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Distinguishing microbially induced sedimentary structures from fluid-induced interfacial deformation structures (MISS versus FIDS)

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ABSTRACT

Fluid-induced interfacial deformation structures (FIDS) are both diverse and common in turbidite successions where they form in soft, cohesive substrates beneath sediment-gravity flows, but their significance has only recently been recognised (Peakall et al. 2024). Their range of forms encompasses most of the morphological types attributed to microbially induced sedimentary structures (MISS) and the two have likely been widely conflated. Variants of FIDS include longitudinal ridges and furrows, polygonal networks and mamillated forms that are identical to structures assigned to MISS. A distinctive MISS form with flat-topped ridges and furrows called "Kinneyia" is also found within the FIDS spectrum. Some FIDS may have also been assigned to Ediacaran taxa, notably the controversial *Arumberia*. Distinguishing FIDS from MISS in hand specimen is difficult, but their environmental context is important. Intertidal MISS occurrences are unlikely to be FIDS because the sediment gravity flows that produce deformation of the substrate are unlikely in such settings. However, MISS (mis)reported from turbidite settings are likely to be FIDS. One of the few distinctions between MISS and FIDS occurs when textured surfaces are developed on the upper

surfaces of sandstone beds and they are overlain by fine-grained sediments; in this case a microbial origin is likely.

The term microbially induced sedimentary structures (MISS) encompasses a range of sedimentary features typically seen on sandstone and limestone bedding planes (Noffke et al., 2001, 2022; Davies et al., 2016). MISS consist of a broad suite of structures that range from narrow, elongate ridges and wrinkle structures to more equidimensional or polygonal forms (Eriksson et al., 2007). MISS are typically only a few millimetres in width and no more than a few millimetres in height and can cover extensive surfaces (e.g., Noffke, 2000). These structures closely resemble modern surfaces covered in microbial mats or biofilms, which can develop irregular, small-scale wrinkle patterns, hence the MISS designation (Hagadorn and Bottjer, 1997). Often interpreted to be structures formed by the direct preservation of surfaces covered by microbial mats, experiments suggest that some wrinkle structures may also be produced through reworking of microbial mat fragments by wave-generated oscillatory flows on otherwise bare sand surfaces (Mariotti et al. 2014). In this scenario, MISS are not "fossil" mats but nonetheless record the presence of microbial mats that have been reworked within the depositional environment. In other cases, modern microbial mats, such as oscillatorian cyanobacterial mats found in salt flat settings, exactly replicate MISS seen in the geological record (Kolesnikov et al., 2017). These MISS show wrinkle and rugose variants considered to be the result of desiccation or the response of a mat to low oxygen conditions (Dietrich et al., 2013). Domal structures, formed by gas bubbles trapped beneath mats, are also seen in modern environments and have been linked with ancient examples (Eriksson et al., 2007).

MISS provide valuable evidence for depositional conditions, especially when they are interpreted as the product of photoautotrophic cyanobacteria (Noffke et al., 2022). Thus, some studies have used the presence of MISS in the rock record to infer deposition in shallower, sunlit conditions than the sedimentology might otherwise suggest (e.g. Pazos et al., 2015). However, chemoautotrophic bacteria, such as *Beggiatoa*, also produce mats and can thrive on the seafloor beyond the reach of sunlight. This raises the possibility that MISS can form in deeper water (Gallardo and Espinosa, 2007; Bailey et al., 2009), although it is important to note that such mats have not been observed to show textured surfaces. In all cases, MISS represent 'true substrates' (Davies and Shillito, 2018, 2021).

Many authors consider microbial mats to be abundant in environments that lack mat-grazing organisms, because they were inhibited by harsh conditions (e.g. Wignall et al., 2016, 2020), they had been eliminated by a mass extinction event (Pruss et al., 2004), or because they had yet to evolve (e.g. in the Precambrian; Hagadorn and Bottjer, 1999). The presence of MISS thus has significance for interpretation of both evolutionary and environmental conditions. Given the varied and sometimes complex morphology of MISS, it is assumed that they "cannot be mimicked by physical sedimentary process" (Noffke, 2009, p. 179) and thus are safely attributed to a biological origin. However, the recent description of similar structures formed by sediment gravity flows passing over lower-density fine-grained substrates, provides an alternative origin for many MISS, which we highlight herein.

The formation of fluid-induced interfacial deformation structures (FIDS) has only been elucidated recently (Peakall et al., 2024), although typical examples such as longitudinal ridges and furrows were investigated 60 years ago (Craig and Walton, 1962; Dżułyński and Walton, 1965). FIDS form when an overriding denser flow passes over a soft cohesive substrate, usually a mud, causing it to deform by a combination of shear and buoyancy processes. Flow-induced shearing sculpts the deforming substrate and produces linear, flow-parallel structures, with more irregular, polygonal and reticulate forms occurring when shear-related forces are weaker (Peakall et al., 2024). The resultant surface is then buried by deposition from the flow. FIDS have been produced experimentally by plaster-of-Paris laden flows run over beds of soft mud (Dżułyński and Walton, 1963, 1965; Dżułyński, 1965; Dżułyński and Simpson, 1966). Surfaces with FIDS are not bypass surfaces (Peakall et al. 2024), or 'true substrates' in the sense of Davies and Shillito (2021), because they are formed by the flow that casts them. It is unlikely that the sharp, steep ridges of mud that define many FIDS (see below) would survive exposure on the seabed for even short intervals. FIDS can cover bedding surfaces extending over tens of metres, but their components range from millimetres to tens of centimetres in scale and closely resemble many MISS. This thus raises the possibility that many examples of MISS encountered in clastic sediments are misidentified FIDS, especially in deep-water turbidite depositional settings where MISS are likely to be rare. Differentiating between MISS and FIDS is thus critical for palaeoenvironmental interpretations, but also for identifying whether the surfaces represent 'true substrates' or not. In the present study, our aim is to document the attributes of both MISS and FIDS and discuss the criteria by which they may be distinguished, and suggest that the abundance of MISS in the geological record has been overstated. Although this finding has major consequences for many palaeoenvironmental interpretations, it does not deny the existence of MISS. Indeed, their abundance in peritidal and supratidal settings is well established both in modern and ancient sediments (e.g. Eriksson et al., 2010; Kolesnikov et al., 2017; Noffke et al., 2022), and there is little likelihood that FIDS could form in such environments.

The present study documents the abundance of diversity of FIDS from several turbidite successions, especially the Booley Bay Formation (Late Cambrian, County Wexford, Ireland; MacGabhann et al., 2007), the Cloridorme Formation (early Katian Stage, Upper Ordovician, Quebec, Canada; (Pickering and Hiscott, 1985; Ningthoujam et al., 2022), the Bude Formation (Serpukhovian Stage, Lower Pennsylvanian, north Cornwall and north Devon, UK; Melvin, 1986; Burne, 1995, 1998) and the Ross Formation (Serpukhovian Stage, Lower Pennsylvanian, County Clare, Ireland; Wignall and Best, 2000; Pyles and Strachan, 2016; Pierce et al., 2018) and compares them with MISS reported from the peritidal strata of the Werfen Formation (Lower Triassic, Dolomites, northern Italy; (Broglio Loriga et al., 1983; Wignall and Hallam, 1992).

