6(a). ‘Wrinkle structures’ – a critical review

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Introduction

In this section, we critically review a variety of so-called ‘wrinkle structures’ in an attempt to help distinguish between crinkly decorations arising from physical processes that acted on siliciclastic bedding surfaces, and true microbially induced ‘wrinkle structures’. The latter, however, are not easily differentiated from the numerous small-scale, crinkly irregularities on ancient bedding surfaces that originate from physical processes without participation of microbial communities, for instance: types of rill marks (e.g., Shrock, 1948; Reineck and Singh, 1980); swash marks (e.g., Reineck, 1956); foam and moving foam impressions (Häntzschel, 1935; Allen, 1966; Wunderlich, 1970; Reineck and Singh, 1980); adhesion warts and adhesion ripples (‘antiripplets’ after van Straaten, 1953; ‘eolian microridges’ after Hunter, 1969; see, e.g., Reineck, 1955; Kocurek and Fielder, 1982); rain impact ripples (e.g., Clifton, 1977; Reineck, 1984; Robb, 1992); and small-scale load structures (e.g., Allen, 1985). All these may occur, like microbially induced ‘wrinkle structures’, in the intertidal to lower supratidal zones. Furthermore, some current marks and fleur-de-lys patterns known from turbiditic successions (e.g., Dzulynski and Walton, 1965) as well as tectonically induced crenulations may develop similar appearances in response to physical processes.

Two types of small-scale, microbially induced sedimentary structures are prominent due to their distinct geometry and mode of occurrence: (1) ‘elephant skin’ (Runnegar and Fedonkin, 1992; Gehling, 1999) textures, characterized by reticulate patterns of sharp-crested ridges forming millimetre- to centimetre-scale polygons, occurring on argillite or argillaceous veneers above fine-grained sandstone and likely reflecting growth structures of microbial mats; (2) ‘*Kinneyia*’ (Walcott, 1914) structures, characterized by millimetre-scale flat-topped, winding ridges and intervening troughs and pits, sometimes resembling small-scale interference ripples. ‘*Kinneyia*’ structures usually occur on upper surfaces of siltstone/sandstone beds, themselves frequently event deposits, and are thought to have formed beneath microbial mats. Finally, some biogenic wrinkly structures resulting from tractional mat deformation or mat slumping are occasionally preserved. ‘Wrinkle structures’ occur more frequently in Proterozoic than in Phanerozoic siliciclastic rocks.

Historical review and discussion of terms

The term ‘wrinkle marks’ (Runzelmarken) was introduced by Häntzschel and Reineck (1968) to describe systems of straight or winding, flat-topped ridges, 0.5-1 mm wide and a few millimetres apart, which may run parallel or form honeycomb-like patterns with round or elongate pits between intervening ridges (see Fig. 6(a)-1). Modern structures identical to these have not been observed yet, but ancient examples are numerous. They have been described as ‘*Kinneyian* ripples’ (Martinsson, 1965; Bloos, 1976), ‘*Kinneyia* structures’ (e.g., Beukes, 1996) or briefly ‘*Kinneyia*’ (Seilacher, 1982; Pflüger, 1999) and are grouped with ‘wrinkle marks’ since the

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publication of Reineck and Singh (1973). Based on the original structures presented by Häntzschel and Reineck (1968) and Reineck (1969), the term ‘wrinkle marks’ has a two-fold, divergent meaning. It refers to (1) *Kinneyia* structures likely resulting from microbial activities, and (2) structures of physical origin, likely miniature load structures (Allen, 1985). The two types of structures may show similar appearances on bedding surfaces, but differ distinctly in cross-section (see Fig. 6(a)-1).

In 1997 (p. 1047) and 1999, Hagadorn and Bottjer distinguished between ‘wrinkle marks’ forming “elongate to honeycomb-shaped surface networks of sharp to round-crested ridges” (1999, p. 74) and ‘*Kinneyia* ripples’ which “exhibit similar relief but have more parallel, typically flat-topped ridges” (1999, p. 74), and stated that both are “closely related sedimentary structures” which are “frequently confused for each other in the literature”. Because both structures frequently “occur together and may represent preservational end-members of similar structures”, they suggested to “refer to them collectively as wrinkle structures” resulting from microbial activities or representing mats (1997, p. 1047). However, the two types of ‘wrinkle structures’, as documented by Hagadorn and Bottjer (1997) in their Figs. 1 A-F, may all be described as variations of *Kinneyia*, when compared with examples presented by Pflüger (1999, his Fig. 1 A-C) and Bloos (1976, his Plate 9, Figs. 1-4). Also, it is observed that on larger, *Kinneyia*-carrying bedding surfaces, the two types grade into each other (see Fig. 6(a)-4E). On this basis, the term ‘wrinkle structures’ would be synonymous with the original term ‘wrinkle marks’, as introduced by Häntzschel and Reineck (1968), and with ‘*Kinneyia*n ripples’, as described by Martinsson (1965). In other words, Hagadorn and Bottjer’s (1997, 1999) ‘wrinkle structures’are indeed *Kinneyia*.

Subsequently, Hagadorn and Bottjer (1999, p. 74) stated that ‘wrinkle structures’ such as *Kinneyia* are “likely formed beneath buried microbial mats”, whereas ‘wrinkle structures discussed in their 1999 study “largely reflect original surface features”. They described from modern mats, freshly formed in supratidal pools “immediately after they were flooded by a storm-induced high tide”, small-scale linear growth patterns produced by vertically oriented cyanobacterial filaments on the mat surface, and suggested that these structures are the modern equivalents of ancient ‘wrinkle structures’. Hagadorn and Bottjer (1999) thus grouped together *Kinneyia*-type ‘wrinkle structures’, formed beneath mats, and some other ‘wrinkle structures’ reflecting growth patterns on mat surfaces. But, as in their 1997 paper, examples shown on their Fig. 1 may throughout be described as variations of *Kinneyia*.

