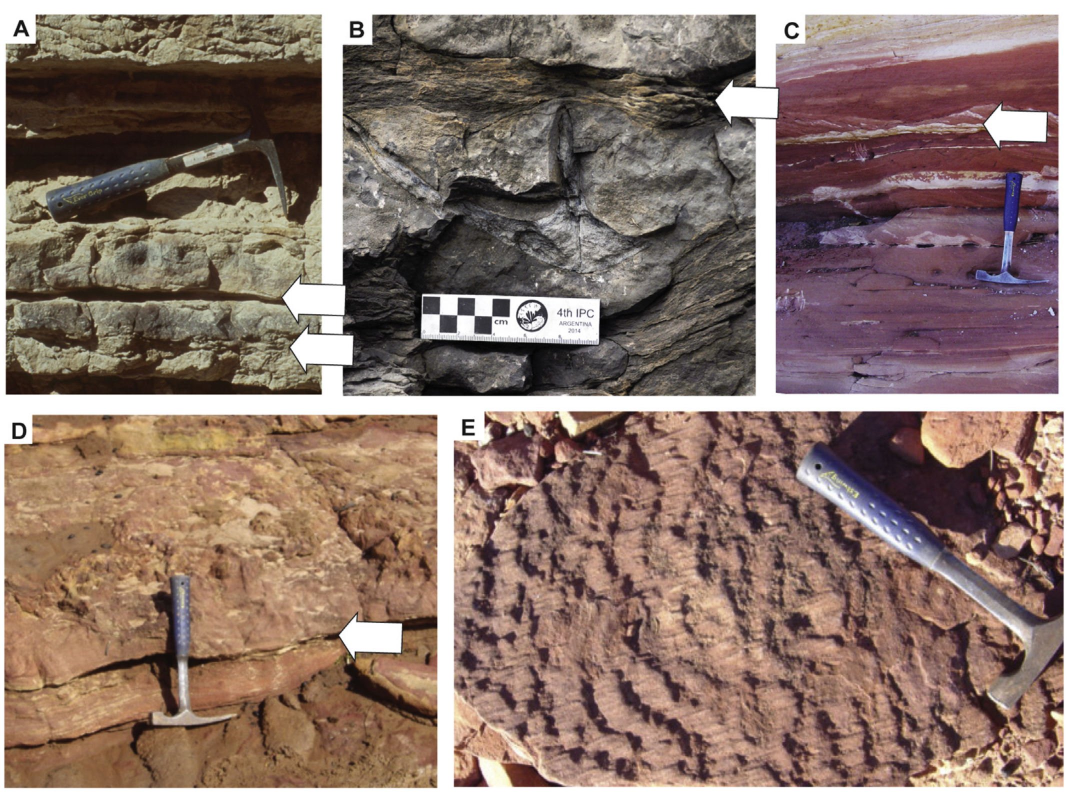

Fig. 11. Interflag sandstone laminae (at arrows) from non-calcareous, sandstone, fluvial levee facies of Phanerozoic geological age: (A), mid-Cretaceous, Dakota Formation, near Hoisington, Kansas; (B), middle Devonian, Panther Mountain Formation near Summit, New York; (C), Early Ordovician, Grindstone Range Formation in Ten Mile Creek, South Australia; (D–E), paleosol (D) and wind-dissected ripples (E) in Ordovician, Tumblagooda Sandstone, Kalbarri National Park, Western Australia.