MISS Characteristics

Many terms are used widely to describe the range of MISS seen on bedding surfaces (Davies et al., 2016), with the most common being wrinkle marks, elephant skin texture, and a distinctive (and controversial) type given the biological name of “Kinneyia” (Porada and Bouougri, 2007; Noffke, 2009). We note that “Kinneyia” has been argued to be abiogenic in some cases (Davies et al., 2016; Stimson et al., 2017; and later discussion). Furthermore, it has been argued that the term itself should be abandoned (Stimson et al., 2017). However, given its widespread use we retain it here, albeit in quotation marks. Wrinkle marks are a broad category that include “oddly contorted, wrinkled, irregularly pustulose, quasi-polygonal, commonly oversteepened surface morphologies that can occur on bed tops and bottoms” (Hagadorn and Bottjer, 1999), whilst Davies et al. (2016) described them as being irregular, parallel ridges or networks of millimetre-scale ridges. Here, we restrict the term slightly to describe sub-parallel, discontinuous and somewhat sinuous ridges (Fig. 1A), whilst using the term elephant skin texture to describe polygonal to reticulate patterns with ridges and troughs 1–2 mm wide (*sensu* Porada and Bouougri, 2007; Fig. 1B). Both wrinkle marks and elephant skin textures typically have rounded crests and troughs, although examples of the latter can have flattened crests (e.g. Feng, 2021, fig. 3A; Fig. 1B). The microbial origin of these structures is supported by cases where there are gaps or holes in the structures, or isolated patches of MISS, suggesting that the mat has been removed, or partly broken up, due to either erosion or grazing (Porada and Bouougri, 2007; Eriksson et al., 2010; Fig. 1B), as is commonly observed in modern examples (Noffke et al., 2022).

“Kinneyia” mats consist of flat-topped ridges (Hagadorn and Bottjer, 1997, 1999; Pflüger, 1999), defined by Porada et al. (2008, p. 65) as “comparatively short, curved, frequently bifurcating, flat-topped crests, 0.5–1 mm high and 1–2 mm wide, which are separated by parallel, round-bottomed depressions. The crests are usually steep sided and may run parallel or form honeycomb-like patterns”. We note that not all ridges are “comparatively short”, because they can often be traced over distances >10 cm (e.g. Fig. 1C; and fig. 5b in Wignall et al., 2016), and the “bifurcation” is commonly anastomosing. The inclusion of “honeycomb-like patterns” in this definition indicates an overlap with forms that others (including us) term elephant skin texture (Porada and Bouougri, 2007, fig. 4). An important aspect of “Kinneyia” is that it is often developed through consecutive laminae, with the ridges and troughs inheriting the topography of the underlying bed (Fig. 1C; Noffke et al., 2022). The steep-to-vertical sides of the ridges suggest that “Kinneyia” may have formed beneath the sediment-water interface as a sub-mat structure (Bloos, 1976; Porada and Bouougri, 2007). In contrast, Thomas et al. (2013) proposed that “Kinneyia” was produced by shearing of a viscoelastic microbial mat at the sediment surface. However, the ridges and troughs are generally not deflected around seabed obstacles such as bivalves (Fig. 1D), suggesting that this mechanism is not an explanation for all occurrences of this type of MISS. Alternatively, “Kinneyia” may be produced by the trapping of gas bubbles beneath a microbial mat that has been buried beneath a thin layer of sediment (Pflüger, 1999). Adding to the diversity of possible origins, Pratt (2021) suggested that “Kinneyia” may be soft-sediment deformation features generated by earthquakes, Davies et al. (2016) suggested some “Kinneyia” may form as abiotic adhesion structures generated by wind moving over water films, whilst Noffke et al. (2022) proposed the texture may be produced by burial of organic mats “with jetting water squeezed out of the ……microbial mats” producing the texture. Ultimately, the origin of “Kinneyia” remains rather enigmatic.

FIDS Characteristics

FIDS vary considerably in form and scale (Peakall et al., 2024) and, like MISS, show gradations between the types. Forms showing a predominantly linear trend have been termed longitudinal ridges and furrows (Craig and Walton, 1962; Dżułyński and Walton, 1965). These consist of broadly parallel, but often slightly sinuous and sometimes bifurcating, ridges ranging from ~1 mm to several centimetres wide, and they can be many tens of centimetres long (Fig. 2A-F). The smallest examples consist of narrow ridges less than a millimetre high (Fig. 2A,B) with the largest examples 1–2 cm wide. When preserved on the soles of sandstones, the ridges are often narrower than the furrows in between (Fig. 2, all examples except for 2D). When preserved on the top surface of mudstone or siltstone beds, the ridges form sharp positive structures that contrast with the more rounded and broader troughs (Fig. 2E). However, examples with both rounded ridges and furrows with equal spacing also occur (Fig. 2D). A distinct variant of FIDS, commonly encountered in the Cloridorme Formation, resembles “Kinneyia” in consisting of flat-topped ridges and furrows of equal width (Fig. 3A). Like “Kinneyia”, they anastomose and bifurcate (Fig. 3A) and exhibit a similar size range, being ~5 mm, but never more than 10 mm, in width. Thus, this FIDS morphology has a narrower range of sizes than other types. In rare examples, “Kinneyia”-like FIDS have ridges ornamented with cuspate and oblique lamination (Fig. 3B), a feature not recorded in true “Kinneyia”.

Longitudinal ridges and furrows often have scales (cuspate structures) developed along the length of the furrows (Fig. 3C – E). This type of FIDS co-occurs occasionally on bedding planes with flow indicators such as flutes, which indicates that the scales widen downstream, thus providing a palaeoflow indicator and showing that the lineation of ridges and furrows is flow parallel (Fig. 3F; Craig and Walton 1962; Peakall et al. 2024), as also shown experimentally (Dżułyński and Walton, 1965). However, not all FIDS have an orientation, and many examples are more equidimensional or irregular in pattern, although such structures can pass laterally over a short distance into ridges and furrows (Figs 3D,F, 4A). These irregular FIDS have been called polygonal forms, or sometimes "dinosaur leather" where they cover entire surfaces (Chadwick, 1948; Peakall et al., 2024). More rounded examples have a distinctly mamillated texture (Fig. 4B). As with other types of FIDS, the size range of these irregular polygonal forms is considerable, spanning two orders of magnitude in which components range from a millimetre to tens of centimetres (Fig. 4C and Fig. 5). There are also examples that are termed 'network FIDS' herein, which form reticulate patterns. In these examples, the form of the ridges (as seen in casts on the soles of turbidite sandstones) is straight-sided, and the polygonal structures (Fig. 4D) are sometimes reminiscent of graphoglyptid traces such as *Paleodictyon*. It is noteworthy that some purported graphoglyptid traces have been reinterpreted as MISS (Buatois and Mángano, 2003). We suggest that in some cases they could be further reinterpreted as FIDS. A key aspect of such structures is that they grade laterally into other styles of FIDS (e.g. Fig. 4E, 6A) indicating that they are part of the FIDS spectrum. When seen on the soles of sandstone beds, network FIDS differ from the polygonal/dinosaur leather variety in having ridges separated by depressions of similar width, whilst in the latter, the bulbous polygons are separated by narrow clefts.

The final common variety of FIDS are wrinkled forms, which can again occur over a range of scales, with ridges ranging from a few millimetres up to a centimetre in width (Figs 4F, 6A). The wrinkles may be sub-parallel to each other, but can also show changes in orientation and swirling patterns over short distances, and rapidly grade laterally into other FIDS types, such as polygonal networks (Fig. 6A). Note that this type of wrinkle is different from transverse wrinkles, a rarely encountered type of FIDS, described by Dżułyński and Sanders (1962), which have crest lines oriented orthogonal to flow (Peakall et al., 2024).

All types of FIDS are found on the soles of turbidite sandstone beds, although in some examples they extend up through several laminae in the base of the sandstone, with each lamina faithfully draping the one beneath (e.g. the mamillated FIDS in Fig. 4B). This observation indicates that, once formed, the FIDS were covered by suspension fallout of sand during the purely aggradational stage of turbidite emplacement. FIDS are also commonly observed on the top surfaces of beds where they are preserved in mudstone or siltstone (Figs 2D,E, 4C and 6, either A, B). The scale of FIDS is partly dependent on the thickness of the fine-grained substrate that was being deformed (Peakall et al. 2024). Thus, the largest FIDS are developed on the surface of beds that are at least a few centimetres thick (e.g. Fig. 5). We have also observed FIDS in laminated siltstones, both on upper and lower surfaces, where they are present on every surface (Figs 4C, 6A,B), extending through several centimetres of strata. In this case, the beds are very thin (< 1 mm) and the scale of the FIDS is correspondingly small.