Microbially induced wrinkle structures

From the historical review it becomes apparent that the term ‘wrinkle structure’ in its present use is not meaningful, if genetical aspects are addressed in detail. The term is historically cumbered due to its similarity with ‘wrinkle marks’ which has been applied to both biologically and physically induced structures. It is therefore suggested here, to use the term ‘wrinkle structure’ only if microbial participation is likely but a clear classification not possible. Otherwise, use of the well introduced terms ‘*Kinneyia*’ and ‘elephant skin’ is recommended here (see Fig. 6(a)-1).

Identification of microbially induced ‘wrinkle structures’should be based on the following criteria: (a) the structures should occur in association with other mat-related structures, e.g. spindle-shaped cracks, ‘sand chips’; (b) their origin on an upper bedding surface or on a sedimentary surface beneath a microbial mat should be possible; (c) their formation by localised growth of mat-forming microbes or mat expansion, or by physical deformation of epibenthic mats should be possible; (d) the structures should possess specific geometries and a size in the millimetre-range.

It is not intended here to explain ancient ‘wrinkle structures’ by a range of possible genetic processes acting on microbial mats. Instead, small-scale structures observed on modern mats will be described and possible ancient equivalents will be shown. This approach is not sustainable, however, for ‘*Kinneyia*’ structures, which have not been observed in modern mats yet. With a view to the life and burial history of modern microbial mats, ‘wrinkle structures’ may reflect morphological surface and subsurface features, mat deformation patterns, or be structures arising from subsurface processes, e.g. gas trapping, dewatering, or liquefaction.

Structures reflecting mat surface morphologies

Reticulate growth pattern and ‘elephant-skin‘

A specific type of modern mat surface structure that occurs rather frequently and in successive mat layers repeatedly, is related to mat growth and bacterial reaction to environmental stresses (Gerdes et al., 2000a). It is characterized by a reticulate pattern of bacterial bulges and tufts, in which the bulges tend to form polygonal networks with tufts or pinnacles in junctional positions (Fig. 6(a)-2A). The bulges are 2-3 mm high and sharp-crested when fresh; the polygons are of varying size, ranging in diameter from less than 1cm to more than 3 cm. Inside completed polygons, new tufts and radiating bulges may form, thus subdividing larger polygons into smaller units. At an advanced stage, diameters of the polygons may be less than 0.5 cm.

For the formation of the pattern, Gerdes et al. (2000a, p. 285) suggested that, “if the surface cover [mat] becomes too thick, or light conditions change because of increasing water cover after intermittent exposure”, specific filamentous bacteria (*Microcoleus chthonoplastes*, *Lyngbya aestuarii*) phototactically respond by reorienting filaments upwards or by moving cell aggregates upwards and accumulating on the surface. According to Gerdes et al. (2000a), it is particularly *Lyngbya aestuarii* that forms elongated bulges, which are stabilized by EPS (extracellular polymer substances) produced by succeeding coccoidal cyanobacteria.

An ancient structure that shows striking similarity with the reticulate growth patterns in modern mats is named ‘old-elephant-skin texture’ (Runnegar and Fedonkin, 1992) or briefly ‘elephant skin’ (Gehling, 1999) (Fig. 6(a)-2B). It has been described mainly from Vendian shallow-marine siliciclastic deposits (e.g., Runnegar and Fedonkin, 1992; Gehling, 1999, 2000; Steiner and Reitner, 2001) and rarely from older successions (Prave, 2002, his Fig. 2A). The structure is characterized by 1-2 mm high, sharp-crested ridges on upper bedding surfaces, or respective impressions on lower bedding surfaces, forming irregular polygonal networks with a width of mesh of 0.5-1 cm. This faint, but geometrically distinct network clearly distinguishes ‘elephant skin’ from other ‘wrinkle structures’, which usually exhibit a certain linearity.

Linear patterns

Mat growth structures consisting of subparallel, linear ridges with exposed bacterial filaments at ridge crests, have been described by Hagadorn and Bottjer (1997, 1999) from a freshly flooded supratidal pool at Redfish Bay (Texas). In this example, intercrest distances are between 0.5 and 1 cm and individual ridges may extend for tens of centimetres. Similar structures, though on a slightly larger scale, have been observed by the authors along the margin of an evaporating supratidal pool at Bhar Alouane tidal flats in southern Tunisia (Fig. 6(a)-2C). The structures, dominated by linear ridges of bacterial filaments but partly also showing the typical reticulate growth pattern, are oriented about perpendicular to the water limit and appear more and more desiccated with increasing distance from the water, likely corresponding to the duration of subaerial exposure. At some distance from the pool, a pattern of sub-parallel, shallow and narrow, occasionally bifurcating, sharp-crested ridges remains (Fig. 6(a)-2D). The straight to irregular ridges are developed at distances of 1-2 cm and are locally interrupted or reduced to faint lines on the flat mat surface. It appears that, with persisting subaerial exposure, the filamentous ridges develop distinctly sharp-crested shapes and a smooth and rigid surface, and are incorporated in stepwise fashion into the mat, the structure thus being a transient feature reflecting transitional conditions. It has to be mentioned that similar structures have been considered to result from deformation of a mobilized microbial slime-sediment sludge on slightly inclined slopes, or from microbial overgrowth of faint surface ridges (G. Gerdes, Chapter 2; pers. comm., 2006). Strong arguments in favour of a microbial growth origin, however, would be provided by transitions between typical reticulate and linear patterns, and by a similar geometry of the ridges in all the transitional stages.

Some ancient structures observed on flat bedding surfaces of siltstone layers within Neoproterozoic intertidal successions of Zambia and Namibia (Fig. 6(a)-2E) strongly resemble the linear pattern described above. Similar structures previously interpreted as wind-induced ‘wrinkle marks’ by Robb (1992), and exhibiting sharp-crested ridges with transitions from linear to reticulate patterns, may be of similar origin. As with ‘elephant skin’, linear ancient mat growth structures have in common that they consist of narrow, sharp-crested ridges on upper bedding surfaces. Due to the transient nature of the original structure, a wide range from continuous ridges to relict short ridges may be preserved.

