4(c). Mat-destruction features

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Introduction

In this section, sedimentary features preserved in sandstones due to mat-destruction processes (largely physical) are detailed. The sedimentary features which result in modern sandy settings or are preserved in ancient sandstone beds encompass:

(1) microbial shrinkage cracks within modern mats, which may also penetrate into underlying sandy bed surfaces to form sand cracks;
(2) sand cracks of all types, including *"Manchuriophycus"/"Rhysonetron"*; also, crack-marginal features such as: curled crack margins, and overgrown, upturned crack margins; filled sand crack features, including petee ridges; ripple-top sand crack features;
(3) flipped-over (mat) edges, and rolled-up mat fragments (cf. 'jelly-rolls', 'roll-ups');
(4) mat chips and sand chips;
(5) (destructive) wrinkle structures;
(6) ripple patches, and patchy reworking of ripples;
(7) non-penetrative micro-faults.

The reader is referred to Chapter 3, where classification schemes of mat-related features are discussed in detail; the above features are based on Schieber's (2004, and later modifications thereof) scheme, with some minor refinements. The descriptions and discussions presented below rely also to a large extent on a set of critical references on the mat destruction features in sands/sandstones: Astin and Rogers (1991); Bloos (1976); Bouougri and Porada (2002); Clemmey (1978); Eriksson et al. (2000); Garlick (1981, 1988); Gavish et al. (1985); Gehling (1999, 2000); Gerdes et al. (1985b, 1993, 2000a); Hagadorn and Bottjer (1997, 1999); Häntzschel (1975); Hofmann (1967, 1971); Noffke et al. (2001a, 2003a and b); Parizot et al. (2005); Porada and Löffler (2000); Pflüger (1999); Pflüger and Gresse (1996); Reineck (1979); Reineck et al. (1990); Schieber (1998a, 1999, 2004); Simonson and Carney (1999).

Definition and genesis of mat destruction features

In modern mats, various crack features can be observed (Fig. 4(c)-1), including leaf-shaped or spindle-shaped incipient tears that are not yet connected to each other; once they do thus connect, often, triradiate or 'triple junction' crack patterns result; however, triradiate cracks can also form as incipient structures on their own. In other cases a more polygonal or reticulate crack pattern may emerge as increasing numbers of cracks join up. Other more complex crack patterns observed include sinuously curved, to sigmoidal, circular or even, locally, figure-8 shaped features (Fig. 4(c)-1). All of these features may also be found preserved in ancient sandstone beds (Figs. 4(c)-2 to -4). It is possible that these more complex curved crack patterns develop from the simpler spindle-shaped incipient tears and triradiate cracks (see also Fig. 4(c)-2 for

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ancient examples of this possible progression), and that mat thickness plays a role in determining the detailed crack patterns that result.

Once cracks occur in a microbial mat growing above an unconsolidated sandstone bed, they may penetrate into the underlying sand layer, provided with cohesiveness by the mat, or the cracks within the living/desiccating/decaying mat may become filled by sand, either from above or below. If filled from above, it is likely (although not axiomatic) that the crack-fill material will differ from the sand of the bed originally beneath the mat. In contrast, if microbial shrinkage cracks within a mat are filled from below, by sand driven into the cracks under pressure from overlying beds or over-standing water, or due to tidal water depth changes, then the crack-fill has the same composition as the bed below, and there will also be soft-sediment deformation features preserved below the resulting petee ridges *sensu lato* (filling the cracks) (note discussion on the meaning and use of the term ‘petees’ below), which disturbs the upper few laminae of sand(stone) (Figs. 4(c)-8 to 4(c)-10). It should be noted that petees (*sensu stricto*) may also form from growth-expansion of the mat or due to escaping gas from decaying buried mats, resulting in deformation of the mat surface and concomitant sinuous to polygonal surface ridge patterns (Gehling, 1999).

The appearance of preserved sandy crack-fills, whether ‘petee’s’ (petee ridges, filled from below) or formed from above, is very similar, and they generally require detailed study of a sawn section or even of a microscopic thin section cut across the bedding at the top of such a sandstone layer, to discriminate them; examples of both types are shown in Figures 4(c)-7 to -10. What is also noticeable in many ancient examples is the similarity of such positive sandstone ridges to the negative crack patterns (see Fig. 4(c)-3 for good examples); all combinations of curvilinear, parallel, spindle-shaped and circular to figure-8 forms may be seen, and this supports the inferred link between initial crack (in the mat overlying the sand surface) and its later filling by sand from above or below (e.g., compare Figs. 4(c)-1 and 4(c)-2 to -4, with Figs. 4(c)-7 to -10). As shown in Fig. 4(c)-9, negative sand cracks and positive petee ridges, with similar complex geometrical forms, may occur together in one sample; a modern example of sand cracks passing into petee ridges is shown in Fig. 4(c)-8D. Filled sand cracks and petee ridges thus also imply the presence of an original crack, either in the living mat, or in the sand beneath. We here differentiate between preserved negative features (sand cracks) and positive features (either petee (*s.l.)* ridges or filled sand cracks), noting also that they often occur together (e.g., Fig. 4(c)-3).

The term ‘petees’ was introduced by Gavish et al. (1985) where it referred exclusively to modern mats. In this earliest study, these authors addressed tepee-like structures which they considered, however, to be of biogenic origin and related to microbial mats. They found that undulation and wrinkling of microbial mat surfaces resulted from either wind or gravity, and they termed these features ‘petees’. Subsequently, Reineck et al. (1990) suggested a classification of petees into alpha-, beta- and gamma-petees, and considered petees in general to be biologically modified overthrust structures, including single domes, multitudes of buckles and transitions of the latter into domes; in all cases in these two original definitions, the dome-like crests were closed and rounded, reflecting the cohesiveness of the microbial mats. Reineck et al. (1990) interpreted genesis of petees as due to either (1) subsurface gas concentration which deformed the overlying cohesive mat, or (2) wind or water friction, or gravity, leading to deformation of soft biogenic surface tissues.

The petees observed in modern mats by these early workers were positive deformation features in the mats themselves and obviously stood little chance of preservation, other than as vague irregularities on sandstone bed upper surfaces, once decay set in. However, modern mats from Tunisia do in some cases show positive features of analogous geometry in the sandy substrate, which are thought to have formed by upward movement of sediment filling the ‘open space’ beneath the buckles in the mat. In terms of the original and strict definition of the term petees, these are secondary structures reflecting the existence of the petees in the overlying mats themselves.

Thus, according to the original definition of Gavish et al. (1985) and the subsequent remarks by Reineck et al. (1990), petees are clearly denoted as domes, buckles and folds developed on a flexible mat surface. These earlier workers did not see any relation of petees to mat-cracks or filled cracks, even if the domes, buckles and folds may occasionally have undergone some cracking under desiccation. Later workers (e.g., Gehling, 1999, 2000), however, did bring in a possible association with cracks formed in a microbial mat, thereby expanding the original definition. At the same time, Gehling (1999) also discusses petees *sensu stricto*, which he related to genesis through mat growth expansion and gas pressure from underlying mat decay. In his 2004 classification scheme, also that adopted as the basis for this book, Schieber similarly encompassed this broader definition and genetic association of petees with mat-cracking – he uses the term ‘petee ridges’ to denote positive petee-like features related to this rupturing of microbial mat surfaces, and notes that simple polygonal petee ridge networks or more complex sinuous ridge patterns may result. Implicit in this more modern and expanded definition of the term ‘petee’ is that petee ridge patterns may often resemble the geometry of desiccation cracks in the microbial mats that aided their formation. Following on the discussion above and also based partly on the usage of Noffke et al. (2001a) we use the term ‘petee’ or ‘petee ridge’ in a loose and generalised sense to denote positive epirelief on mat surfaces; strictly speaking one should then differentiate between petees *sensu stricto*, related to the original definitions of Gavish et al. (1985) and Reineck et al. (1990) and the usage of Gehling (1999), and petees *sensu lato*, which have a relation to cracks in microbial mats.