Discussion

Similarities of MISS and FIDS

How can structures formed by these different biological and abiological processes be distinguished? There are several morphological distinctions (Table 1). Wrinkle marks that are produced microbially have their counterpart in FIDS (compare Figs 1A and B with Figs 6A and B). Even the characteristic "gaps" where a microbial mat has been torn and partially removed (Fig. 1B) can also be seen in FIDS-covered surfaces that have "bald" patches (Fig. 4A). The polygonal pattern of elephant skin MISS (Fig. 1B) is also seen in polygonal FIDS (Fig. 4D). "Kinneyia"-covered surfaces, with their anastomosing and bifurcating, flat-topped ridges are also not a unique form of MISS because they have their FIDS parallel (Fig. 3A). Furthermore, the accretion of "Kinneyia" through multiple laminae (Fig. 1C) is a feature also seen in some FIDS (Fig. 4B).

Amongst the few differences, is the observation that FIDS frequently intergrade into each other on the same bedding surfaces over short distances (Fig. 3C, D, E; Peakall et al., 2024) and co-occur with structures such as scales that have no MISS parallel. Furthermore, erosional bedforms, such as flutes and grooves, are also encountered on FIDS surfaces and the flow direction they record is parallel with the lineation of longitudinal ridges and furrows because they are formed by the same flow (Fig. 3F; Peakall et al., 2024). This would not occur if the ridges and furrows were of microbial origin (Table 1). The components of FIDS also show a much greater size range and include examples with components that are decimetres in size, a scale that is orders of magnitude greater than any reported MISS (e.g. Figs 2D, 5).

MISS (and Ediacaran biota) reinterpreted as FIDS

The question is therefore: have FIDS been inadvertently misidentified as MISS, especially in deep-water settings where they are common and where the activity of photosynthetic microbial mats would be restricted or absent? The comparisons presented above suggest this may be true. For example, the Miocene Viamonte Formation, Argentina, is a deep-marine turbidite succession in which “Kinneyia”-like MISS are common (Olivero and López-Cabrera, 2023). The MISS were reported to have formed on the top surfaces of thin, silty mudstones, but are generally found as impressions on the soles of the overlying fine-grained sandstone turbidites — a typical style of FIDS preservation. These Miocene specimens are highly comparable to the longitudinal ridges and furrows described herein, in terms of both morphology and scale (Fig. 7A). Similarly, examples of possible MISS reported from the soles of Oligocene turbidite sandstones in Poland, closely resemble the longitudinal ridges and furrows and mamillated forms of FIDS (Uchman and Wetzel, 2025, their fig. 3, *this volume*).

The Silurian-Devonian turbidite-like Río Seco de los Castaños Formation, Argentina, has been interpreted to be the product of storm deposition, because it contains abundant MISS, suggesting shallower-water deposition than is typically associated with turbidite successions (Pazos et al., 2015). Illustrations show structures that closely resemble longitudinal ridges and furrows, small-scale network FIDS and “Kinneyia” (Figs 7B, C). Reinterpretation of these structures as FIDS is in better accord with the turbidite-like sedimentology of the Formation and also agrees with the presence of diverse *Nereites* in the succession, a trace fossil typical of turbidite successions (Uchman, 2004).

The Ediacaran Cíjara Formation in Spain, also exhibits structures on the soles of turbidites that are interpreted as MISS (Álvaro et al., 2024, their fig. 3), and yet these closely resemble longitudinal ridges and furrows, and other FIDS. The presence of amorphous organic matter associated with these structures, interpreted as organic mat fragments, and thus further evidence for MISS (Álvaro et al., 2024), would indicate the transport of organic mat fragments by turbidite flows, in the case where these are interpreted as FIDS.

Diverse MISS have been illustrated from the Republic of Gabon in the 2.1 billion-year-old Francevillian B Formation, a shale succession with thin siltstones and massive sandstones interpreted as deposited from “waning storm surges” (Aubineau et al., 2018), and linked to turbidite deposition (Parize et al., 2013; Reynauld et al., 2018). The structures include wrinkle marks showing swirly patterns, polygonal networks called “elephant skin”, which are identical to the network FIDS described here, and “Kinneyia” with characteristic flat-topped ridges and furrows, comparable to ridge-and-furrow type FIDS. In addition, disc-shaped structures are present (Fig. 7D). These Paleoproterozoic “discs” are some of the oldest reported macrofossils (El Albani et al., 2010; Aubineau et al., 2018, p. 476) and thus have great macroevolutionary significance. However, their biological origins have been questioned, with the disc-shaped structures interpreted to be concretions (Anderson et al., 2016), whilst a FIDS origin is a more likely explanation for the purported microbial features.

A younger record of MISS comes from deep-water shales and siltstones of the Middle Cambrian of Sweden. Illustrations of “Kinneyia” from this setting shows their characteristic form of elongate ridges and furrows, although they grade laterally into more reticulate patterns (Porada and Bouougri, 2007, fig. 4C). These structures are seen on the top surface of siltstone beds, and once again a FIDS origin for these structures is likely.

The presence of microbial structures in deep-water is unusual because mats formed by photoautotrophs cannot be readily invoked, and this has led some authors to postulate other origins for apparent MISS. Vodrážková et al. (2019), following the model of Brett et al. (2003), suggested that MISS from the Devonian deep-water Srbsko Formation of Czechia could be the product of earthquake deformation. However, seismic shaking of the sediment surface might be expected to produce liquefaction and soft-sediment deformation structures (e.g. Owen, 1996), whilst the illustrated examples, on the bedding surfaces of sandy siltstones, are identical to small-scale FIDS (e.g. mamillated, reticulate and wrinkled FIDS, such as those seen in the Cloridorme Formation).

Other potential examples of FIDS come from shallower-water strata. The Ediacaran-aged Cerro Negro Formation of Argentina is considered to have formed at shelfal depths (Arrouy et al., 2016, 2023). The presence of wave ripples with wrinkle structures restricted to the troughs (Arrouy et al. 2016, fig. 4a) is good evidence for both shallow water and the presence of microbial mats; it is unlikely that FIDS would form on the top surface of ripples. However, the considerable diversity of proposed MISS in the Cerro Negro Formation includes “Kinneyia”, elephant skin, and wrinkle structures. The latter are parallel-sided and show current lineations (Fig. 7E), and therefore are more akin to longitudinal ridges and furrows, whilst “honeycomb-like features” (Arrouy et al., 2023, fig. 4c) and “slightly reticulate elephant skin” (Arrouy et al., 2023, fig. 4f) resemble reticulate and mamillated FIDS, respectively. These structures were identified in loose blocks, from a succession composed of tabular sandstones that include examples of flutes and discontinuous tool marks on their bases (Arrouy et al., 2023). There is clearly scope for reinterpreting the Cerro Negro MISS, which are not associated with wave ripples, as FIDS that formed on the soles of turbidites within this relatively shallow water setting (above wave base).

Microbial mats are considered integral to the development and preservation of communities of Ediacaran organisms in the late Precambrian because they stabilized the seabed, thus allowing these primarily sessile organisms to thrive (Seilacher, 1999; Buatois and Mángano, 2016). Many of the reported mats resemble FIDS, but as they occur within sandstone-dominated successions (e.g.

Droser et al., 2022) they are likely to have been MISS because FIDS require a fine-grained substrate in which to form. However, some mat textures occurring on the soles of beds include a form called “weave” that has a “directional fabric” consisting of “undulate, sub-parallel ridges and grooves” (Gehling and Droser, 2009, p.200). The examples illustrated on the soles of sandstone beds (e.g. Fig. 4F) closely resemble longitudinal ridges and furrows, and have ridges that are broad and rounded and separated by narrow, sharp furrows, a typical characteristic of this type of FIDS when cast on the soles of sandstone beds (e.g. Fig. 2). Thus, we suggest that not all of these reported Ediacaran MISS are necessarily of microbial origin.