Another mat surface structure characterized by parallel, discontinuous, sharp-crested ridges at a few millimetres distance from each other has been observed on the steep slope of a tidal channel at Sabkhat El Grine, southern Tunisia (Fig. 6(a)-2F). The ridges run along the irregular sloping surface like contour lines and are not developed on less inclined parts. This indicates that slow downslope creeping of the mat may have been involved in their formation, whereas the sharp-crested geometry of the ridges would agree with microbial growth structures as described above. The structures may thus be considered as transitional between mat growth and mat deformation features.

Structures related to mat deformation in general

Active microbial mats forming cohesive to leathery surface layers on fine-grained siliciclastic sediments, usually resist low-energy wave action in the upper intertidal to lower supratidal zones. At higher wave energy during spring tides or storms, however, they may undergo deformation, become locally detached and crumpled or may be torn into pieces and eventually eroded. Thin mats, desiccated to some extent, may undergo partial floatation after renewed flooding (Cameron et al., 1985) and also be intensely deformed, if still cohesive and plastic (Fig. 6(a)-2E). In shallow pools, thin microbial mats may "behave like the 'skin' on top of a pudding" (Hagadorn and Bottjer, 1999, p. 76) and become deformed by strong winds driving the water (Singh and Wunderlich, 1978). Finally, down-slope gliding may lead to local slumping and folding. In all these cases, a cohesive surface layer (mat or biofilm) is deformed by tractional or gravitational forces. Usually, resulting folding and crumpling of the mat is on a decimetre-scale with fold amplitudes up to several centimetres (see Fig. 6(a)-3A). Such structures do not meet the definition of 'wrinkle structures' which are on a millimetre-scale, but may rather be referred to as 'petees' in the original definition of Gavish et al. (1985). Very thin mats, however, may develop small-scale deformation features in the range of typical 'wrinkle structures', and there may be transitions between the various scales. It is thus not possible to draw a clear-cut borderline between 'deformation wrinkles' and larger linear structures related to mat deformation. Nevertheless, some 'wrinkle'-sized structures thought to have resulted from mat deformation will be discussed briefly.

Wrinkle structures resulting from mat deformation

Small-scale, wrinkle-like mat deformation structures are scarcely documented from modern mats (e.g., Hagadorn and Bottjer, 1999) and only a few examples have been reported from the geological record (Singh and Wunderlich, 1978; Clemmey, 1978; Kopaska-Merkel and Grannis, 1990; Seilacher, 1999; Bouougri and Porada, 2002). Commonly, the structures are developed on fine-grained sandstone or siltstone and exhibit subparallel, slightly curved, continuous crests and troughs (Fig. 6(a)-3B). Height of individual crests usually ranges from 1 to 2 mm, spacing from 5 to 10 mm, and length from 1 to 10 cm. The crests typically are asymmetric, the steeper sides facing in a common direction considered to be the direction of unidirectional stress (e.g., tractional current or wind). As a further common feature, the crests tend to fade out sideways and in the direction of shear stress. Altogether, the structures resemble miniature, arcuate fold-thrust belts.

Mat slump structures

'Mat slump structures' may be highly variable in shape and size but are basically characterized by irregularly folded bulges on otherwise smooth bedding surfaces (Figs. 6(a)-3C, -3D). Impressive examples of 'mat slump structures' have been documented by Bernier et al. (1971) who described 'crescentic wavy structures' with crest heights of a few millimetres and spacings from 2-3 cm to more than 10 cm, developed on a bedding surface of Jurassic micritic limestone.

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They attributed the structures, which partly resemble ‘wrinkle structures’, to downslope gliding of a detached microbial mat.

‘Mat slump structures‘ are not necessarily restricted to the uppermost cohesive layer of a mat, but may involve stacks of intercalated sand and microbial mat layers (‘biolaminites’ after Gerdes and Krumbein, 1987) which together undergo deformation. Within a biolaminite succession they may be bound to specific horizons. Millimetre- to centimetre-scale recumbent and overfold structures of thin carbonaceous laminae, reported by Simonson and Carney (1999) from Late Archaean lutites and by Schieber (1986, 1998a, 1999) from Mesoproterozoic interlaminated silt and mud deposits, may be examples of ‘mat slump structures’ within biolaminites. In both these cases, the structures have been related to penecontemporaneous deformation of cohesive, epibenthic microbial mats.

Structures suspected to have formed beneath microbial mats

Two groups of structures developed in the sediment beneath or in the less cohesive underpart of microbial mats are distinguished: (1) ‘subsurface structures’ likely reflecting morphological details of the microbial mat, imprinted on the underlying sediment or sediment-rich lower part of the mat; (2) ‘*Kinneyia*’ structures possibly produced by gas trapping below a sealing mat.

Subsurface structures

During periods of subaerial exposure and increasing shortage of ground and surface water, microbial mats may desiccate and shrink, due to loss of water mainly bound in EPS (Decho, 1990; Dade et al., 1990; Krumbein et al., 1994; Neu, 1994). At a certain stage, the mat may crack and lose contact with its substratum, and may partially be removed by wind action. The exposed subsurface may then exhibit an irregular morphology dominated by rounded to elongate bulges, 3-10 mm in size, and intervening depressions (Fig. 6(a)-4A). The preservation potential of exposed subsurface structures is considered low, but increases if the exposed surface is soon stabilized by microbes and overgrown by new cyanobacterial layers.

Figure 6(a)-4B shows patches of suspect subsurface structures consisting of small-scale, subrounded to elongate bulges, preserved on an upper bedding surface of fine-grained quartzite. The structures occur in a Neoproterozoic intertidal succession of quartzite/siltstone and argillite that hosts a range of microbially induced sedimentary structures, like ‘elephant skin’, circular cracks, and *Kinneyia* (see Bouougri and Porada, 2002). Similar structures with irregular, elongate, millimetre-size bulges have been documented from Cambro-Ordovician quartz arenites by Hilowle et al. (2000; their Fig. 2) who suggested that they “record the subsurface morphology of a subsequently degraded microbial mat”. Also, a structure characterized by millimetre-scale round bulges and referred to as ‘transparent wrinkles’ (Noffke et al., 2002, their Fig. 7B) may be of a similar origin.