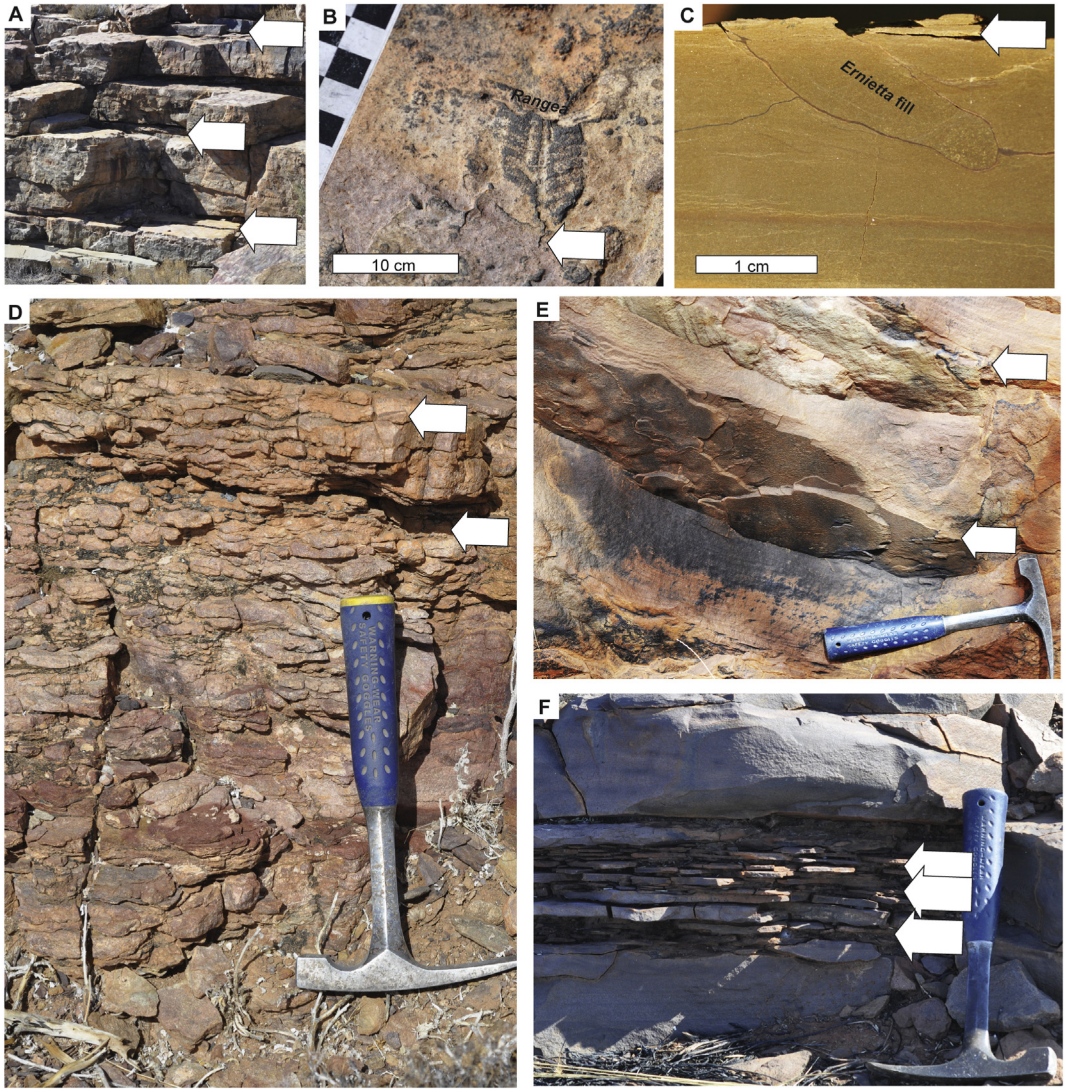

Fig. 12. Interflag sandstone laminae (at arrows) of Ediacaran age: (A), interflag sandstone laminae in Kliphoek Member, at Aarhausen, Namibia; (B), interflag sandstone lamina (at arrow) covering red old elephant skin (*Rivularites repertus*) and gray quilted sandstone cast of vendobiont (*Rangea schneiderhoehni*) in Kliphoek Member, at Aarhausen, Namibia; (C), polished slab cross-section of the hollow vendobiont (*Ernietta plateauensis*) filled with coarse sandstone, Aar Member, Dabis Formation at Ernietta Hill, Namibia (Namibia Geological Survey specimen F122–21); (D), levee facies with interflag sandstone laminae (arrows) above red Inceptisol paleosol, Kanies Member, Dabis Formation, at Pockenbank, Namibia; (E), interflag sandstone laminae in Arumbera Formation, Valley Dam, near Alice Springs, Northern Territory; (F), interflag sandstone laminae in Central Mount Stuart beds, Central Mount Stuart, Northern Territory. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with these fossils (Fig. 12B, C) may indicate that they lived underground in the more usual terrestrial sense. Three dimensional fossils such as *Ernietta* and *Pteridinium*, that were sessile within sandstone matrix, do not show clear field characters of paleosols, such as nodules and sand crystals. Thus, if they were paleosols, they would have been very weakly developed. These fossils in quartz sandstones are in very distinct facies from limestones and calcareous sandstones with Ediacaran marine fossils including *Cloudina*, *Namacalathus*, and *Wyattia* (Kaufman et al., 1991; Hall et al., 2013; Vickers-Rich et al., 2016). The shallow paleochannel with interbedded shale and sandstone and many specimens of *Rangea schneiderhoehni* is at the transition from sandstones to limestones of the Aar Member of the Dabis Formation (Hall et al., 2013). This shallow mud-filled paleochannel has high sinuosity and marked seaward flaring (Vickers-Rich et al., 2013) found uniquely in channels of intertidal flats (Dalrymple and Choi, 2007; Hood, 2010). Interflag sandstone laminae in the Arumbera Sandstone (Fig. 12F) of central Australia are associated with the vendobiont *Arumberia*, in flaggy sandstone associated with massive to trough cross bedded sandstone of fluvial channels, of "coastal or delta plain" facies of Mapstone and McIlroy (2006) and "delta plain sedimentary environments" of Kolesnikov et al. (2012).

7. Modern mechanisms for interflag sandstone laminae

Interflag sandstone laminae in the Mansfield and Wasatch Formations are in flagstone facies interpreted as fluvial levees, scroll bars, crevasse splays and floodplains (Archer and Maples, 1984; Mohrig et al., 2000; Lorenz and Nadon, 2002). Comparable windblown laminae are documented in modern scroll bars, chutes, and levees of the Amite River of Louisiana and Colorado River of Texas, U.S.A. (McGowen and Garner, 1970), Tana River of Norway (Collinson (1970), and Ganges, Yamuna, and Son Rivers of India (Singh and Kumar, 1974). The Colorado River in Arizona also has outstanding examples seen in plan as thin white drapes on point bars (Draut and Rubin, 2008, their fig. 7), and also in excavations as white, "subaerial (thin)" layers between thick brown "fluvial" layers (Draut et al., 2008, their fig. 5). Other pits show the contrast between short-wavelength, sinuous-profile fluvial ripples and long-wavelength, chevron profile wind ripples (Draut et al., 2008, their fig. 3).