It is also worth considering that some Ediacaran organisms may themselves be FIDS, especially the enigmatic and controversial form called *Arumberia* (Glaessner and Walter 1975; McIlroy and Walter, 1997; Seilacher, 1999; Retallack and Broz, 2021; McMahon et al., 2022; Arrouy et al., 2023). As originally defined from the Arumbera Sandstone of the Northern Territories, Australia, *Arumberia* consist of aligned (sometimes radiating), narrow ribs and grooves preserved on the base of sandstone beds overlying fine-grained sediment (Glaessner and Walter, 1975). These attributes are closely similar to the smallest examples of longitudinal ridges and furrows noted herein (Fig. 2A, B). More recent discoveries have increased the diversity of *Arumberia* morphologies and shown that some can transition laterally into reticulate patterns (McMahon et al., 2022, fig. 3h, i) that again is a common attribute of FIDS. Since its original definition, the biogenicity of *Arumberia* has been questioned. McIlroy and Walter (1997) noted the similarity to sedimentary structures, including flutes, generated in the experiments of Dżułyński and Walton (1965). However, McIlroy and Walter (1997) noted the problem that, if they are sedimentary structures, then why is *Arumberia* restricted to the Ediacaran interval? We would argue from the examples shown herein, that there is no such time-specific problem for *Arumberia* because longitudinal ridges and furrows resembling this taxon are known from a much greater timespan. In contrast, Retallack and Broz (2021, p. 1969) consider *Arumberia* to be a body fossil and reported the presence of “complex internal structures of chambers defined by ferruginized seams and filaments” with supporting struts. However, McMahon et al. (2022, p.18) also noted that the transitions between linear, reticulated and curled varieties of *Arumberia* rule out the claim of Retallack and Broz (2021) for an animal origin, and instead suggested that a microbial mat origin is more likely, for which there are modern analogues (Kolesnikov et al., 2017). The presence of desiccation cracks and rain imprints on surfaces associated with *Arumberia* supports this MISS origin (McMahon et al., 2022), but we contend that some occurrences of *Arumberia* may be better attributed to FIDS, especially those that are found in deep-water facies (e.g., MacGabhann et al., 2007; Arrouy et al., 2023).

Distinguishing between MISS and FIDS

Both MISS and FIDS come in a broad range of morphologies that, as illustrated herein, can be closely comparable (Table 1). Thus, distinguishing these structures based on morphology alone is dubious, although only surfaces covered in FIDS show an intergradation between different types — an attribute that likely reflects subtle variations of substrate consistency and overlying fluid shear during their formation (Peakall et al., 2024). Preservation styles can also be used as distinguishing criteria. FIDS are formed in fine-grained substrates beneath overriding denser flows prior to being preserved by deposition from the same flow (Peakall et al., 2024). Thus, FIDS form in mudstone or siltstone substrates and are cast at the base of the overlying bed. The casting flow, deposited by the sediment gravity current responsible for the FIDS, can be any grain size from silt to coarse sand. FIDS can be found on the tops of beds where mudstones are exposed, particularly in settings where that mudstone is strongly indurated. MISS also form on the top surface of beds but the draping bed can sometimes be mudstone, which is not an attribute of FIDS surfaces that have overlying beds of siltstone or sandstone. Where structures form on sandstone or limestone substrates, these are likely to be MISS, as FIDS are not recognised on such substrates. Petrographic analysis has also provided criteria for identifying microbial mats, with ancient mats preserved as fine grained, organic-rich, laminae with features including isolated sand grains “floating” in the matrix (Noffke, 2009; Noffke et al., 2002, 2022). If such laminae drape a MISS surface, then a microbial origin is likely.

Facies occurrence could also potentially distinguish MISS from FIDS (Table 2). Modern MISS are recorded from peritidal settings where microbial mats thrive in sunlight (Noffke, 2009; Kolesnikov et al., 2017). Furthermore, such settings are unlikely to be associated with the high-density flows that produce FIDS. In some cases, the presence of MISS has been employed as a key line of evidence for a shallow-water setting (e.g., Pazos et al., 2015). Given that MISS may be misidentified FIDS, other evidence for shallow-water conditions is needed. For example, identification of structures such as hummocky-cross-stratification (HCS), which is often associated with combined flows between storm and fairweather wave bases (Arnott and Southard, 1990; Dumas and Arnott, 2006; Wu et al., 2024), may be useful. However, there is now recognition that simple aggradational hummocks are also prevalent in many deep-water settings, and thus care should be taken in using these structures as indicators of shallow water (Tinterri, 2011; Hofstra et al., 2018; Privat et al., 2021; Tinterri et al., 2022; Keavney et al., 2025). It thus follows that other independent diagnostic criteria for shallow water (e.g. wave ripples, desiccation cracks) are ideally required. Furthermore, whilst the examples of FIDS documented herein are from deep-water turbidite systems, it is likely that further investigations will show that they can also be encountered in shallow waters (Table 2). Examples could be sought in delta-front locations where high concentration hyperpycnal flows move across muddy substrates, and in overbank settings where the breaching of levees by sediment-laden currents could produce FIDS in fine-grained floodplain sediments.

FIDS can potentially form over a broad range of water depths, and MISS are similarly reported from shallow and deeper waters below the photic zone. For deeper occurrences, filamentous, sulphur-oxidising bacteria found in poorly oxygenated sea beds (Bailey et al., 2009) may provide a modern-day analogue. Such mats may have been widespread in the poorly ventilated oceans of the Precambrian and Early Paleozoic (Sperling et al., 2021; Mills et al., 2023). However, these chemosynthetic mats are not associated with sediment textures, rendering their significance somewhat moot.

Conclusions

Fluid-induced interfacial deformation structures are produced when sediment gravity flows pass over a less dense cohesive substrate that is deformed by buoyancy and shear forces. The resultant structures are preserved as the flows deposit sediment, and show a broad range of morphologies over a range of scales, from a millimetre to many centimetres. Longitudinal ridges and furrows are amongst the most common variety and are aligned parallel to flow, indicating formation by shear and buoyancy processes. In some cases, scales are formed in the furrows that record the palaeocurrent direction. The diapiric ridges are usually much narrower and sharper than the grooves and can be several millimetres high. However, examples with equal-width ridges and furrows also occur and include a variant with flat-topped, anastomosing ridges and furrows (Fig. 3A). Where shear is of lesser importance in the formation of some FIDS, this results in forms that are much more irregular in planform. These FIDS include wrinkly forms that can form swirly patterns, polygonal forms (sometimes called “dinosaur leather”), and mamillated forms. Network FIDS also occur, consisting of reticulate patterns of ridges when seen as casts on the lower surface of beds. These patterns can resemble the polygonal traces of graphoglyptids like *Paleodictyon*. Importantly, this considerable variety of FIDS can often be seen on the same bedding surface within a few decimetres of each other (e.g. Fig. 3D) and unoriented networks can transition laterally into forms with distinct elongation (e.g. Figs 4B, E). All these observations indicate that there was considerable local variation in flow and bed conditions at the base of the overriding currents, thus contradicting the notion that complex morphologies can only be produced by biogenic processes.

Microbially-induced sedimentary structures also show a broad range of morphologies (Davies et al., 2016), with modern analogues having been recorded from shallow water settings, notably salinas (Koselnikov et al., 2017; Noffke et al., 2022). The broadly-termed "wrinkle marks" can be irregular in planform, but also show elongate varieties, including a distinctive form with flat-topped ridges and furrows often called "Kinneyia". The great majority of morphologies attributed to MISS are also seen with FIDS, thus raising the possibility that some, perhaps many, purported MISS occurrences are spurious, and we demonstrate numerous examples where this is likely. There are only a few criteria available to distinguish between the different origins. The components of FIDS structures range up to sizes that are considerably larger than any known MISS (Table 1) and are formed on fine-grained clastic substrates (up to silt) found beneath turbidite sandstones. Thus, a textured surface overlain by mudrock is highly unlikely to be a form of FIDS. The sedimentary context of occurrences is also important (Table 2). FIDS are abundant in turbidite successions, whilst MISS are abundant in shallow waters, reflecting the growth of photosynthetic mats in the photic zone. However, high concentration mud-rich flows across less dense muddy substrates may also occur in shallower waters, such as delta fronts and crevasse splays into floodplain lakes, raising the possibility that FIDS may also occur in some shallow-water settings. Many of the structures identified in Arrouy et al. (2023) may indeed be examples of such FIDS in shallow water. However, can MISS form in deep water? Chemosynthetic mats offer a possible origin, although modern observations suggest that they do not form the textured surfaces seen in shallower waters. Finally, we note that some specimens of the more controversial Ediacaran fossils, such as *Arumberia*, whose origin has raised intense debate, may also be examples of FIDS.