Kinneyia structures

‘*Kinneyia*’ is the most typical, most frequent and genetically most problematic ‘wrinkle structure’. It is characterized by sinuously curved, frequently bifurcating, flat-topped crests, usually 1 mm high and 1-2 mm wide, which are separated by parallel, round-bottomed depressions (Fig. 6(a)-4C, -4E). The usually steep-sided crests may run parallel or form honeycomb-like patterns, sometimes with lateral transitions between the two shapes on the same surface (Fig. 6(a)-4E). The depressions frequently show winding trends with ‘neckings’ (localised pinch-outs), but may be reduced to isolated, round or elongate pits. Intercrest distances vary between 2 mm and almost 10 mm in different occurrences, but are rather constant on the same bedding plane. The varying proportions of winding troughs vs. isolated pits, together with interference features of crests bring about a wide range of shapes with distinctly linear and distinctly pitted end-members. Further variations may result from weathering, by which crests gradually lose their steep-sided and flat-topped geometry and attain more rounded shapes.

According to reports in the literature (e.g., Martinsson, 1965; Häntzschel and Reineck, 1968; Bouougri and Porada, 2002; Noffke et al., 2002) and observations by the authors in Morocco and Namibia, *Kinneyia* structures preferentially (or exclusively?) occur on flat upper surfaces of fine-grained event layers, deposited in the intertidal to shallow subtidal zones. A section across *Kinneyia* (Fig. 6(a)-4F; see also Bloos, 1976) reveals that the structure is developed in a millimetre-thick layer, which discordantly overlies the truncated foreset lamination of an event deposit. *Kinneyian* troughs and ripples are overlain by dark, fine-grained sediment, usually silty argillite which typically includes carbonaceous laminae and isolated silt-sized grains and which has been considered to represent former microbial mats (e.g., Noffke et al., 2002, 2003b; Bouougri and Porada, 2002). The occurrence of filamentous microstructures resembling trichomes of modern cyanobacteria, as reported by Noffke et al. (2003a) from similar layers above *Kinneyia*, corroborate this interpretation. These observations suggest that *Kinneyia* structures form beneath cohesive microbial mats and likely do not represent the microbial mat itself.

Kinneyia structures have frequently been documented in the literature and almost just as often been interpreted in different ways (e.g., Quenstedt, 1858; Geinitz, 1863; Shrock, 1948; McKee, 1954; Allen, 1966; Hunter, 1969; Kummel and Teichert, 1970; Wunderlich, 1970, Goldring, 1971; Bloos, 1976; Reineck and Singh, 1980; Seilacher, 1982; Seilacher and Aigner, 1991). They have been considered as small-scale interference ripples, rain impact ripples, or adhesion ripples and other wind-induced surface patterns. None of these interpretations is sustainable, as the steep to sometimes vertical slopes of ‘*Kinneyia*‘ ripples are unlikely to have formed at the sediment/water or sediment/air interface. Consequently, Seilacher and Aigner (1991) considered ‘*Kinneyia*’ to be a post-burial, intrasedimentary structure, whereas Pflüger (1999) proposed that it results from gas trapping beneath sealing microbial mats. The interpretation of ‘*Kinneyia*’ as a load structure (Noffke et al., 2002, 2003a) appears unlikely, as siltstone layers overlying ‘*Kinneyia*’-microbial mat doublets (see Fig. 6(a)-4F) do not exhibit the typical downward protrusions but instead exhibit flat lower surfaces.

Non-biogenic structures that may be mistaken for ‘*Kinneyia*’ are mainly small-scale load structures, partly formed in the presence of soft microbial mat layers which are deformed under load pressure, but also adhesion ripples and other wind-induced structures may develop similar shapes and patterns.

Small-scale load structures (Fig. 6(a)-4G) may develop on lower bedding surfaces of thin sand/silt layers overlying mudstone/argillite. A range of patterns resulting from loading has been documented by Allen (1985) from modern intertidal sediments in which they formed without participation of microbial mats. Some of them bear amazing resemblance to *Kinneyia* structures. In section, load structures are distinguished from *Kinneyia* in that they overlie mudstone/argillite, whereas *Kinneyia* invariably is developed at the top of sandstone/siltstone beds and is overlain by argillite. Ancient small-scale load structures are characterized by circular to elongate, round-crested bulges, separated by comparatively narrow depressions, on lower bedding surfaces. They have rarely been addressed as load structures in ancient sedimentary rocks, but rather as unexplained 'runzelmarken' or 'wrinkle marks'.

Adhesion ripples form when dry, wind-blown sand grains adhere to a wet or moist surface. The resulting structure consists of a series of winding, asymmetric ridges, ca. 2 mm high and 5 mm wide, at distances of ca. 1 cm (see also Reineck, 1955; Hunter, 1969; Kocurek and Fielder, 1982 and further references therein). Though a general linear trend is recognized, the ridges usually are oriented in various directions and partly overlap thus inducing rather irregular patterns, in detail (Fig. 6(a)-4H). The preservation potential of adhesion ripples is considered low and ancient examples have only rarely been described (e.g., Kocurek and Fielder, 1982). Examples documented by Hunter (1969, his Fig. 4) and Goldring (1971, his Plate 3c) are here interpreted as *Kinneyia* structures.

Discussion and conclusions

In a wide range of small-scale crinkly structures occurring on ancient bedding surfaces, 'wrinkle structures', following Hagadorn and Bottjer (1997, 1999), are defined as forming a specific group developed in close relationship to microbial mats. Consequently, other structures of similar size and appearance but suspected to be non-biogenic in origin do not fall into this group, and it is suggested here that these are named according to their specific origins (e.g., small-scale load structures, adhesion ripples etc.).

The identification of 'wrinkle structures' in ancient siliciclastic successions may give valuable information about the depositional environment and facies. Thus, if compared with the distribution of modern microbial mats, 'wrinkle structures' may indicate deposition in intertidal to lower supratidal zones, e.g. on low-gradient tidal flats with occasional deposition of event layers. Assuming such environments, 'wrinkle structures' may occur in heterolithic successions of laminated siltstone/argillite and intercalated siltstone/sandstone beds. Indeed, many wrinkle structures have been described from just such successions (e.g., Martinsson, 1965; Häntzschel and Reineck, 1968; Bouougri and Porada, 2002; Noffke et al., 2002; 2003a).