‘*Manchuriophycus*’ (cf. ‘*Rhysonetron*’) represents a special type of microbial shrinkage crack, developed within thicker mats found within the troughs between ripples – various examples of ancient occurrences are shown in Figs. 4(c)-11 and -12, together with one example of a living mat surviving reworking by currents within the relatively protected hollows between ripple crests. Some deviations from characteristic ‘*Manchuriophycus*’ cracks have been observed, including such cracks developed preferentially on ripple crests, and a more reticulate pattern of the normal trough-located cracks (Fig. 4(c)-13). In contrast to these ripple-trough features, ripple crest sand cracks also occur; those shown form a reticulate pattern of sand cracks, where longer negative cracks tend to follow wave ripple crests, and are connected by shorter ‘cross-cracks’ across the intervening troughs (Fig. 4(c)-4B; see also, Fig. 4(a)-15).

It is most important to emphasise that all of the cracks discussed here can easily be confused for non-biogenically formed features in the ancient sandstone record. It is thus of critical importance that any cracks and crack-like features are studied in cross-section, to ensure that no mudstone is present between the apparently cracked lower sandstone bed and that overlying it (see also, caption to Fig. 4(c)-7). If only one bed surface, the lower, is studied and carries sand cracks of any type, the possibility that mud(stone) was indeed present upon the sandy crack-laden surface of the lower bed cannot be disproved and the cracks cannot be assigned a microbial mat genesis with any confidence at all. If part-counterpart specimens of a lower, cracked sandstone bed and its immediately overlying successor sandstone bed are not available, at the very least, close to the site of an exposed, single (lower) cracked sandstone bed, the overlying sandstone bed must be observable, *in situ*, forming part of the outcropping succession of sandy beds. In Figs. 4(c)-2A, -2D, -2E and -2F, for example, the undisturbed overlying sandstone bed (without mudstone between the two sandy beds) can be observed within centimetres of the lower, cracked sandy bed. Non-application of this very basic principle to investigations of any inferred microbial mat-related features in sandstones would essentially negate any such possible biological interpretations. It is emphasised that all examples shown in this book have been subject to this important test of potential ‘bio-validity’.

Microbial shrinkage cracks in modern mats can locally develop curled crack margins, which may also be preserved in ancient sandstone beds (Fig. 4(c)-5). These features form the first step in a continuum: curled crack margins – flipped-over mat edges – rolled-up mat fragments; in all cases, when the lower, sediment-rich part of the mat remains attached to these desiccating and partly reworked mat margins, these features are preserved in the clastic sedimentary rock record. Curled crack margins can also become overgrown by renewed mat growth, forming ‘overgrown upturned margins’, modern and ancient (Fig. 4(c)-6). Flipped-over mat edges, also commonly termed ‘flip-overs’, reflect a complete inversion of a mat-edge, while rolled-up mat fragments (Figs. 4(c)-14 and -15) form when more extreme mat desiccation, normally allied to sedimentary reworking, leads to breakup of the mat or at least parts thereof and the formation of rolled-up mat portions wherein several complete 360^{o} revolutions often occur. These rolled-up mat fragments (often termed just ‘roll-ups’ or ‘jelly-rolls’) often occur together with variously shaped and sized mat fragments, such as mat chips and sand chips, discussed below.

Schieber (2004) notes that sand chips are a particular sort of eroded mat fragment, which form an end-member of the continuum mentioned in the previous paragraph. They tend to be smaller (≤ few cm) than rolled-up mat fragments (or their sandy ancient versions) and tend to have rounded and plastically deformed shapes (Fig. 4(c)-17). Like rolled-up mat fragments, current alignment (Fig. 4(c)-15 for roll-ups) or even imbrication of sand chips may occur (Pflüger and Gresse, 1996; Bouougri and Porada, 2002). Microbial mats provide cohesiveness for these deformed sand chips to form and to survive sedimentary transport. When a microbial mat dries out, curved, rigid mat chips will result, which are then also subject to potential transport and reworking – in sub-Recent sandy sediments they can be preserved as carbonaceous clasts, and in ancient examples, the sediment associated with the basal portions of the mat will be preserved within these chips. In the example shown from the c. 1.8 Ga Waterberg Group (South Africa), hematitic siltstone – very fine-grained sandstone forms these chips, and they are associated with roll-ups (Fig. 4(c)-16).

Wrinkle marks, *sensu lato*, represent a problematic group of microbial mat-related features as they can just as easily form and be preserved from mat-growth settings (e.g., Fig. 4(a)-4) as from mat-destruction settings, and because they can easily be confused with features formed from soft sediment deformation processes or even tectonically-formed structures (see Chapter 6(a)). In section (a) of this chapter, wrinkle marks related to mat growth settings are detailed, but the continuum from such features to wrinkles related to mat destruction makes it difficult to draw a definitive line between these two groups. In this section, we consider only wrinkle marks which show evidence of significant detachment of the mat from its sandy substrate to fall within the destruction-related features (e.g., Fig. 4(c)-18). In Chapter 6(a), a more comprehensive discussion of the wrinkle mark problem is provided by Porada and Bouougri.

Ripple patches (see also Figs. 4(a)-13 and -14) will form when a mat-protected sandy bed is exposed locally due to removal of the mat in certain patches, leaving the exposed sand amenable to sedimentary reworking with the concomitant formation of ripple marks within those patches; such ripple patches tend to have margins marked by a smooth gradation of the ripples into the surrounding featureless sandstone bed-top (Fig. 4(c)-19). Analogously, patchy reworking of a rippled sandstone bed suggests that a microbial mat protected the areas where the original ripple set is preserved (Fig. 4(c)-19).

The cohesion given to sandy beds by microbial mats growing on them can also remain for some time after burial, and this can enable unique behaviour of such beds under deformation (Schieber, 2004); an example of this is non-penetrative micro-faults (Pflüger,1999; Gehling, 1999). The various microbial mat-related features associated with mat destruction, discussed above in brief, are detailed below and illustrated in the accompanying figures.

Formal description of mat destruction features

Microbial shrinkage cracks (modern): Fig. 4(c)-1

Name of structure: Microbial shrinkage cracks.
Other terms used: Synaeresis cracks, desiccation cracks, *'Manchuriophycus', 'Rhysonetron'*.
Description of structure: Surface of thin microbial mat marked with isolated lenticular, sinuously curved and even subcircular cracks, spindle shaped and tri-radiate shrinkage cracks; ends of cracks generally taper; locally, figure-8 patterns occur. Cracks may extend downward into sediment layer below mat. In other cases, crack patterns comprise linear, lenticular to sigmoidal cracks, following the linear trends of shallow bulges. Active growth of cyanobacterial filaments can occur along margins and openings of cracks, forming bridge-like structures between margins, thus favouring progressive closure of the cracks and preservation of sediment filling the cracks.
Associated sedimentary structures: (1) small current ripples (2 cm wavelength, 3 to 5 mm amplitude) within organo-sedimentary layers; (2) interbedding of microbial mat layers and event layers of a few millimetres-scale; horizons of gypsum; (3) desiccation cracks; (4) burrowing (mainly by gastropods).