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Figure Captions

Fig. 1 A. Wrinkle marks showing sub-parallel, sinuous and discontinuous ridges and grooves. Campil Member, l'Uomo section. B. Elephant skin texture showing a polygonal pattern trending from equidimensional to more elongate versions. Gaps in the pattern (arrowed) likely record sections of mat that were torn out. Campil Member, l'Uomo section. C. Kinneyia covering bedding planes showing parallel ridges and grooves, sometimes bifurcating, and the continuity of structures between consecutive laminae. Campil Member, l'Uomo section. D. Kinneyia marks on a surface with convex-up disarticulated bivalves (*Unionites*). The trend of the ridges is not disrupted by the presence of the bivalves. Andraz Member, l'Uomo section. All specimens show the upper surfaces of calcareous siltstone or fine sandstone beds from the Werfen Formation, Dolomites, northern Italy, and have been coated in ammonium chloride to highlight the features.

Fig. 2 The morphological diversity of longitudinal ridges and furrows. A. Small longitudinal ridges cast on the sole of a turbidite sandstone. Ross Formation, south side of Ross Bay, County Clare, Ireland. B. Enlargement of same surface seen in A) showing the narrow furrows with a spacing of ~1 mm. C. Ridge and furrows cast on the sole of a turbidite sandstone showing a slight variation in orientation. Ross Formation, south side of Ross Bay, County Clare, Ireland. D. Broad, low amplitude ridges and furrows showing frequent bifurcation, seen on the top surface of a 2-mm thick siltstone capping a bed of fine-grained sandstone. Cloridorme Formation, Petite Vallée, Gaspe Peninsula, Quebec. E. Strongly parallel ridges and furrows preserved in mudstone on the top surface of a bed, showing sharp, narrow ridges, and broader, rounded furrows. Gull Island Formation, Confusion Bay, County Clare, Ireland. F. Large-scale examples of ridges and furrows on the base of a turbidite sandstone. Scale bar marked in centimetres. Ross Formation, Beal, County Kerry, Ireland. Note that specimens in A – D were coated in ammonium chloride to highlight their features.

Fig. 3 A. Flat-topped, longitudinal ridges and furrows that anastomose and bifurcate on the basal surface of a turbidite sandstone. Cloridorme Formation, Grande Vallée, Gaspe Peninsula, Quebec. B. Basal surface of turbidite sandstone with ridges and furrows showing cuspate and oblique laminations ornamenting the ridges. Flow is from left to right. The surface was coated with ammonium chloride. Cloridorme Formation, Petite Vallée, Gaspe Peninsula, Quebec. C. Basal surface of a sandstone turbidite showing scale structures indicating flow from bottom to top of the image. Centimetre scale bar in bottom right. Cloridorme Formation, Pointe-à-la-Renommée, Gaspe Peninsula, Quebec. D. Basal surface of a sandstone turbidite showing a diversity of FIDS. Scales dominate the centre of the block to the left of the coin (25 mm in diameter), longitudinal ridges and furrows occur in the upper left of the block, whilst polygonal structures occur elsewhere. Cloridorme

Formation, Pointe-à-la-Frégate, Gaspe Peninsula, Quebec. E. Basal surface of a turbidite sandstone showing ridges and furrows, several of which are ornamented by scales indicating flow to the left. Booley Bay Formation, Booley Bay, County Wexford, Ireland. Scale bar is marked in centimetres. F. Diverse FIDS on the basal surface of a turbidite sandstone. Longitudinal ridges and furrows occupy the central part of the surface and pass into polygonal FIDS to the right of the dashed yellow line. The FIDS are cross-cut by flutes, indicating flow to the right, with isolated examples in the lower left, a flute train (white arrow) at the bottom, and a concentrated field of flutes in the upper right. Booley Bay Formation, Booley Bay, County Wexford, Ireland. 8 cm scale bar.

Fig. 4 A. Diverse FIDS on the basal surface of a turbidite sandstone. Small-scale, longitudinal ridges and furrows are present in the lower part and on the right-hand side of the image, whilst higher relief polygonal FIDS occur in the upper left. Note also the bare patches where no FIDS developed. The coin is 24 mm in diameter. Cloridorme Formation, Petite Vallée, Gaspe Peninsula, Quebec. B. Mamillated basal surface of turbidite sandstone overlain by four sandstone laminae that drape the surface. Note the slight elongation of structures in the upper right of the surface. Cloridorme Formation, Pointe-à-la-Renommée, Gaspe Peninsula, Quebec. C. Upper surface of thin bed of siltstone (coated in ammonium chloride) showing slightly elongate, aligned small ridges. Cloridorme Formation, Petite Vallée, Gaspe Peninsula, Quebec. D. Small scale polygonal network of FIDS on the lower surface of turbidite sandstone. Coin is 27 mm in diameter. Cloridorme Formation, Pointe-à-la-Frégate, Gaspe Peninsula, Quebec. E. Network FIDS cast on the basal surface of turbidite sandstone. There is considerable variation in the complexity of the network, ranging from a discontinuous, mamillated appearance on the left edge to a more continuous network with preferred orientation shown by double-headed arrow. Booley Bay Formation, Booley Bay, County Wexford, Ireland. F. Wrinkle marks on multiple lower surfaces of thin siltstone beds, oriented vertically. Cloridorme Formation, Grande Vallée, Gaspe Peninsula, Quebec.

Fig. 5 Exceptionally large polygonal FIDS seen on the lower surface of a turbidite sandstone in an accessible cliff face in which bedding is vertical. The cliff face is approximately 3 – 4 m high. Bude Formation, Upton Cliffs, north Cornwall, UK.

Fig. 6 Two surfaces of the same thin slab of siltstone (coated in ammonium chloride) showing predominantly wrinkle-style FIDS that locally grade into network FIDS, especially in the top right of image A). This small slab was collected as a loose block and thus one side is the upper surface, whilst the other side is the lower surface. Cloridorme Formation, Petite Vallée, Gaspe Peninsula, Quebec.

Fig. 7 A. Longitudinal ridges and furrows seen on the sole of a turbidite sandstone. Originally interpreted as “Kinneyia”-like ripples by Olivero and López Cabrera (2023, fig 9a). Reproduced with permission of SEPM. B. Small-scale network FIDS on bedding surface, Río Seco de los Castaños Formation, Argentina. Originally interpreted as wrinkle marks produced by microbial mats by Pazos et al. (2015, fig. 4c). Reproduced with the permission of Elsevier. C. Flat-topped, longitudinal ridges and furrows of equal spacing, seen in the Río Seco de los Castaños Formation and similar to the examples seen in the Cloridorme Formation (Fig. 3A). Originally interpreted as elongate wrinkle marks produced by microbial mats by Pazos et al. (2015, fig. 5c). Reproduced with the permission of Elsevier. D. Mamillated FIDS from the Francevillian B Formation resembling similar structures seen in the Cloridorme Formation (Fig. 4B). Originally interpreted as a “putative macro-tufted microbial mat” by Aubineau et al. (2018, fig. 4d). Reproduced with the permission of John Wiley and Sons. E. Longitudinal ridges and furrows, Cerro Negro Formation (reproduced from Arrouy et al. 2023 under the Creative Commons CC-BY licence). These were originally interpreted as linear wrinkles, a form of MISS, in Arrouy et al. (2016, fig. 4b; 2023, fig 4a). F. Patch of “weave” fabric on the sole of a sandstone bed, showing gradual fading out at the margins, from the Ediacara Member of the Rawnsley Quartzite Gehling and Droser (2009, fig. 4f). Interpreted as MISS, they resemble longitudinal ridges and furrows (i.e. FIDS). Reproduced with the permission of Elsevier.

Table Captions

Table 1. Comparison of the attributes of fluid-induced interfacial deformation structures (FIDS) and microbially induced sedimentary structures (MISS).