In analogy to modern mats, it may furthermore be expected that 'wrinkle structures' occur in association with a set of other microbially induced structures, all together being components of a ‘microbial mat facies’. As documented and discussed in the literature (e.g., Pflüger and Gresse, 1996; Pflüger, 1999; Porada and Löffler, 2000; Bouougri and Porada, 2002), fillings of short spindle-shaped cracks, longer curved cracks, and sinuous to circular cracks, frequently combined in unusual networks, as well as ‘sand chips’ may form part of the association. The significance of wrinkle structures clearly increases if some of these associated structures are additionally observed.

Within the group of ‘wrinkle structures’, two types are well defined and easily identified, due to their specific geometry and mode of occurrence, respectively. The one is known as ‘elephant skin’, reflects mat growth patterns, and occurs frequently on argillaceous siltstone or silty argillite bedding surfaces, sometimes together with numerous small flakes of detrital muscovite, which adhered to the sticky surface of the previous mat. The structure is characterized by sharp-crested ridges, up to 1 mm high, which typically are combined in a reticulate pattern forming networks with polygons, 0.5–1 cm wide (Fig. 6(a)-2B). However, there may be transitions to incomplete networks and to more linear ridges running parallel to each other and at about 1 cm distance.

The other well defined type is ‘*Kinneyia*’ which likely formed underneath microbial mats and usually is preserved on flat upper surfaces of siltstone or sandstone beds, mostly being event deposits. It is the classical and likely most frequent ‘wrinkle structure’ and has been documented from the Archaean to the Jurassic (e.g., Häntzschel and Reineck 1968; Bloos, 1976; Noffke et al., 2003a). The structure resembles millimetre-scale interference ripples with all transitions from crest-dominated linear shapes to pit-dominated honeycomb-like patterns (see Fig. 6(a)-4C, -4E). Characteristic features are the flat tops and steep sides of the ripple crests. Although quite distinctive when observed closely, some small-scale load structures, adhesion ripples and other wind-induced structures may be mistaken for ‘*Kinneyia*’ (see Fig. 6(a)-4G, -4H).

Besides these two types which by themselves indicate the former presence of mats, there remain other suspect microbial ‘wrinkle structures’ that are more variable in shape and size and are thus not clearly defined and unequivocal. Some of them may reflect mat deformation and mat slump structures. They usually appear as localized, more or less irregular, small-scale ‘fold belts’ on bedding surfaces (see Fig. 6(a)-3B). Such structures have to be evaluated critically, and additional observations of sand cracks, ‘sand chips’ and other mat-indicative structures are required to support them as possibly microbially-induced.