Environment: Upper intertidal to lower supratidal zones of tidal flat. Preconcentration basin of a saltern.
Ideas on genesis: Subaerial shrinkage and related cracking of thin mats may lead to a wide range of structures depending on the maturity and cohesiveness of the mat, and on the position in the intertidal-supratidal zones. Within these zones, limited shrinkage and formation of isolated and rarely interconnected cracks of various shapes and sizes are the main shrinkage features of cohesive mats strongly attached to the substrate. Cracks formed are filled by sand- to silt-sized sediment transported by tidal currents and/or wind. The filling stage is accompanied and followed by active growth of bacterial filaments in and on the cracks leading to their sealing, preservation, and separation from sediment layers above. Cracks may also be filled by deposition of sands from the overlying bed, before sealing is complete.

Sand cracks: Figs. 4(c)-2 to 4(c)-4A

Name of structure: Sand cracks (compare with modern equivalents above, the microbial shrinkage cracks).
Other terms used: Synaeresis cracks, desiccation cracks, '*Manchuriophycus*', '*Rhysonetron*', microbial shrinkage cracks.
Description of structure: Upper bedding surface with isolated, lenticular and spindle-shaped microbial shrinkage cracks; sigmoidal to sinusoidal, curved, circular and sinuous ('wriggly') microbial shrinkage cracks; minor figure-8 forms. The isolated spindle-shaped cracks may possibly join up into triradiate cracks (however, 'triple junctions' are often incipient structures themselves, similar to isolated spindle-shaped cracks) or the beginnings of reticulate crack patterns, and these may be linked, locally, with the more sinuous crack forms. Polygonal/reticulate networks as well as complex interference patterns of more sinuous cracks occur commonly, and superimposed crack generations on sequential sandstone beds are found.
Associated sedimentary structures: (1) heterolithic deposits with cm-scale interbedded sandstone and organo-sedimentary sericitic layers; (2) event deposits related to fluvial sheet floods or storms; millimetre- to centimetre-scale alternation of sedimentary sandstone event layers of storm or fluvial origin, and organo-sedimentary laminated layers of siltstone and sericitic argillite; (3) few small fluvial/tidal channels; (4) mud clasts; (5) oscillation, interference and current ripples, and wave and current ripple laminations; (6) desiccation cracks; (7) adhesion warts; (8) small-scale load structures.
Palaeoenvironment: Intertidal to lower supratidal zones of a peritidal coastal plain; playa lake or saline pan lenses within thick aeolian palaeo-desert succession.
Ideas on genesis: Isolated spindle-shaped cracks are thought to be incipient tears, the first cracks to form; these then link up, commonly in 'triple junction' or triradiate intersections of incipient cracks, and these may in their turn form complex intersections of either essentially straight crack patterns (polygonal to reticulate patterns) or, less commonly, curved crack patterns (some of these have a bead-like morphology and may have formed from linked, small incipient tears). Finally, there appears to be a second generation of more complex curved cracks, with smaller widths, which show no relationship to 'triple junction' features. All these crack features are inferred to reflect mat desiccation and subaerial shrinkage, with concomitant cohesiveness provided by the mat to underlying sands which then preserve these same features. By comparison with modern situations, incomplete, limited shrinkage appears to be controlled by

the maturity and strong cohesiveness of 'inactive' thin mats in environmental settings like the upper intertidal to supratidal zones. Opened cracks are filled by sediment particles transported during exceptionally high tide, storm and rainfall, or by wind. In contrast, 'active' thin mats of lower to middle intertidal settings and around ponds tend to develop cracks with 'curled margins'. Preservation of thin shrunken mat layers from erosion by the next sedimentary event may be explained by incomplete shrinkage and a high degree of attachment (adhesion) to the substrate below.

Curled crack margins: Fig. 4(c)-5

Name of structure: Curled crack margins (new term additional to Schieber, 2004 classification).
Other terms used: none.
Description of structure: Mat surface (modern) with shrinkage cracks, in which crack margins show curling. The latter encompasses various stages of crack margin evolution, from slightly upturned margins (straight or curved in themselves, seen from above), to complex forms surrounding subcircular openings in the mat surface; old curled margins may become partly or, locally, even fully overgrown by a new mat layer. In ancient preserved examples, irregular subcircular or linear ridges occur which are distinctly flattened, and may be inferred to reflect the curled margins of a subcircular opening in a thin microbial mat that previously covered a sandy sediment surface, or a narrow linear crack with curling edges, respectively. May occur in biolaminites.
Associated sedimentary structures: (1) small current ripples (2 cm wavelength, 3 to 5 mm amplitude) within organo-sedimentary layers; small-scale current, oscillation and interference ripples; wave and current ripple laminations; (2) interbedding of microbial mat layers and event layers of few millimetre-scale; horizons of gypsum; (3) millimetre- to centimetre-scale alternation of sedimentary sandstone event layers of storm or fluvial origin, and organo-sedimentary laminated layers of siltstone and sericitic argillite; (4) desiccation cracks; (5) burrows (mainly by gastropods); (6) small-scale load structures; (7) small tidal channels; (8) mud clasts; (9) wavy and lenticular bedding.
Environment: Upper intertidal to lower supratidal zones of tidal flat/coastal plain. Preconcentration basin of salterns. Intertidal to supratidal shallow back-barrier setting, with small tidal channels and few high energy storm deposits.
Ideas on genesis: The structures form subaerially in a thin mat that undergoes shrinkage and cracking. Initial linear or triradiate cracks may evolve into irregular to subcircular openings with progressive curling of the crack margins. If the sediment-rich lower part of the mat remains attached to the curling margin, sediment may be entangled in the involute structure. Overgrowth of the curled margins by new mat layers leads to their preservation.

Overgrown, upturned crack margins: Fig. 4(c)-6

Name of structure: Overgrown upturned crack margin (new term additional to Schieber, 2004 classification).
Other terms used: 'pillow-like bulges at crack margins' (Noffke et al., 2003a). They are sometimes confused with petees.

Description of structure: The polygonal network of shrinkage cracks (in other examples, cracks are curved to sinuous) within a modern biolaminite will be marked by upturned, overturned and partly overfolded polygon edges; in the crack openings, a new thin mat forms, partly overgrowing the polygon edges. The cracks may also be partly filled by sediment before mat overgrowth occurs. In ancient examples antiformal, inverted-V shaped structures occur parallel to and along both margins of shrinkage cracks in preserved biolaminites; in other cases, upturned crack margins are preserved within polygonal crack networks. In cross-sections of ancient examples, a vertical (subvertical) attitude of the upturned margins is seen; these can become totally overgrown by further biolaminite deposits.
Associated sedimentary structures: (1) heterolithic succession of interlaminated (sericitic) siltstone/fine-grained sandstone and argillite; (2) storm event sandstone layers, 8-15 cm thick; (3) desiccation cracks; (4) mud chips and mat chips; (5) shallow tidal channels; (6) burrows, mainly by gastropods, in modern examples; (7) wavy and lenticular bedding/lamination; (8) small-scale oscillation and interference ripples.
Environment: Intertidal zone of a peritidal coastal plain, regularly flooded during high tide. Intertidal to supratidal shallow back-barrier setting, with small tidal channels and few high energy storm deposits.
Ideas on genesis: The structure occurs in the upper 2-3 cm of a biolaminite covered by an active microbial mat that underwent subaerial shrinkage. As a result, wide cracks with upturned margins develop, partly involving the underlying biolaminite. Cyclic, tidally controlled processes of mat growth and overgrowth, alternating with progressive upturning of crack margins, form the structure.