Table 2. Comparison of environmental settings, reported and potential, of MISS and FIDS.

	FIDS	MISS
Composition	Formed in fine-grained clastic substrates (mud – silt) and often cast by overlying sandstone beds.	Mats can bind a range of clastic sediments from mud to sand and also carbonates.
Size	Components of FIDS range from a millimetre (Fig. 2a) to decimetric (Fig. 5). Larger examples are usually found on the top surface of thicker mud beds.	Components of MISS have a narrow size range from 1 to ~5 millimetres (Fig. 1). There is no relation between bed thickness and the size of MISS components.
Varieties	Longitudinal ridges and furrows that can possess cuspate structures (scales) that open down-flow. Ridges are typically sharp and narrower than furrows. Irregular FIDS (sometimes called dinosaur leather), can grade into network FIDS that show a reticulate or polygonal pattern. Mamillated surfaces. “Kinneyia”-like surfaces.	Elongate wrinkle marks. Elephant skin (or irregular wrinkle marks), that can show reticulate or honeycomb patterns. Domal and pustulose surfaces (formed by gas bubbles trapped beneath a mat). “Kinneyia” (flat-topped ridges and depressions 1-2 mm wide).

Occurrence	Typically occur on the sole of sandstone beds, but also on bed tops of mudstones and siltstones. Sometimes associated with sole marks (flutes and grooves) whose orientation is parallel with oriented FIDS on the same surface. They can intergrade between varieties.	Found on bed tops and cast on bed bases. Never associated with sole marks.

Table 1

	MISS	FIDS
Floodplain		Potentially present where crevasse splays enter floodplain lakes and ponds.
Delta		Potentially present, especially in delta front settings where hyperpycnal flows develop over muddy substrates in mouth bar settings.
Supratidal flats	Common on fine-grained clastic and carbonate surfaces, associated with desiccation cracks and birds eye structures.	
Peritidal settings	Common, often seen in troughs between wave ripple crests.	
Shelf	Present on the top surfaces of sandstone beds, and at sandstone-on-sandstone bedding contacts.	Present on the soles of tempestites resting on fine-grained strata.
Deepwater basin floor turbidites	Potentially formed by chemosynthetic mats, although modern analogues are not associated with surface textures assigned to MISS (see text), and neither are they known from turbidite settings.	Common on the bases of sandstone turbidites in contact with underlying fine-grained beds. Can also be found on upper surfaces of indurated muds.