Figures

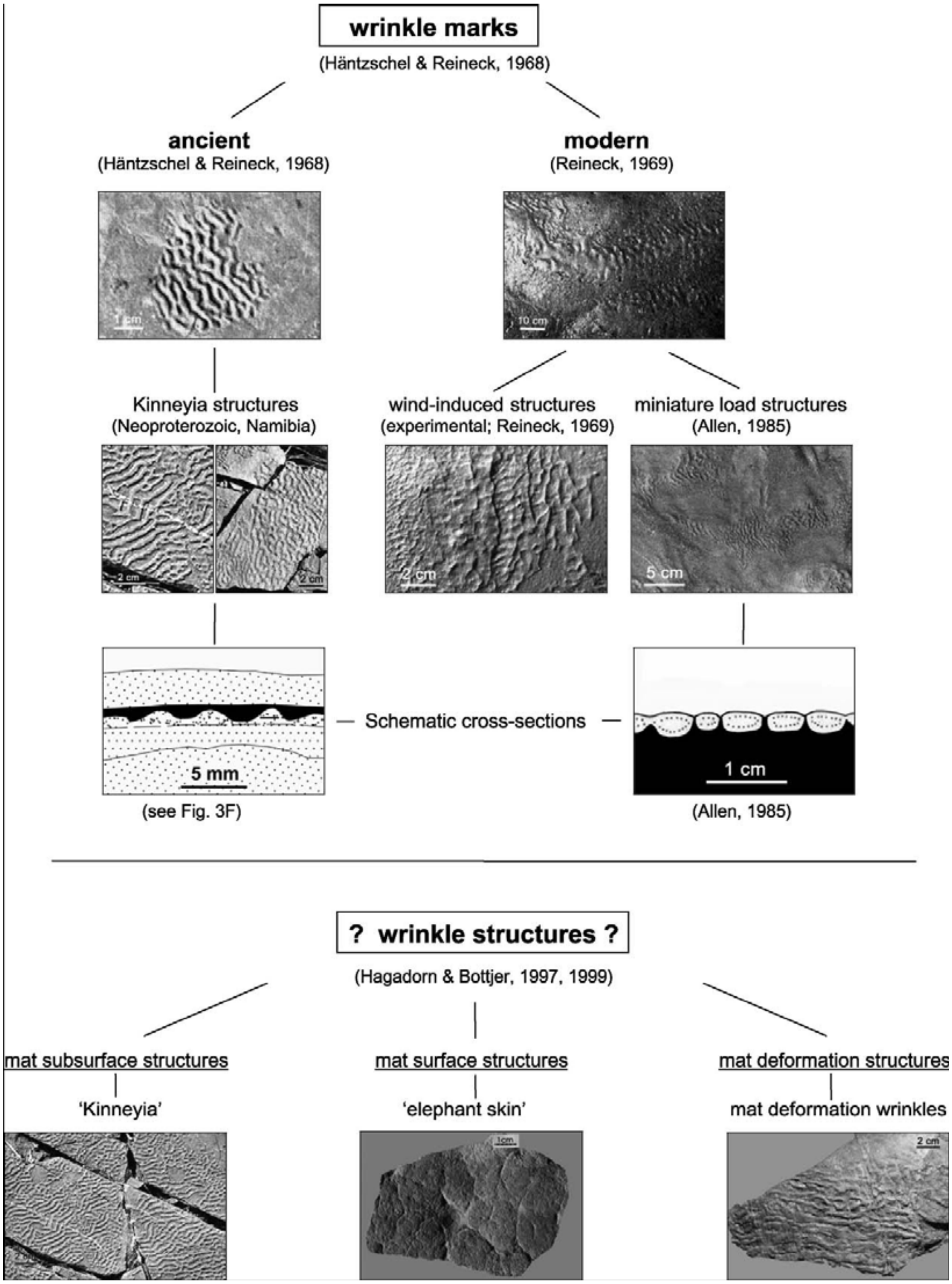

Figure 6(a)-1: Chart showing appearance and relationships of structures referred to as 'wrinklemarks' and 'wrinkle structures' in the historical context.
'Wrinkle structures' in the meaning of Hagadorn and Bottjer (1997, 1999) are suggested to represent mat surface structures, mat deformation structures, or mat subsurface structures, respectively.

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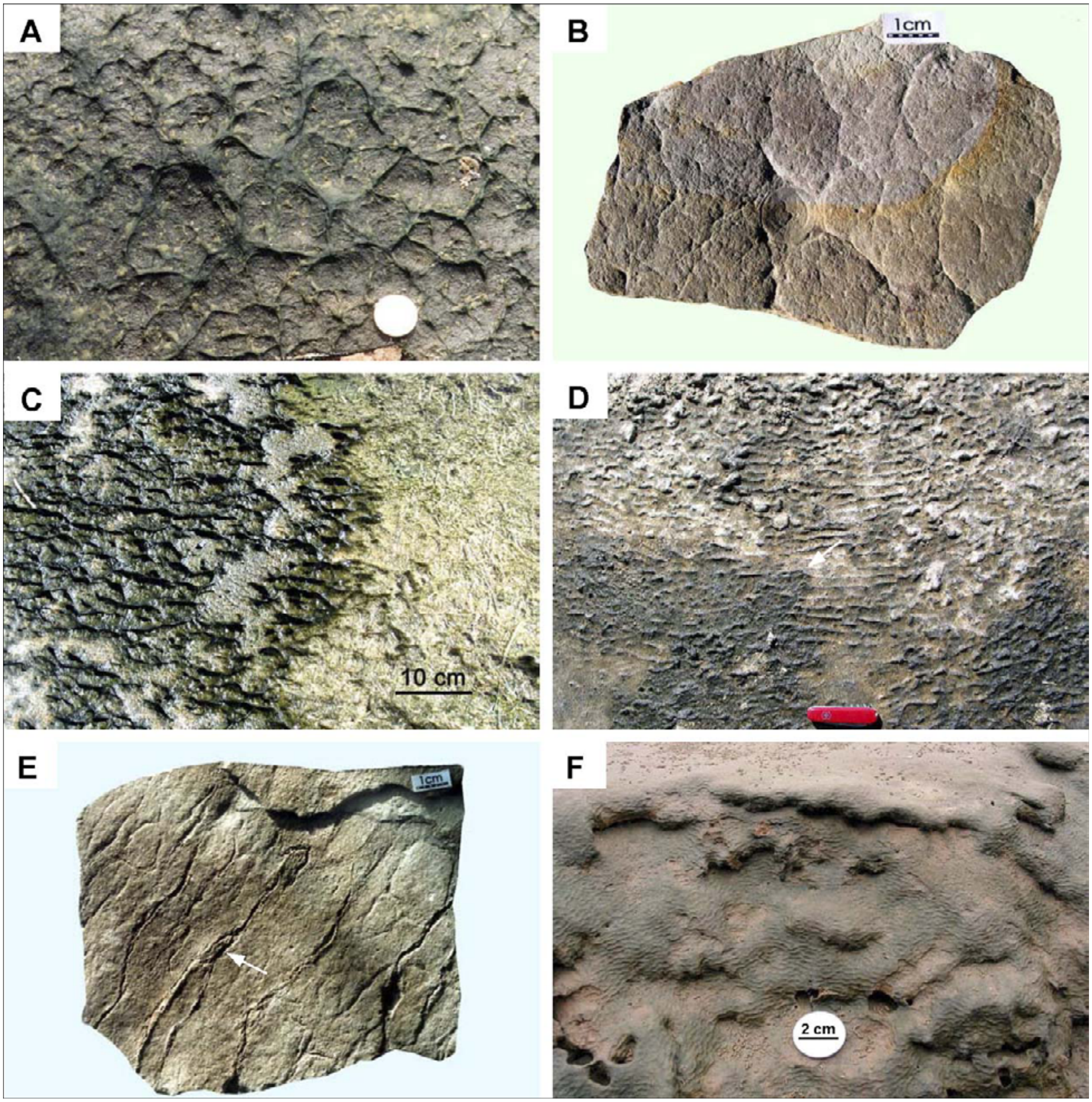

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Figure 6(a)-2: Mat surface structures.
(A) Modern mat surface exhibiting reticulate growth pattern produced by sharp-crested bulges and pinnacles in junctional positions. Pinnacles result from “induced polarity changes of filamentous cyanobacteria”, whereas “bulges are produced by *Lyngbya aestuarii* ” (Gerdes et al., 2000a, p. 284). Coin is 20 mm in diameter. Supratidal pond, Bhar Alouane tidal flats, southern Tunisia. (B) ‘Elephant skin’ texture on lower bedding surface of finegrained sandstone bed. Note Ediacara-type fossil of *Irridinites multiradiatus* near centre of sample. Upper Neoproterozoic Penaga Formation, East Archangelsk, Russia. (C) Modern mat developing more linear growth patterns along margin of evaporating supratidal pool (right part of photo). Note individual bulges may be more than 20 cm in length. Bhar Alouane tidal flats, southern Tunisia. (D) Linear growth pattern on modern mat after subaerial exposure and drying up of the mat surface. Arrow indicates structural detail to compare with similar structure observed in Figure 6(a)-2E. Bhar Alouane tidal flats, southern Tunisia. (E) System of linear to slightly curved shallow ridges (partly destroyed by weathering), developed on upper surface of thinly bedded, fine-grained quartzite. The structure is considered to represent linear growth features of a previous microbial mat. Note sub-circular to elliptic structures (upper left and right side) partly resembling ‘elephant skin’. Arrow indicates structural detail as observed on modern example shown in Figure 6(a)-2D. ‘Ore formation’, Roan Group, Katanga Supergroup; Mindola open pit mine, copperbelt of Zambia. (F) Linear surface pattern developed on thin microbial mat covering the steeply inclined slope of a tidal channel. The pattern consists of small, discontinuous, sub-parallel, sharp-crested ridges, arranged like contour-lines at distances of a few millimetres from each other. Note that the pattern is not developed on flat portions of the slope. Sabkhat El Grine, southern Tunisia.