Ripple-top sand cracks: Fig. 4(c)-4B

Name of structure: ripple-top sand cracks.
Other terms used: sand cracks, cracked ripple crests (see Fig. 4(a)-15, this chapter).
Description of structure: these are negative sand crack features that show variable degrees of association with wave ripple crests. Essentially parallel, elongated cracks (with wide bases and steep, slightly curved sides), parallel and mostly coincident with the crests of straight to slightly sinuous wave- and wind-formed ripples; shorter cracks link the elongated features across ripple troughs; both cracks and ripple crests tend to bifurcate.
Associated sedimentary structures: (1) wave, oscillation, current and wind ripples; (2) sand cracks; (3) '*Manchuriophycus*'; (4) tidal channels; (5) petee ridges; (6) wrinkle structures.
Environment: Braid-deltaic – tidally controlled epeiric marine coastline.
Ideas on genesis: Shrinkage of a desiccating mat draped over rippled sands is inferred; tensile stress was maximised across ripple crests, leading to a preferential crack occurrence there.

Filled sand cracks: Fig. 4(c)-7

Name of structure: filled sand cracks.
Other terms used: petees/petee ridges, sand cracks.
Description of structure: These structures resemble the sand cracks discussed above, in all their variability, but instead of being negative features, they are in the form of positive ridges. They are differentiated from petees (petee ridges) by a noticeable difference in sandstone

composition/type between the crack-fill (=ridge) and that in the bed within which the cracks formed; also, unlike petees, there is no observable deformation of the upper few sandstone laminae within the cracked bed. Some flattening of these sandstone ridges can be observed.
Associated sedimentary structures: sand cracks.
Environment: Braid-deltaic – tidally controlled epeiric marine coastline; intertidal settings generally.
Ideas on genesis: Based on the description above, these features are interpreted as reflecting filling of cracks within microbial mats growing/desiccating on a sandy surface from above, by other sands brought in either by aqueous currents or aeolian action. If the mat then decays or is eroded away, these crack-fills will remain behind as positive ridges, with the same plan-form geometry as the original microbial shrinkage cracks. Alternatively, the mats, with their sandy crack-fills may become buried beneath later sediments, and then the mat will, in time, decay and disappear and the crack-fill ridges will become flattened beneath the weight of overlying beds, which is commonly seen in ancient examples, including some of those shown here. It is distinctly possible that crack-fill and immediately overlying sandstone bed will have the same composition, reflecting a single sedimentation event, laid down on top of the original, cracked mat. This would appear to be relatively common.

Petees/petee ridges: Figs. 4(c)-8 to 4(c)-10

Name of structure: petees or petee ridges.
Other terms used: sinuous antiformal ridges.
Description of structure: Normally in the form of large numbers of ridges, which display polygonal, reticulate-polygonal and sinuous patterns in plan-view; spindle-shaped ridges are also common, and elongated, parallel forms occur also. Local flattening of ridges is seen quite often, and the more polygonal patterns commonly have multiple orders of ridges, up to three orders being recorded in some instances. Petees/petee ridges *sensu stricto* should be associated with concave-upward segments between the ridges, when seen in cut cross-sections of occurrences, as well as being associated with soft sediment deformation of thin planar beds underlying the mat/petee surface; in addition, the sand/sandstone making up the petee ridges should be the same material as that comprising the bed immediately beneath the mat/previous mat. If these features (last sentence) are not observed, it is likely that the observed structures are 'filled sand cracks' (above) and not proper petees.
Associated sedimentary structures: (1) tidal channel-fills; (2) oscillation, current, wave and aeolian ripples (petees may also occur on ripples); (3) sand cracks; (4) '*Manchuriophycus*'; (5) destructive wrinkle marks.
Environment: Braid-deltaic – tidally controlled epeiric marine coastline; intertidal settings generally. Less common in supratidal settings; few examples known from the lower shoreface setting.
Ideas on genesis: The evidence for soft sediment deformation and for the source of petee ridge sand in the bed immediately underlying the mat supports either a synaeresis-like origin (due to overlying beds' pressure causing post-burial movement of sand into cracks in the mat) for these features, or that the liquefied sand moved laterally into the cracks within the microbial mat from beneath, under pressure from overstanding water or even (spring) tidal oscillation. In all cases, inferred crack-filling is from the unconsolidated sand bed beneath the mat. In the case of the few

shoreface examples of petees, a synaeresis-style origin would appear to be the most logical. Some dense networks of petees appear to be bunched up against each other, suggesting that the mat allowing ridge formation was also subject to (partial) detachment and wrinkling (see Fig. 4(c)-9). Petees may also form under mat growth conditions, as well as due to mat destruction. In the former case, updoming and even rupturing of the mat due to wind, current action and gas development will allow petee ridge formation; their genesis during mat destruction is related to a high level of mat-cracking and desiccation and forms the latter part of a genetic continuum of petee origins.

'Manchuriophycus': Figs. 4(c)-11 to 4(c)-13

Name of structure: '*Manchuriophycus'*.
Other terms used: '*Rhysonetron'* (Hofmann, 1967, 1971; see also Häntzschel's " Treatise on Invertebrate Paleontology, Part W", 1975). Essentially a specific type of microbial shrinkage crack; sand cracks (ancient examples).
Description of structure: Within the upper, rippled (or interference rippled) surface of sandstone beds, within the ripple troughs, complex crack patterns with curved, circular, spiral, triradiate or even figure-8 forms occur, and may follow the edges of these troughs. In other examples, more lenticular or spindle shaped cracks occur, with triradiate intersections thereof; all '*Manchuriophycus'* cracks can also be preserved on the sole of overlying beds.
Unusual forms: in a few cases, a more reticulate crack pattern is observed, marked by petee ridge-like, positive features, and one case, illustrated here (Fig. 4(c)-13), is known where typical '*Manchuriophycus'*-type cracks occur preferentially on the preserved sandy ripple *crests* instead of in the troughs. Both these unusual forms occur within the c. 1.6 Ga Vindhyan Supergroup, India.
Associated sedimentary structures: (1) wavy and lenticular bedding; (2) wave and current ripple laminations; (3) small-scale current, oscillation, wave, wind and interference ripples; (4) lenticular fluvial and/or tidal channels; (5) desiccation cracks; (6) mud clasts; (7) desiccation warts and adhesion warts; (8) heterolithic deposits with centimetre-scale interbedded sandstone and organo-sedimentary sericitic layers; (9) event deposits related to fluvial sheet floods or storms.
Environment: Coastal plains of lacustrine or shallow marine (including epeiric) environments, fringing alluvial braid-delta systems; may also be associated with significant tidal action within such settings; intertidal to lower supratidal zones of a peritidal coastal plain.
Ideas on genesis: Shrinkage (sand) cracks within rippled sandstone, confined to ripple troughs, may form if microbial mats selectively grow, or attain a greater thickness in ripple troughs, where eroded cyanobacteria settle from currents, and where supply of water is greatest and more long-lasting. Possibly, in a few cases, once cracks have occurred within a trough-located mat, petee ridges could occur. The one noted occurrence of 'inverse-*Manchuriophycus'*, situated on ripple crests, may reflect a very thick mat cover within which optimal desiccation conditions for crack formation happened to occur above ripple crests rather than the deeper-lying ripple troughs.