Table 2

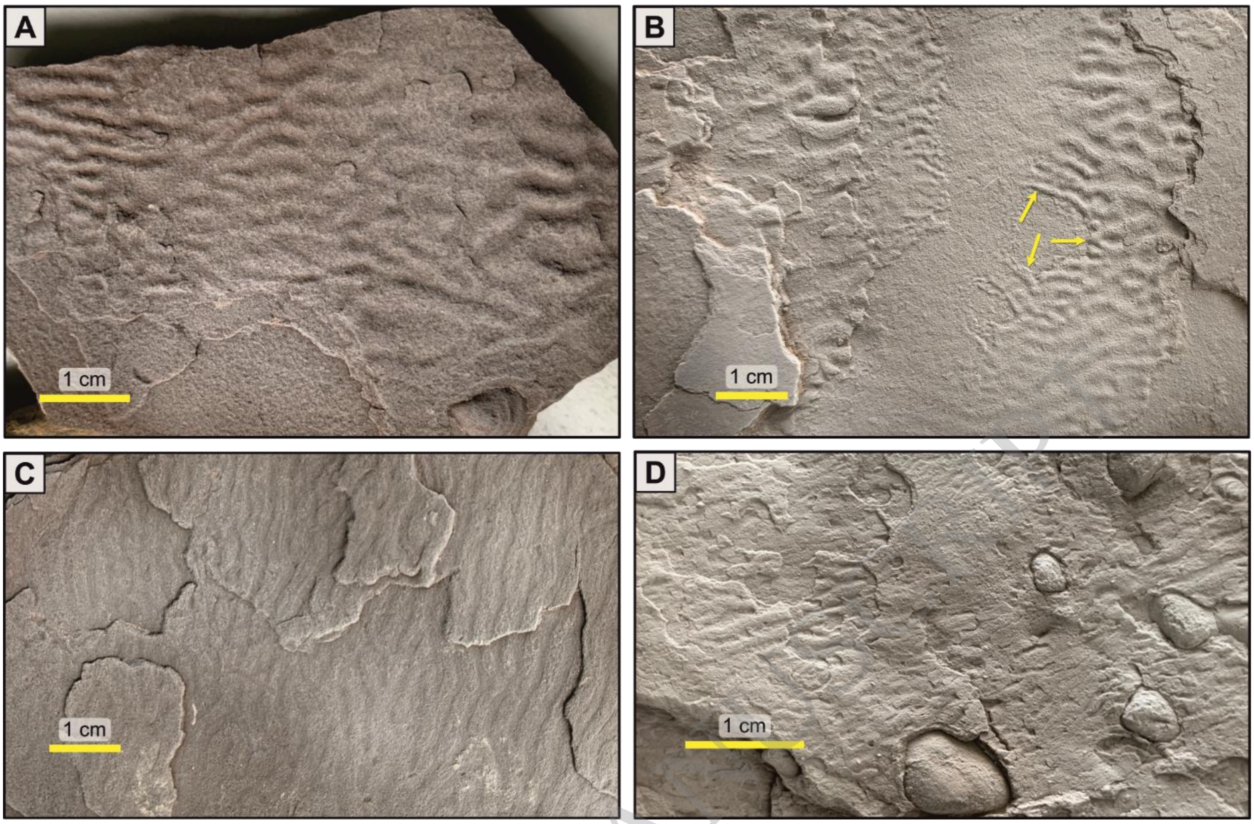


Figure 1

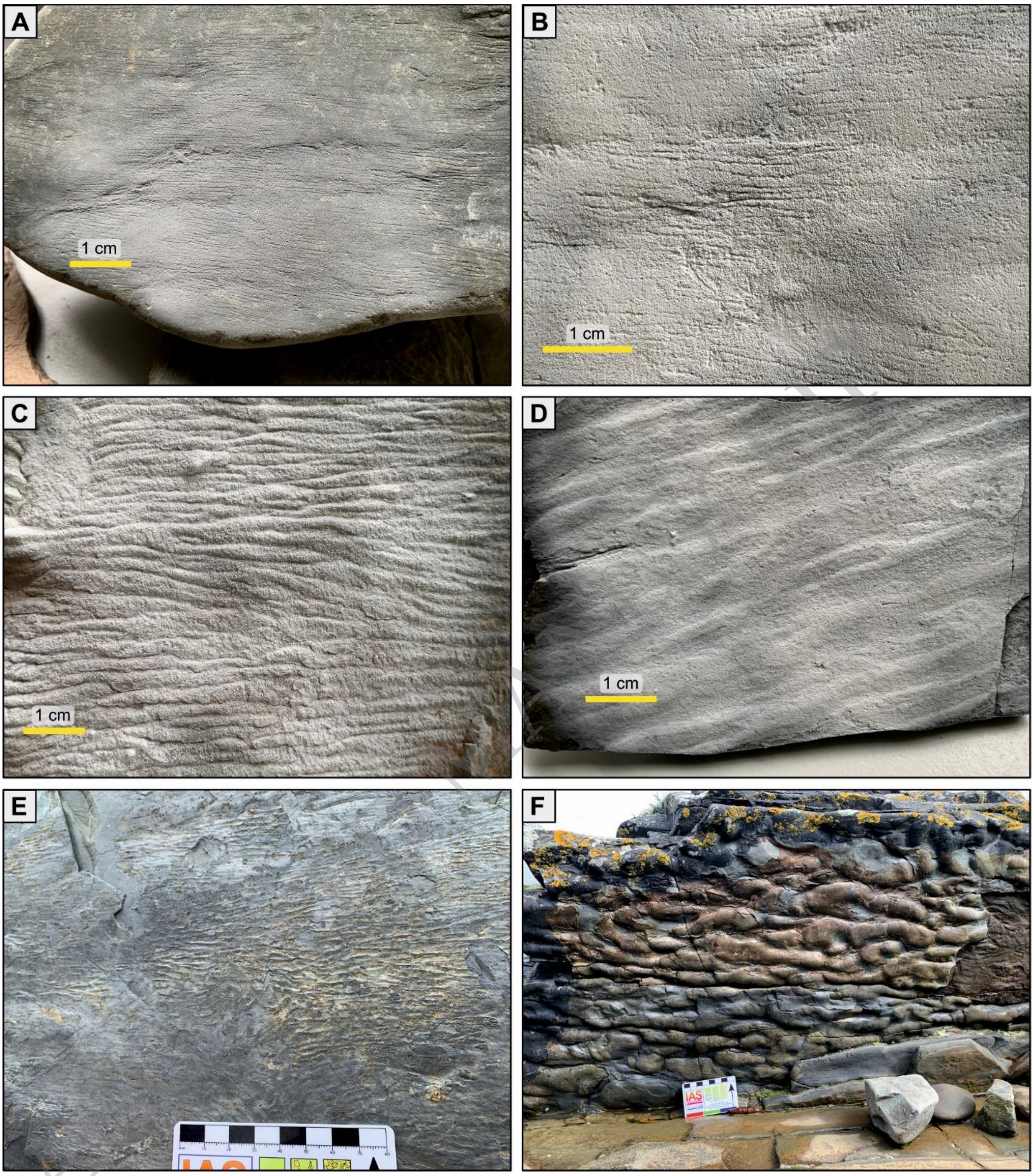
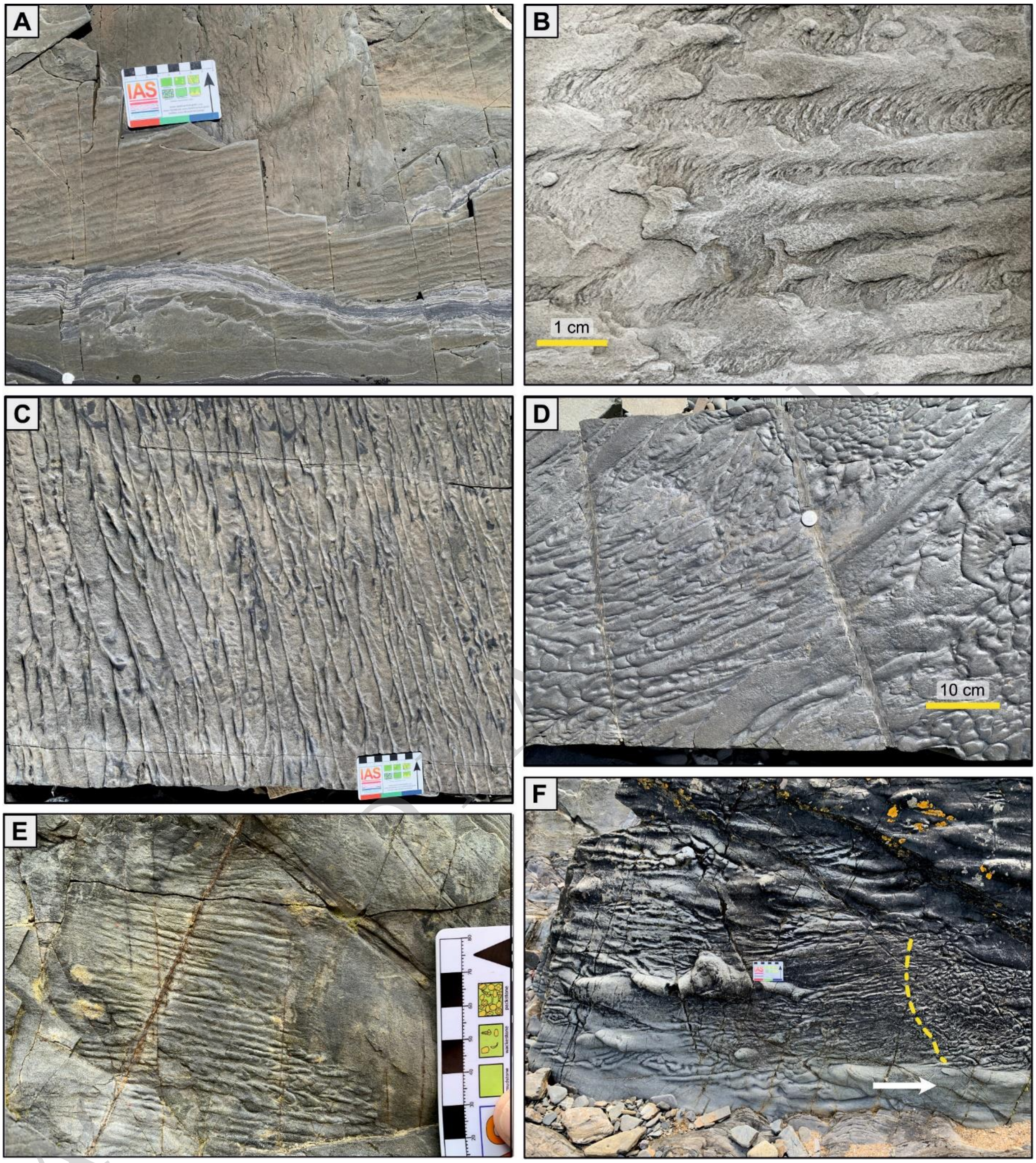


Figure 2



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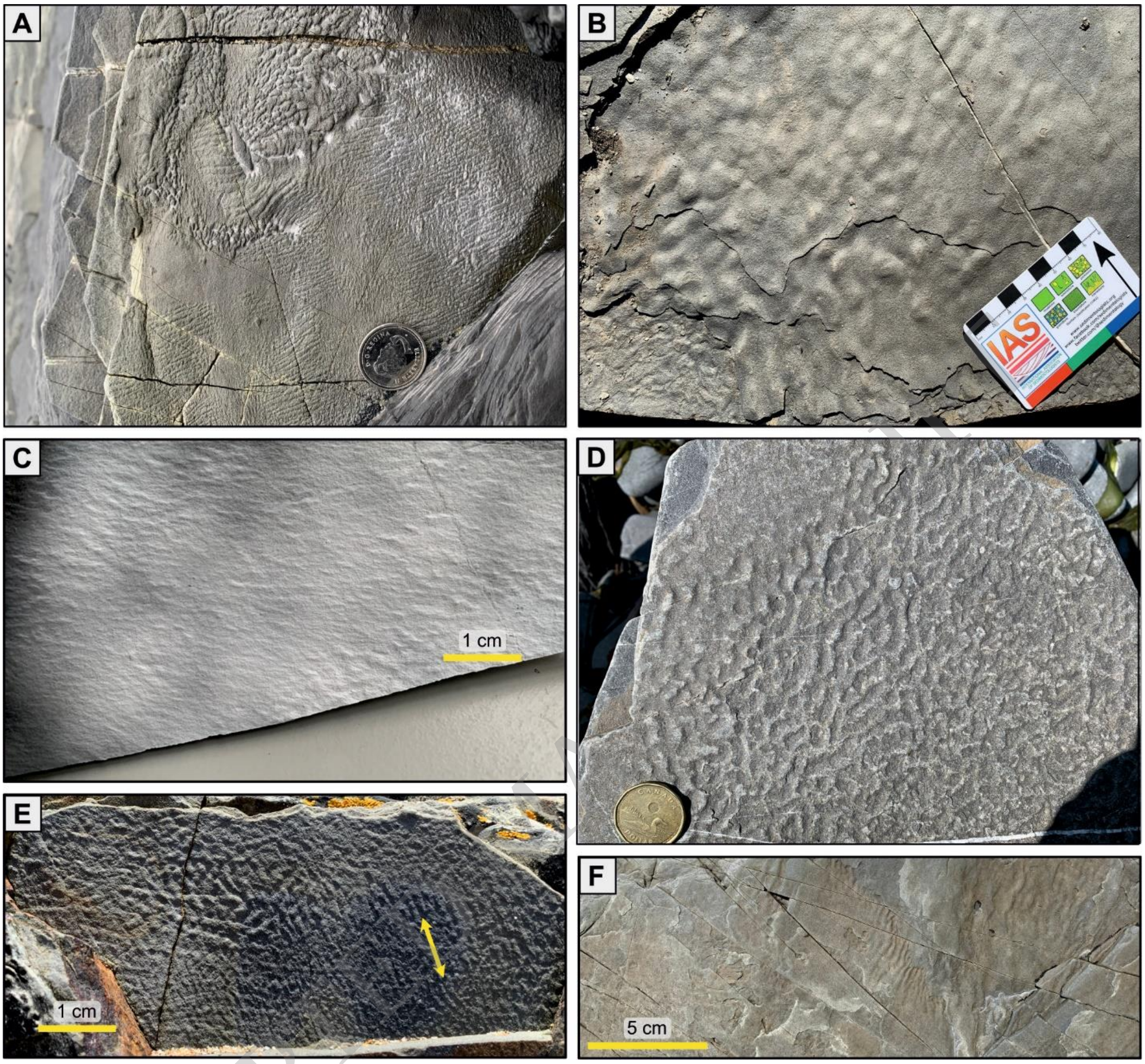