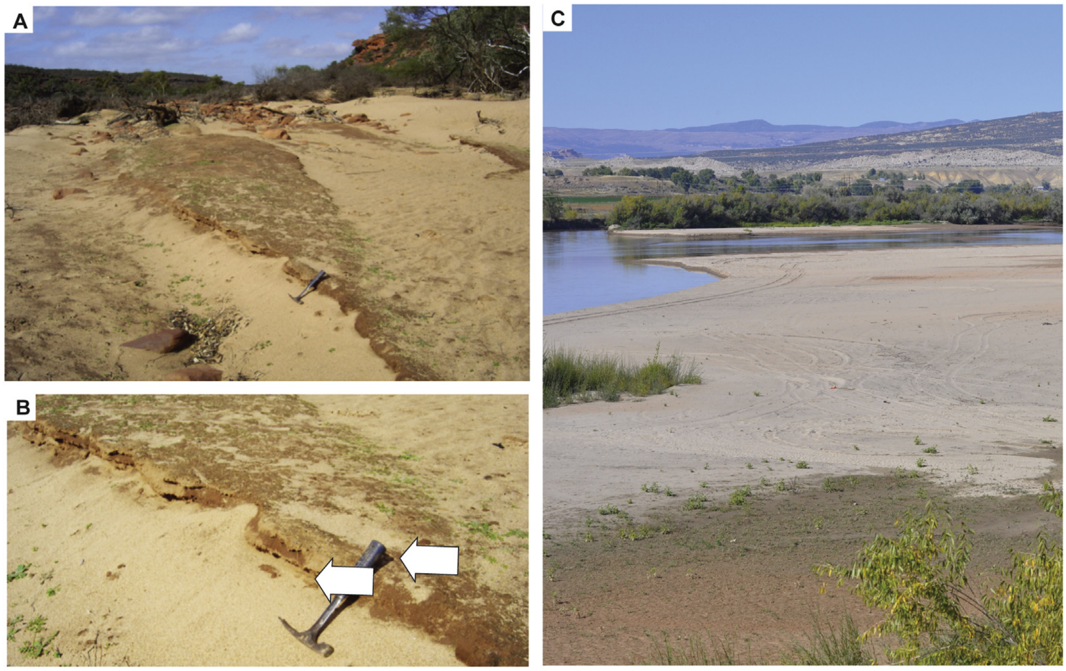

Fig. 13. Modern analogs to interflag sandstone laminae: brown weathered flood deposits mantled with white wind-drift sands in levee of the Murchison River, below Ross Graham Lookout, Kalbarri National Park, Western Australia (A–B), and of Green River near Jensen, Utah (C). Coordinates are S27.814725° E114.487064° (A–B), and N40.80957° W109.33225° (C). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The following observations are based on examination of the Murchison River of Western Australia and Green River of Utah, U.S.A. (Fig. 13). Flooding of the scroll bars observed in the Murchison River (Halse et al., 2000) and in the Green River near Jensen (Grams and Schmidt, 2002) is annual. Both modern rivers recycle sands from sandstones of their source area: Ordovician, Tumblagooda Sandstone of Western Australia (Retallack, 2009b) and Jurassic, Navajo Sandstone of Utah (Retallack, 2009c), respectively. Levees and adjacent scroll bars are covered by water at flood stage, when sand is deposited by moving water, but then dry out to be moved and draped by windblown sand laminae (Fig. 13A, B). Finer grain size of interflag sandstone laminae than associated flagstones are evidence of distinct eolian and fluvial transport. Inconsistency of grain-size differences may reflect local aprons of wind-blown sand versus sand and silt blown in from more distant sources (Fig. 13A). Elevated surfaces are colonized by lichens and small seedlings of vascular plants to form a biological soil crust, but low-lying swales are draped with clay and cyanobacterial mats (Fig. 13A, B). These colonization surfaces prevent amalgamation of interflag laminae and flagstones, and also host insect burrows and plant litter. These clayey swales (Fig. 13C) form mud cracks that are transported as claystone breccias seen in ancient examples (Fig. 7D). Both microbial earths of low ridges and microbial mats of swales can be found on the same point bar and levee (Retallack, 2012b), thus explaining lateral discontinuity of interflag sandstone laminae. However, within the ridge, fluvial beds overlie eolian drapes without evidence of erosion (Fig. 13B). Different directions of transport by floodwaters, and by prevailing winds are also an explanation for orthogonal differences between paleocurrent directions of trough cross-bedding and wind-ripple marks (Bieber, 1954; Potter and Olson, 1954; Mohrig et al., 2000; Lorenz and Nadon, 2002). These beds with microbial crusts, including seedlings with leaves 1 cm diameter, can be compared with flanking eolian drapes with only microscopic life (Fig. 13A, B). Thus modern scroll bars and levees of sandy streams show all 9 features associated with interflag sandstone laminae.