Flipped-over (mat) edges, and rolled-up mat fragments (cf. 'jelly-rolls', 'roll-ups'): Figs. 4(c)-14 to 4(c)-15

Name of structure: Flipped-over mat edges; rolled-up mat fragments.
Other terms used: 'flip-overs'; 'roll-ups' or 'jelly-rolls'.
Description of structure: Flipped-over mat edges are relatively small to larger (centimetres to >10 cm in longest dimensions) portions of the edge of a mat that are inverted locally, due to current action (water, possibly occasionally, wind). They are very easy to identify in modern examples, but may be more difficult to define in ancient examples where compression has occurred. Rolled-up mat fragments, in contrast, are easy to discriminate at all ages; in longest dimension they are up to several tens of centimetres. Their modern versions are literally portions of a mat (either broken-off fragments or mat edges) that have begun to desiccate and whose edges have begun to curl up. This initial stage in the process can be greatly enhanced by current action (again water rather than wind), which commonly results in several full revolutions of rolling-up – 720^0 are commonly observed in ancient examples. In cross-section, roll-ups resemble jelly-rolls or the rolled up tobacco leaves in a cigar, and in longitudinal view, the resemblance to a cigar is more apparent. Current reworking often results in a parallel orientation of several elongated roll-ups, and in certain cases mat fragments of all sizes and shapes (including mat chips) can be bunched up with several rolled-up fragments. In ancient examples the sandy sediment from immediately beneath the mat, or even muddy sediment trapped by the surface of the mat, becomes rolled up as well, and it is this sediment that is preserved to mark these structures.
Associated sedimentary structures: (1) current, wind, combined-flow and wave ripples; (2) suspension deposits; (3) upper flow regime plane bed deposits; (4) aeolian dune deposits and their structures, with evaporite pseudomorphs; also evaporate casts; (5) structures indicative of efflorescent salt crusts; (6) mud cracks.
Environment: Palaeodesert saline pan deposits and interdune deposits (including flash-flood reworking thereof). Also form due to currents in marine coastal settings.
Ideas on genesis: Microbial mats provide enough cohesion to sandy sediments immediately underlying the mats to form either flipped-over or rolled-up sediment-bearing mat fragments. Most of the inversion and rolling implicit in the formation of these features can be ascribed to sedimentary reworking by relatively strong, directed currents, generally due to water rather than wind, as supported also by the common parallel alignment of elongated fragments and roll-ups noted in many occurrences. It is likely that some initial curling is due to desiccation, to be followed by greater rolling-up through current action.

Microbial sand chips and mat chips: Figs. 4(c)-16 and 4(c)-17

Name of structure: Microbial sand chips; microbial mat chips.
Other terms used: Microbial sand clasts; spheroidal pliable sand clasts, also known as 'algal balls', 'sand balls', or 'sand ooids' (see Figs. 4(a)-1 and -2).
Description of structure: Microbial sand chips (see also Fig. 4(a)-3) reflect a feature which is analogous to 'flip-overs' and 'roll-ups' (e.g., Schieber, 2004), but were subject to longer sedimentary reworking, transport and abrasion. They are smaller than the previous class of feature, and generally comprise rounded, plastically deformed, often current-aligned sand clasts (shapes vary from rounded to elongated to partially flattened); they may even locally be imbricated. Mat chips reflect strongly desiccated mat-bound sandy sediment surfaces that form

rigid and curved clasts, several centimetres in their longest dimensions; they are not as rounded as roll-ups and resemble dried-up mudclasts formed when a thin mud layer desiccates and breaks up. The well-known example described by Pflüger and Gresse (1996), from the c. 2.7 Ga Ventersdorp Supergroup of South Africa, consists of formerly microbially-bound fine-grained volcanic ash; although this specific example is often described in literature as microbial sand chips, they are in reality mat chips (e.g., Donaldson et al., 2002a; their figure 2(a)) in the Schieber (2004) terminology system used in this book (see Chapter 3).
Associated sedimentary structures: (1) heterolithic deposits with centimetre-scale interbedded sandstone and organo-sedimentary laminated layers; (2) a few event layers related to storms; (3) few small fluvial/tidal channels; (4) wave ripple-formed cross-lamination; (5) oscillation, interference, current and wind ripples; (6) desiccation cracks; (7) load structures; (8) erosional pockets; (9) suspension deposits; (10) upper flow regime plane bed deposits; (11) aeolian dune deposits and their structures, with evaporite pseudomorphs; also evaporate casts; (12) structures indicative of efflorescent salt crusts; (13) mud cracks.
Environment: Intertidal zone of a peritidal coastal plain; along shoreline of preconcentration basins of salterns; interdune and saline playa environments within a palaeodesert; playa lakes within a semi-arid volcanic-sedimentary setting.
Ideas on genesis: Physical erosion of a thin, microbially-bound sand layer and reworking of fragments by relatively high energy wave, current or even wind action. Can also be related to mat growth conditions (Figs. 4(a)-1 to -3).

Wrinkle structures (destructive): Fig. 4(c)-18

Name of structure: Wrinkle structures (related to mat destruction).
Other terms used: Wrinkle structures (Hagadorn and Bottjer, 1997, 1999) can be confusing (see also Chapter 6(a)), as these features are also associated with mat growth as easily as with mat destruction; as with many of the microbial mat-related structures (e.g., also sand chips, above), there is a continuum of these features, from mat growth to mat destruction associations. The reader is thus referred here also to sections 4(a) and 4(f) in this chapter. H. Porada and E. Bouougri (pers. comm., 2006) suggest the term 'warped mat' for mat destruction-related examples.
Description of structure: Upper bedding surface with millimetre- to, more commonly, centimetre-sized, sinuous to curved, irregular, round to sharp-crested bulges. The deformation is restricted to a thin sandy layer. The underlying, undeformed layer may exhibit a reticulate pattern of 'elephant skin' (see also, 'old elephant skin', Figs. 4(a)-5 to -7) type developed on a surface from which the mat has been removed by tractional forces. In more extreme cases of mat destruction, detached and floating mat fragments may result, with irregular, round to sharp-crested bulges, induced by successive tractional events affecting a thin, loosely attached microbial mat. Such mat fragments can undergo local cracking after a new mat forms on the exposed surface surrounding it.
Associated sedimentary structures: (1) heterolithic deposits with centimetre-scale interbedded sandstone and organo-sedimentary sericitic layers; (2) event deposits related to fluvial sheet floods or storms; (3) few small fluvial/tidal channels; (4) wave ripple-formed cross-lamination; (5) oscillation, interference and current ripples; (6) desiccation cracks; (7) mud clasts; (8) mat

chips; (9) possible examples associated with palaeodesert saline pans and interdune settings with their typical associations of sedimentary structures.
Environment: Intertidal zone of a peritidal coastal plain; upper intertidal zone surrounding a wide tidal channel plain. Uncommonly from palaeodesert pan-interdune settings.
Ideas on genesis: Structure reflecting deformation by wind or current action of a detached or loosely attached, flexible, thin mat. In more extreme cases of mat destruction, mat fragments originate from a floating or loosely attached mat that has been broken up into pieces by wind/water traction. These fragments may be deformed by wind traction, when floating on water uprising from below or originating from tidal incursion.