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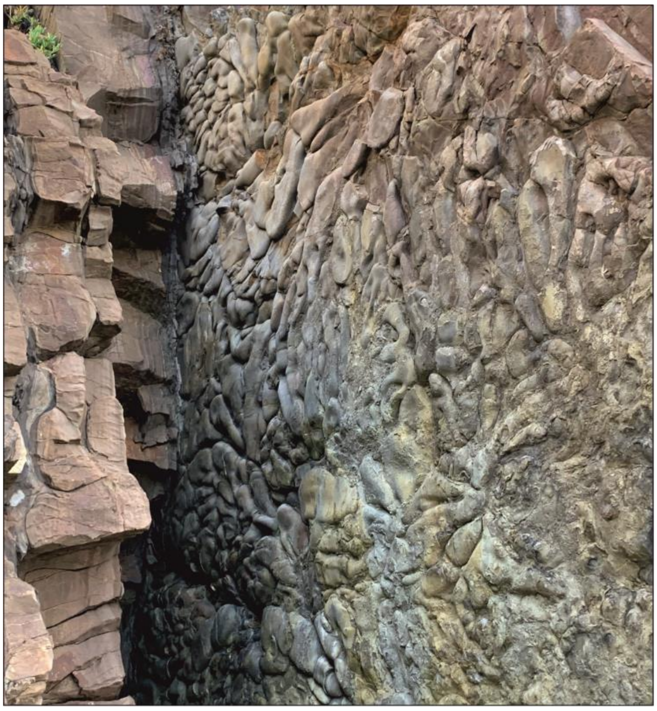

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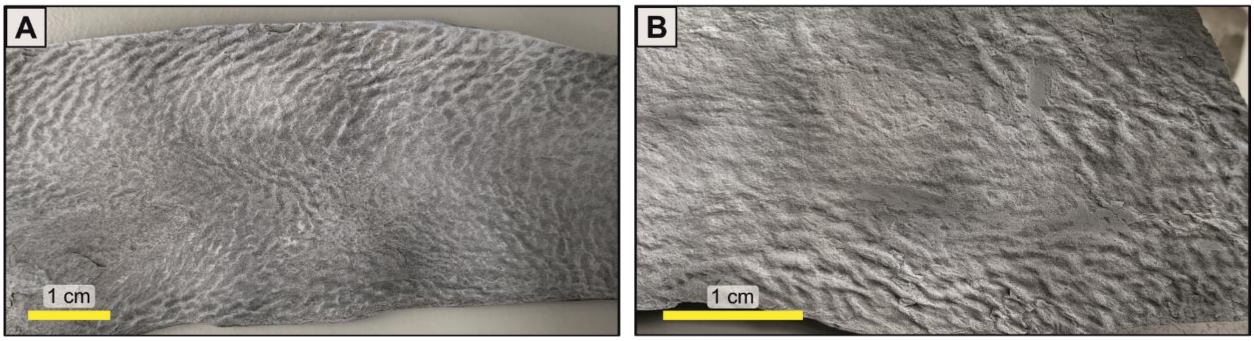

Figure 6

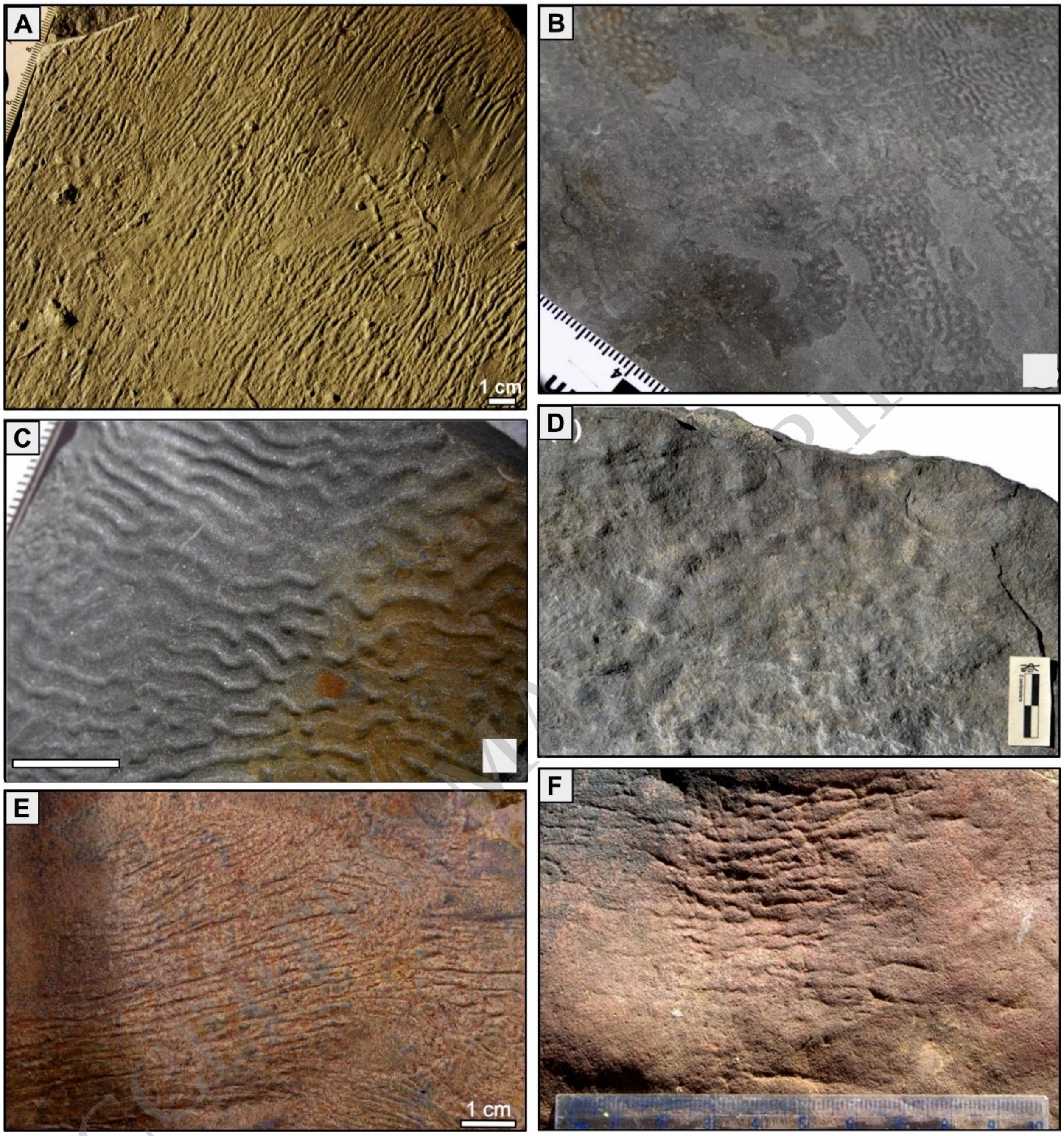

Figure 7