These modern examples also reveal how it is possible to deposit thin silty sand layers, filling depressions, and sometimes piling up into ripples. Unlike smooth to undulating and stromatolitic aquatic microbial mats, microbial earth surfaces have a felted texture with relief of several mm, which can trap saltating grains blown by the wind. In contrast, floodwaters flatten everything in their path and lift out clasts of sandstone or claystone for redeposition in local breccias. There are also scattered small plants, like fronds and other vendobionts of the Ediacaran (Tarhan et al., 2010; Coutts et al., 2016; Reid et al., 2017), that nucleate setulfs (shadow dunes: Fig. 13B on brown surface), reactivation surfaces (Fig. 13B draped over eroded edge), and wind ripples (Fig. 13D middle distance right on thicker sand). This kind of modern environment explains the distinctive sedimentary structures seen in the Ediacaran, Ordovician, Devonian, Pennsylvanian, Cretaceous, and Eocene sites described here (Table 1).

It is unclear how marine or lacustrine microbial mats could create any of these structures. A slow water current would create laminae rich in clay from suspension and organic matter from entrapping microbes, compared with flags poor in clay and organic matter. However, the observed flagstones are brown and gray with organic matter and clay, but the laminae are clean and white. An anactualistic algal model has been created in the laboratory by Hagadorn and McDowell (2012), who showed that cyanobacterial films suppress ripple formation under those conditions, yet both flags and laminae are often rippled. Perhaps there are marine settings in which current flows alternate in intensity so as to create laminae exposed for short periods alternating with flaggy beds exposed for longer times, but they have yet to be identified. One possibility is the thin wind drift laminae of sand seen on Oregon beaches above the still-saturated shoreface sand at low tide. Neither layer has obvious algal colonization, and is eroded by the next tide, because not detected by my excavation of Newport and Gold Beach, Oregon. No fossil examples of such shoreface laminae are known (Table 2).

The only remaining reason to infer a marine environment for interflag sandstone laminae is the outdated idea that Ediacaran vendobionts were marine invertebrates such as worms, sea jellies, and sea pens (Seilacher, 1992). The biological affinities of vendobionts remain a confusing puzzle (Retallack, 2016c; Dunn et al., 2017; Hoekzema et al., 2017; Bobrovskiy et al., 2018; Retallack, 2018).

8. Conclusions

Two distinct models for the origin of interflag sandstone laminae are now available. Tarhan et al. (2017a) proposed a marine microbial mat model in which interflag sandstone laminae were bound by microbial mats developed on the top of the underlying sandstone, and then again on the top of the thin lamina or laminae due to vagaries of current strength (Fig. 14A). In contrast, a fluvial levee flood-wind model proposed here is that the flagstones were deposited by traction currents on levees and scroll bars at high stage stream flow, and the intervening sandstone laminae were formed by wind redistribution of dry sand trapped by thin microbial earth crusts (Fig. 14B).

Tarhan et al. (2017a) call their model anactualistic, because they knew no comparable Phanerozoic marine environments with interflag sandstone laminae, and this study confirms that observation for marine rocks (Table 2). By proposing that both the laminae and the flagstones formed by the same mechanism at different energy levels, the marine microbial mat model of Tarhan et al. (2017a) fails to explain why the finer grained laminae are less clayey or organic than the coarser grained flagstones, and how they became so regularly alternating.

This study has shown that interflag sandstone laminae are not anactualistic, but are common in Phanerozoic fluvial levees and scroll bars (Table 1). Furthermore, these other interflag sandstone laminae in sedimentary rocks and beside modern rivers have all the ancillary features of this novel sedimentary structure: (1) mm-scale thickness; (2) lateral discontinuity; (3) finer grain size; (4) lack of amalgamation; (5) lack of marked erosion; (6) doubly rippled bedforms; (7) microbially textured surfaces; (8) larger fossils in thicker beds; and (9) large rip-up clasts.