Ripple patches (and patchy reworking of ripples; palimpsest ripples): Fig. 4(c)-19

Name of structure: Ripple patches.
Other terms used: Patchy ripples; related terms are patchy reworking of ripples, and palimpsest ripples (see also Figs. 4(a)-3, -13, -14).
Description of structure: Ripple patches are relatively smooth bedding planes within which localized patches exhibit various possible kinds of ripples, generally of an aqueous rather than an aeolian origin. For positive identification, it is important that there be a smooth transition from the ripple patches to the surrounding bedding planes (e.g., Schieber, 1998a). Related features would be ripple fields (also generally aqueous rather than aeolian in origin) with localized patches of reworked ripples. Palimpsest ripples reflect inherited features such as ripples which are still visible beneath later structures such as other ripples.
Associated sedimentary structures: (1) a wide range of inferred mat-related features: petees, sand cracks, 'elephant skin', wrinkle structures and '*Manchuriophycus*'; (2) current, wave, oscillation and minor aeolian ripples; (3) relatively small fluvial and tidal drainage channels; (4) planar bedding.
Environment: Epeiric marine to open-coastline tidally-influenced marine settings.
Ideas on genesis: Ripple patches develop when a smooth sandy bed surface covered by a microbial mat is subject to local erosion under relatively high energy (probably tractional) conditions; the exposed sandy patches resulting from this may then form ripples from the active currents, waves, tides etc. causing the erosion. The smooth transition from ripple patch to surrounding smooth bed surface demonstrates the contemporaneity of the ripple patches and the sand-based mat. Patchy reworking of existing ripple fields is analogous: in this case where a mat covering rippled sands is removed locally by erosion, reworking will occur. In palimpsest ripples, a mat covering an existing rippled sandy bed allows partial preservation of the older structures when a new ripple field develops on top.

Non-penetrative micro-faults

Name of structure: Non-penetrative micro-faults.
Other terms used: Concentric micro-faults, micro-faults.
Description of structure: Occur as micro-faults restricted to a single sand(stone) bed. On flat upper surface of sand bed, examples are known which show concentric microfaults, with millimetric vertical displacement along the curved faults. Downthrows at individual faults accumulate towards the centre of the structure.

Associated sedimentary structures: (1) heterolithic successon of siltstone and argillite; (2) wavy and lenticular bedding; (3) thin storm deposits (fine-grained to medium-grained sandstone); (4) sand cracks, petees, and mat chips; (5) horizons of dolomite and anhydrite.
Environment: Intertidal zone fringed by sabkha.
Ideas on genesis: Cohesion of relatively thin sand bed underlying microbial mat can be retained for some time after burial, and compaction may then result in non-penetrative micro-faults restricted to that bed. Curved concentric micro-faults may reflect differential compaction; the elliptic shape of the structure suggests deposition of an event bed on an irregular microbial mat surface with elongate domes that resisted erosion.

Figures

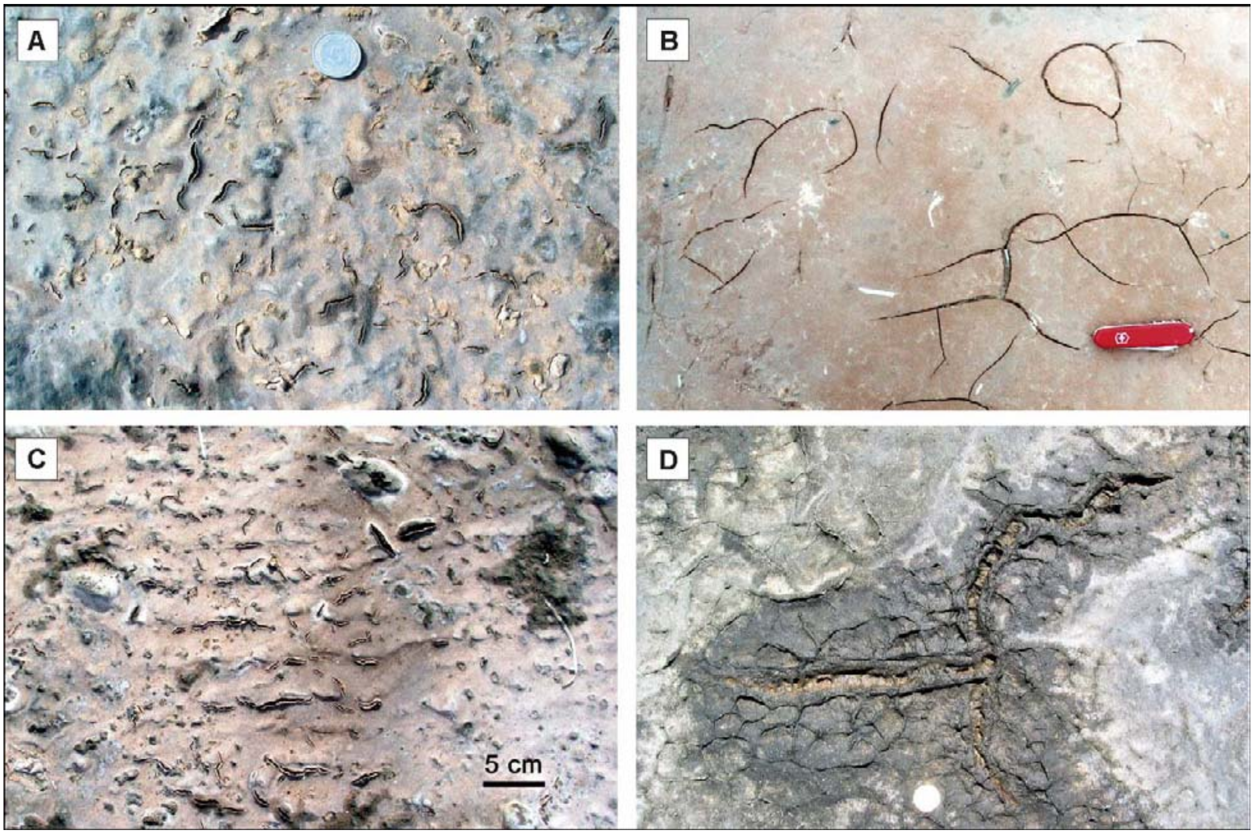

Fig. 4(c)-1: Microbial shrinkage cracks in modern mats:
(A) Microbial shrinkage cracks (term proposed by Porada and Löffler, 2000) in surface of thin, modern microbial mat. Note isolated lenticular, curved, spindle-shaped, and triradiate shrinkage cracks; note also tapering ends of the cracks. Cracks may extend downward into sediment layer below mat. Dark areas around some cracks indicate that groundwater may be rising up from sediment below. Scale (coin): 24 mm. Locality: Bhar Alouane, Mediterranean coast of southern Tunisia; environment: upper intertidal to lower supratidal zones of tidal flat. (B) Microbial shrinkage cracks in thin, modern, flat mat (*Synechococcus*-type?) with simple, triradiate, curved to sinuously curved, and subcircular crack forms. Note that near centre of photo, curved cracks may join to form a figure-8 - shaped pattern. Swiss army knife for scale: 8 cm. Locality: Bahirat Boughrara, Mediterranean coast of southern Tunisia; environment: lower supratidal zone of tidal flat. (C) Irregular surface of modern thin mat (*Synechococcus*-type?) with linear, lenticular to sigmoidal cracks, following the linear trends of shallow bulges. Locality: Bhar Alouane, Mediterranean coast of southern Tunisia; environment: upper intertidal to lower supratidal zones of tidal flat. (D) Close-up view of modern mat surface with shrinkage cracks. Margins and openings of the cracks show active growth of cyanobacterial filaments forming bridge-like structures between margins, and thus favouring progressive closure of the cracks and preservation of sediment filling the cracks. Note groundwater rising up along cracks. Scale (coin): 23 mm. Locality: Salins du Midi, Réserve Nationale Camargue, Southern France;

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environment: preconcentration basin of ‘Salins de Midi’ saltern. All photos: H. Porada and E. Bouougri.