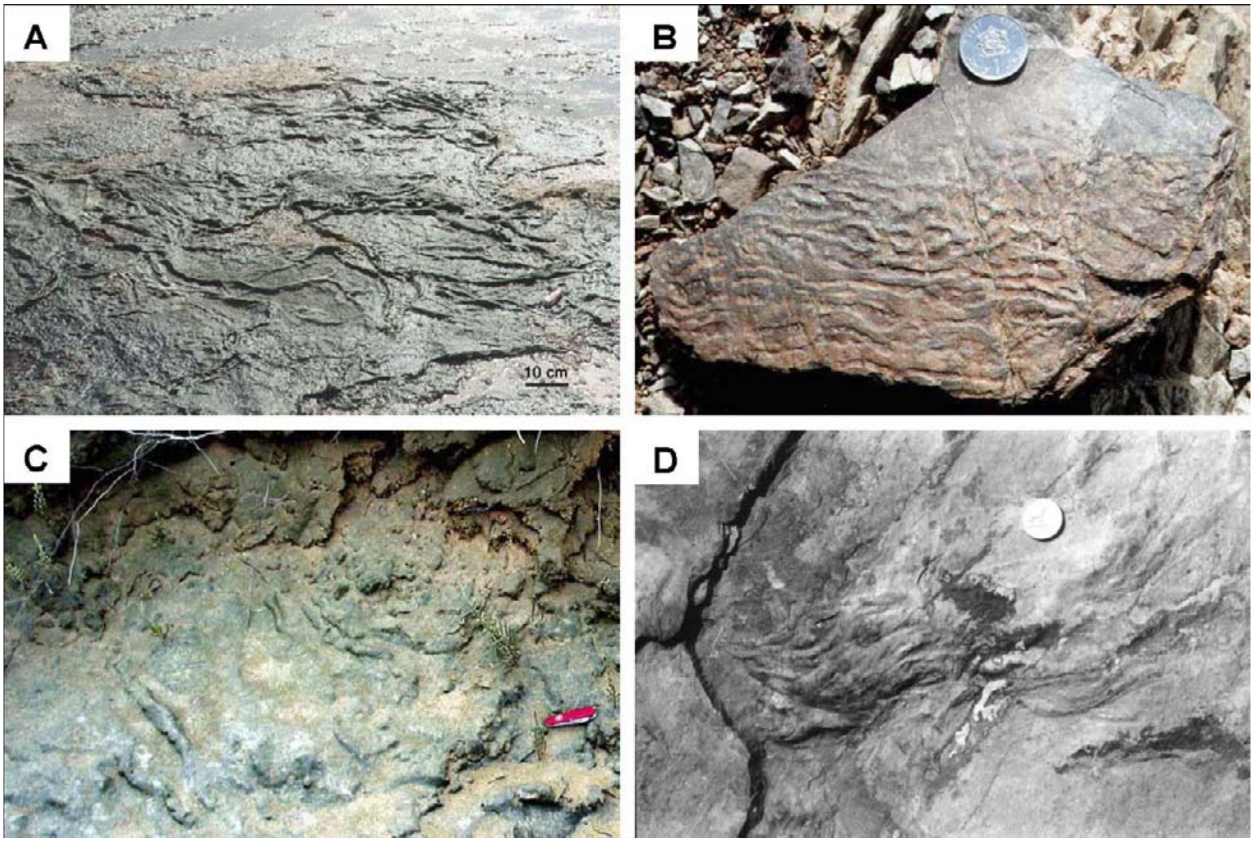

Figure 6(a)-3: Structures related to mat deformation in general.
(A) Detached and floating mat, torn and strongly folded by tractional wind or wind-induced waves. Coastal sabkha, ca. 10 km south of Skhira, southern Tunisia. (B) Wrinkle structure resulting from mat deformation. Belts of continuous, broad and flat-topped crests (lower part of photo) grade into shorter, more irregular and round-topped crests (centre) and eventually disappear (upper part). The structure is considered to result from crumpling of a disrupted and marginally detached mat. Direction of movement is towards upper part of photo. Wanimzi Formation, Neoproterozoic Tizi n-Taghatine Group, Anti-Atlas, Morocco. Coin is 24 mm in diameter. (C) Mat slump structures developed on the steep slope of a tidal channel. Sabkha El Gourine, southern Tunisia. Scale (knife) is 8 cm. (D) Mat slump structure in laminated siltstone/argillite of the Neoproterozoic ‘Ore formation’, Roan Group, Katanga Supergroup; Mindola open pit mine, copperbelt of Zambia. Coin is 21 mm in diameter.