Unlike sedimentary structures with broad paleoenvironmental implications, interflag sandstone laminae are only known from sandy streamside levees and scroll bars, where they form by wind-drift redeposition alternating with floods. Ediacaran vendobionts in place of growth on Nilpena Station in South Australia, on farms Aar and Pockenbank in Namibia, and near Alice Springs, Northern Territory, Australia (Table 1), are found in sequences of flagstones with interflag sandstone laminae, and so may have lived on and in fluvial levees and scroll bars. Interflag sandstone laminae are not only a newly recognized sedimentary structure, but an indicator of terrestrial exposure in sequences where weathering has been too weak to leave a mark as discrete paleosols.

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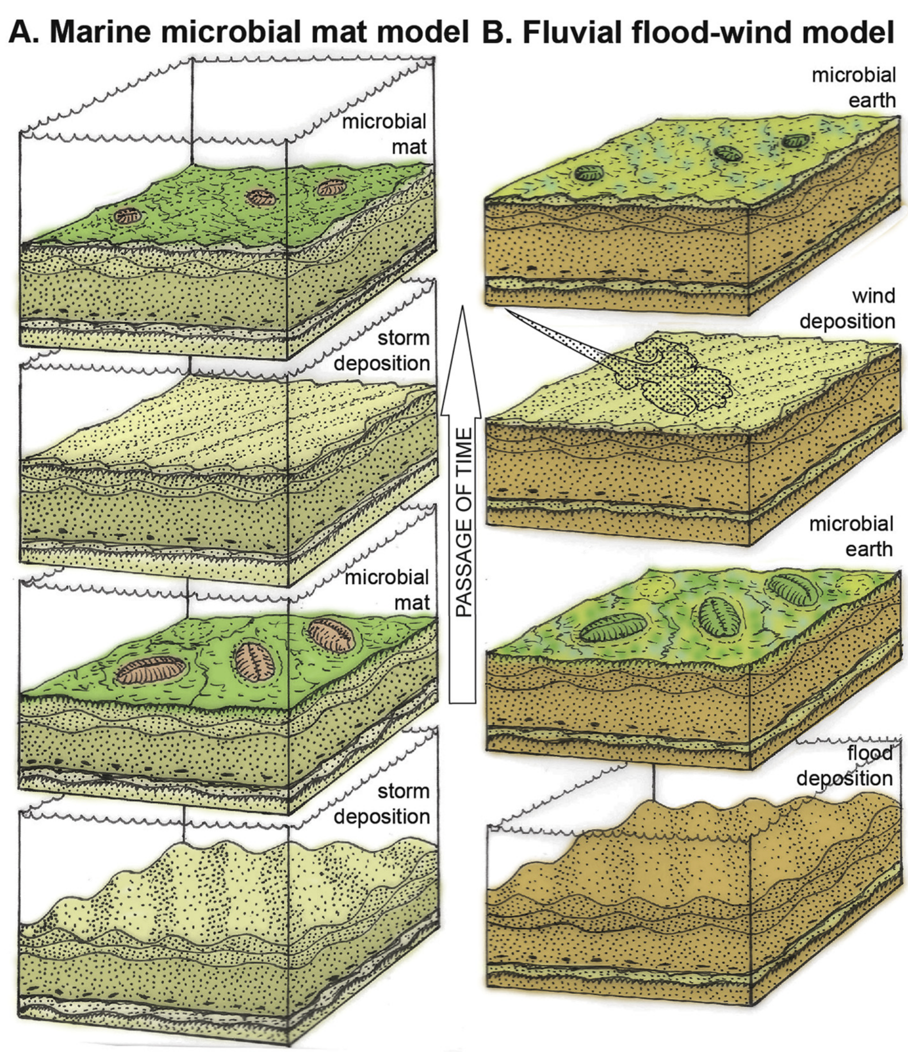

Fig. 14. Marine mat versus fluvial levee model for Ediacaran interflag sandstone laminae, based on sedimentology and fossils (*Dickinsonia costata*) from the Ediacaran locality of Nilpena, South Australia (Tarhan et al., 2017a). The marine mat model proposes formation of interflag sandstone laminae by marine traction currents of less magnitude than for flagstones, but the fluvial levee model proposes that interflag sandstone laminae are wind-drift layers between flagstones laid down by flood waters.

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