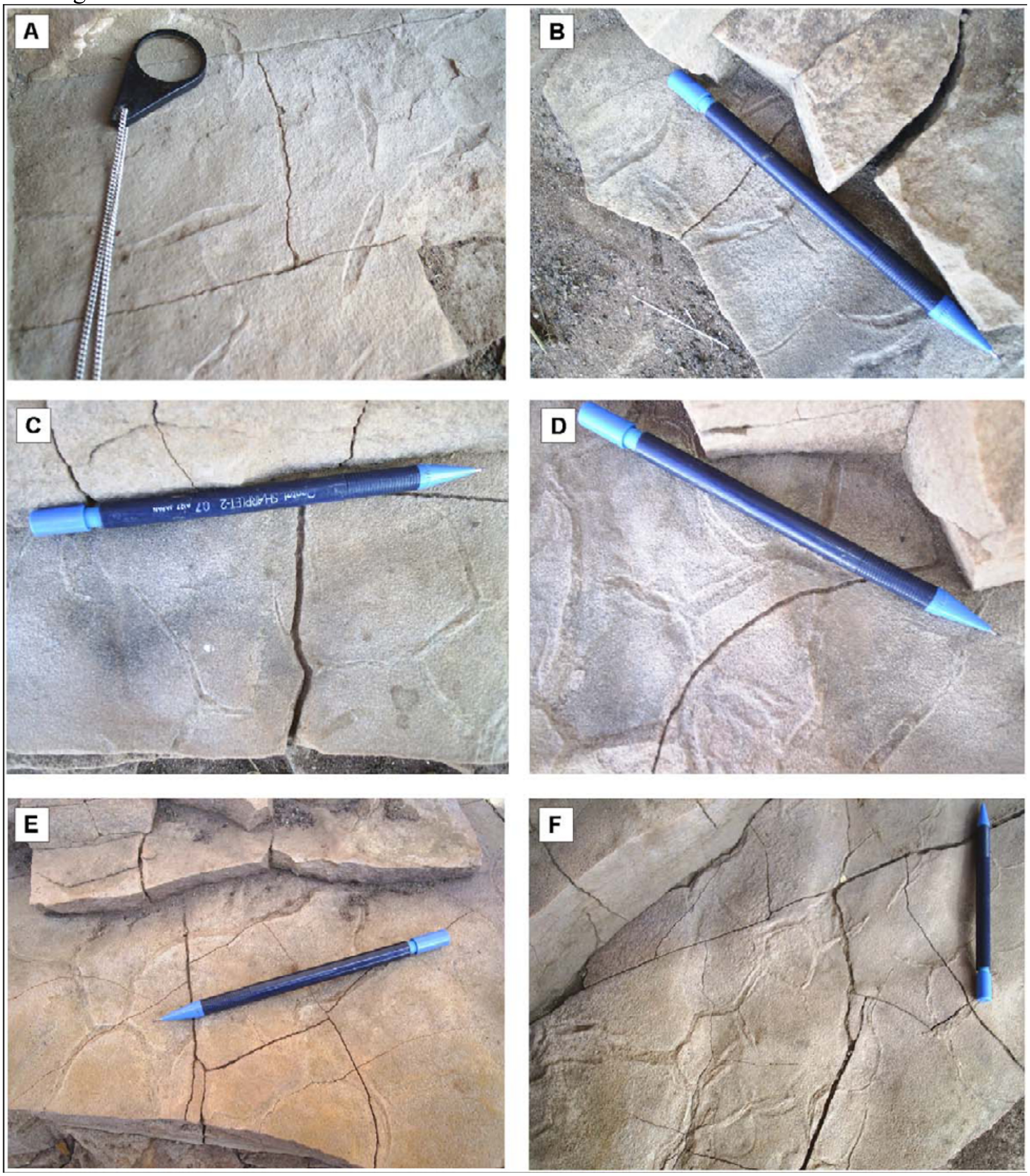

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Fig. 4(c)-2: Sand cracks:

(A) Single incipient tears (inferred from an ancient mat and preserved as cracks within underlying sandstone bed) at relatively high angle orientations to each other. (B) Two incipient tears joining up, to form two parts of a 'triple junction' (triradiate) crack pattern. Note also, below this, an incipient tear passing laterally into a narrow, sinuous sand crack. (C) Sand crack pattern formed from 'triple junction' incipient cracks with as-yet incomplete intersection of incipient cracks. (D) Sand crack mosaic formed by relatively complete intersection of 'triple junction' incipient cracks. (E) Curved crack patterns showing a development from 'triple junction' incipient cracks. (F) Crack patterns formed by intersection of 'triple junction'-type features in centre of photograph; in lower part of photograph is a series of curved cracks which may be secondary after the straighter 'triple junction' types. Note 'triple junction' crack feature just left of the base of the pen, where the three arms have a bead-like morphology; this may reflect joining-up of much smaller incipient tears. All structures in this figure are from planar and rippled (sinuous-crested ripples) sandstone beds within a playa lake lens, enclosed within predominant aeolian sandstones of the Makgabeng Formation (c. 2.0-1.8 Ga), Makgabeng Plateau, Limpopo Province, South Africa. All photos: I. Tonzetic.