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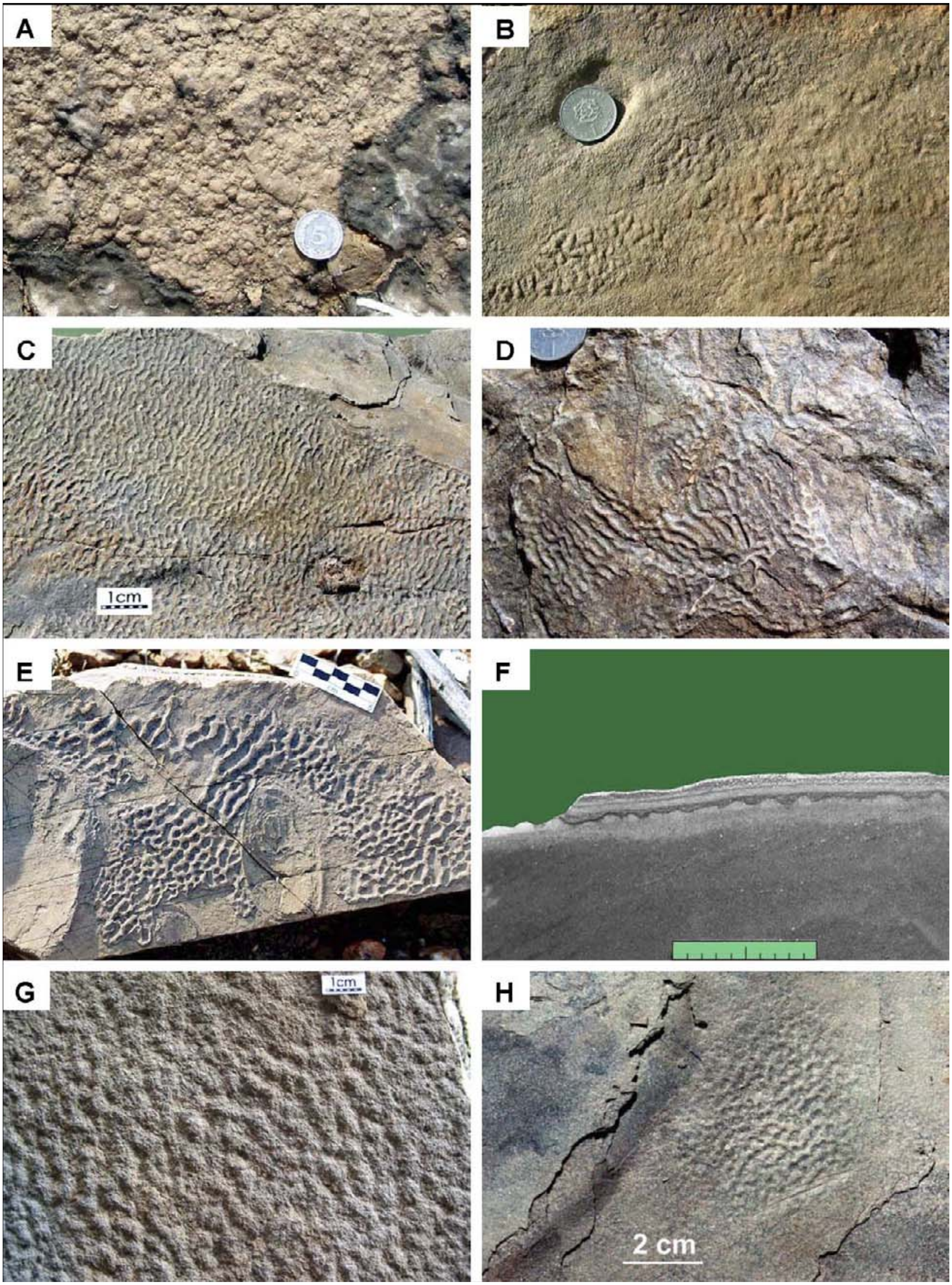

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Figure 6(a)-4: Mat subsurface structures, load structures, adhesion structures.
(A) Morphological features of mat subsurface, subaerially exposed after removal of desiccated mat by wind action. Note round to elongate bulges, 3–10 mm in size. Tidal flats of Bahar Alouane, southern Tunisia. Coin is 24 mm in diameter. (B) Patches of elongate to irregular bulges on upper surface of fine-grained sandstone. The structures are considered to reflect subsurface morphological features developed beneath a microbial mat and biostabilised at subaerial exposure after removal of the mat. Wanimzi Formation, Neoproterozoic Tizi n-Taghatine Group, Anti-Atlas, Morocco. Coin is 24 mm in diameter. (C) ‘*Kinneyia*’ structure with long, flat-topped, winding crests developed on the flat upper surface of a siltstone layer (event deposit). Intercrest distances: 1.5–2 mm. Middle Cambrian *Paradoxissimus* Siltstone; Äleklinta, Oeland, Sweden (type locality of ‘*Kinneyian* ripples’ of Martinsson, 1965). (D) Patchy development of ‘*Kinneyia*’ with long winding crests on upper surface of finegrained sandstone. Intercrest distances: 2–3 mm. Note that crests partly are round-crested, due to weathering. Wanimzi Formation, Neoproterozoic Tizi n-Taghatine Group, Anti-Atlas, Morocco. Coin is 24 mm in diameter. (E) ‘*Kinneyia*’ structure showing transition from more linear to honeycomb-like arrangement of flat-topped crests and intervening elongate to round pits, developed on the flat upper surface of a fine-grained sandstone layer (storm deposit). Neoproterozoic Vingerbreek Member, Nudaus Formation, Nama Group; Farm Haruchas, Namibia. Scale is 5 cm. (F) Section across ‘*Kinneyia*’ crests and troughs developed on top of an event deposit and overlain by silty argillite (dark) and layers of siltstone (lighter colours). ‘*Kinneyia*’ has developed in a thin flat layer that discordantly overlies the event deposit characterised by oblique foreset lamination. The silty argillite which fills and covers ‘*Kinneyia*n’ troughs and crests is considered to represent previous microbial mats. Note flat lower surface of siltstone layer above silty argillite, excluding loading as a process of ‘*Kinneyia*’ formation. Middle Cambrian *Paradoxissimus* Siltstone; Äleklinta, Oeland, Sweden. Scale is 10 mm. (G) Lower bedding surface with small-scale load structures forming miniature, subcircular to elongate bulges. Lower Jurassic (Hettangian); Helmstedt, Lower Saxony, Germany. (H) Upper surface of wave-rippled fine-grained sandstone with a patch of crinkly structures. The structures are considered to have formed by adhesion of wind-blown sand grains to the still wet surface in a shallow depression. Note that structures fade out towards the margins. Upper Neoproterozoic (Vendian) Cerro Negro Formation; Cerro Negro Quarry, Tandilia System, Argentina.

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