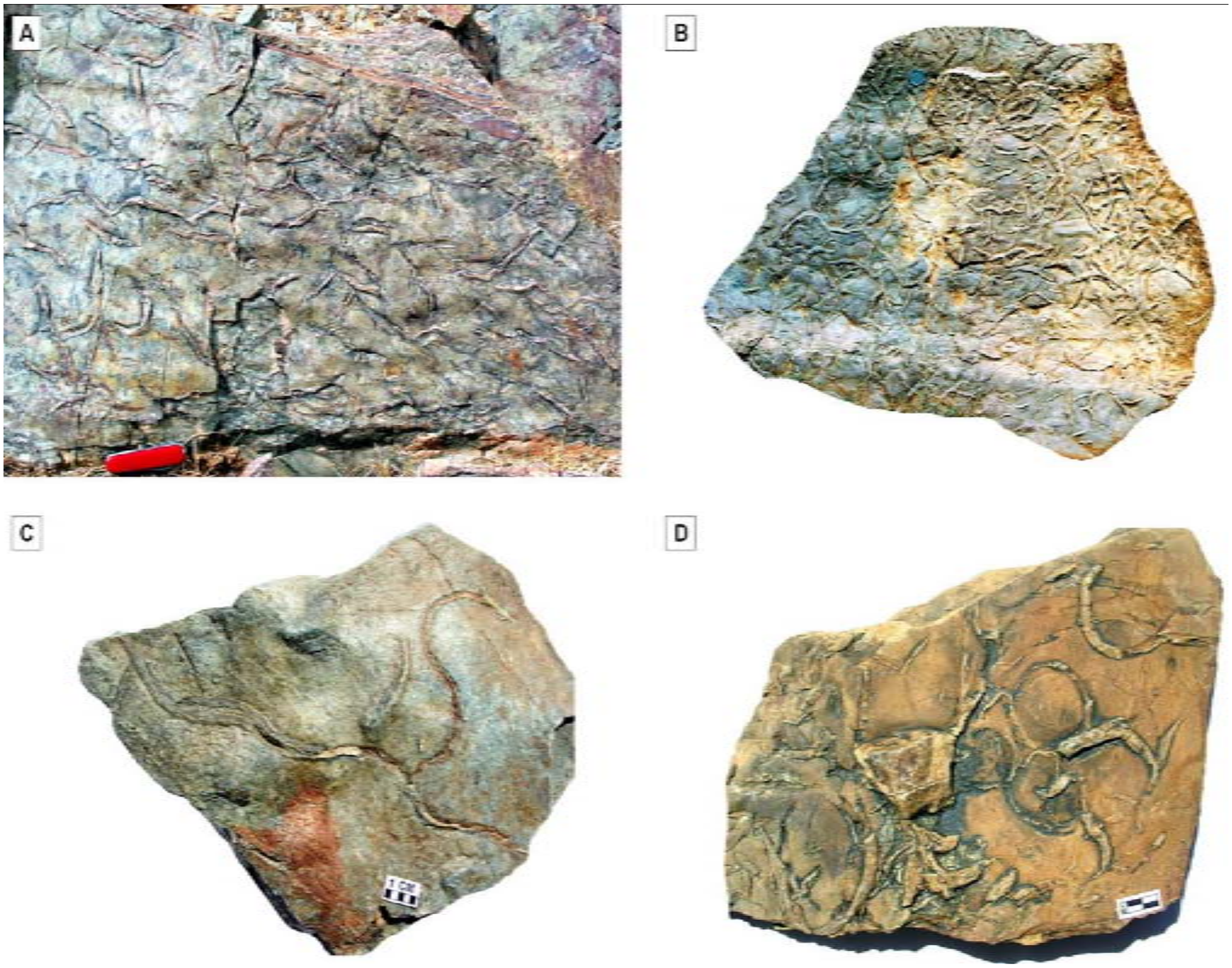

Fig. 4(c)-3: Sand cracks:

(A) Upper sandstone bedding surface with spindle-shaped, lenticular, triradiate, and sinuous sand cracks. (B) Network of sand cracks, consisting of two superimposed crack generations (right side of photo). In the sandstone layer below (left side of photo) only one generation of cracks is developed. (C) Upper sandstone bedding surface with sigmoidal to sinusoidal, and sinuous sand cracks. (D) Upper sandstone bedding surface with spindle-shaped, curved, and figure-8 - like sand cracks. All structures within this figure are from: Morocco, Anti-Atlas, Agoummy area; Neoproterozoic Imi n-Tizi Formation, n-Tizi n-Taghatine Group; palaeoenvironment: intertidal to lower supratidal zones of a peritidal coastal plain. All photos: H. Porada and E. Bouougri.

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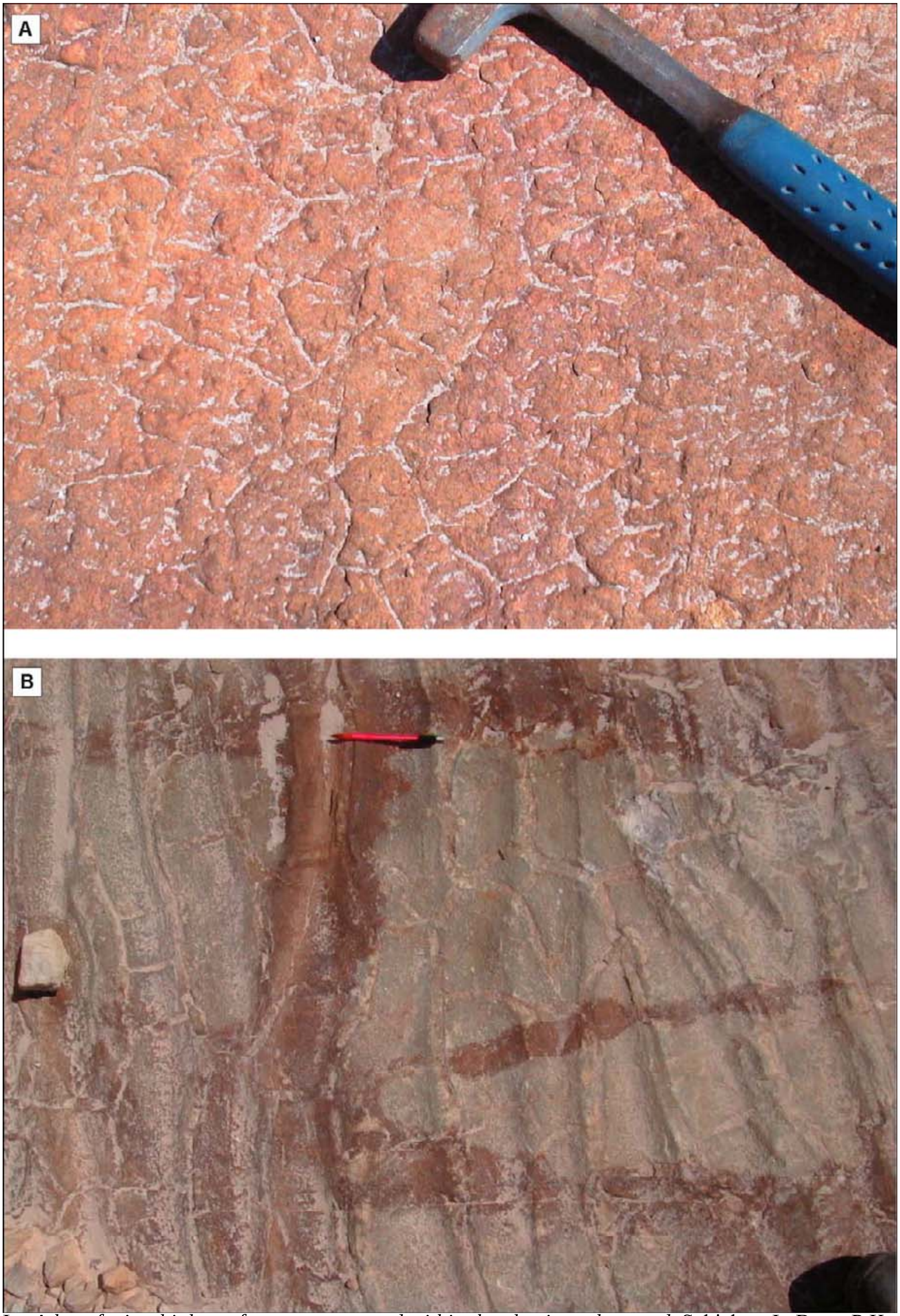

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Fig. 4(c)-4: Sand cracks, and ripple-top sand cracks:

(A) Well-developed first-order sand cracks (filled by modern windblown sand) with poorly developed second-order cracks visible locally. Locality: c. 2.1 Ga Magaliesberg Formation (Pretoria Group, Transvaal Supergroup), B and E Silica Mine, c. 50 km east of Pretoria, South Africa; palaeoenvironment: tidally reworked braid-deltaic epeiric marine coastline. Photo: M. Parizot. (B) Sand cracks developed preferentially on wave ripple crests, with crack orientation predominantly parallel with these crests and with lesser cracks at approximately right angles to this, joining ripple-crest cracks across ripple troughs. Note bifurcation of ripple-crest cracks (detailed discussion in Parizot et al., 2005). Compare with Figure 4(a)-15. Locality: c. 2.1 Ga Magaliesberg Formation (Pretoria Group, Transvaal Supergroup), B and E Silica Mine, c. 50 km east of Pretoria, South Africa; palaeoenvironment: tidal flat – braid-delta setting on an epeiric sea coastline. Pen is 8 mm wide. Photo: M. Parizot.

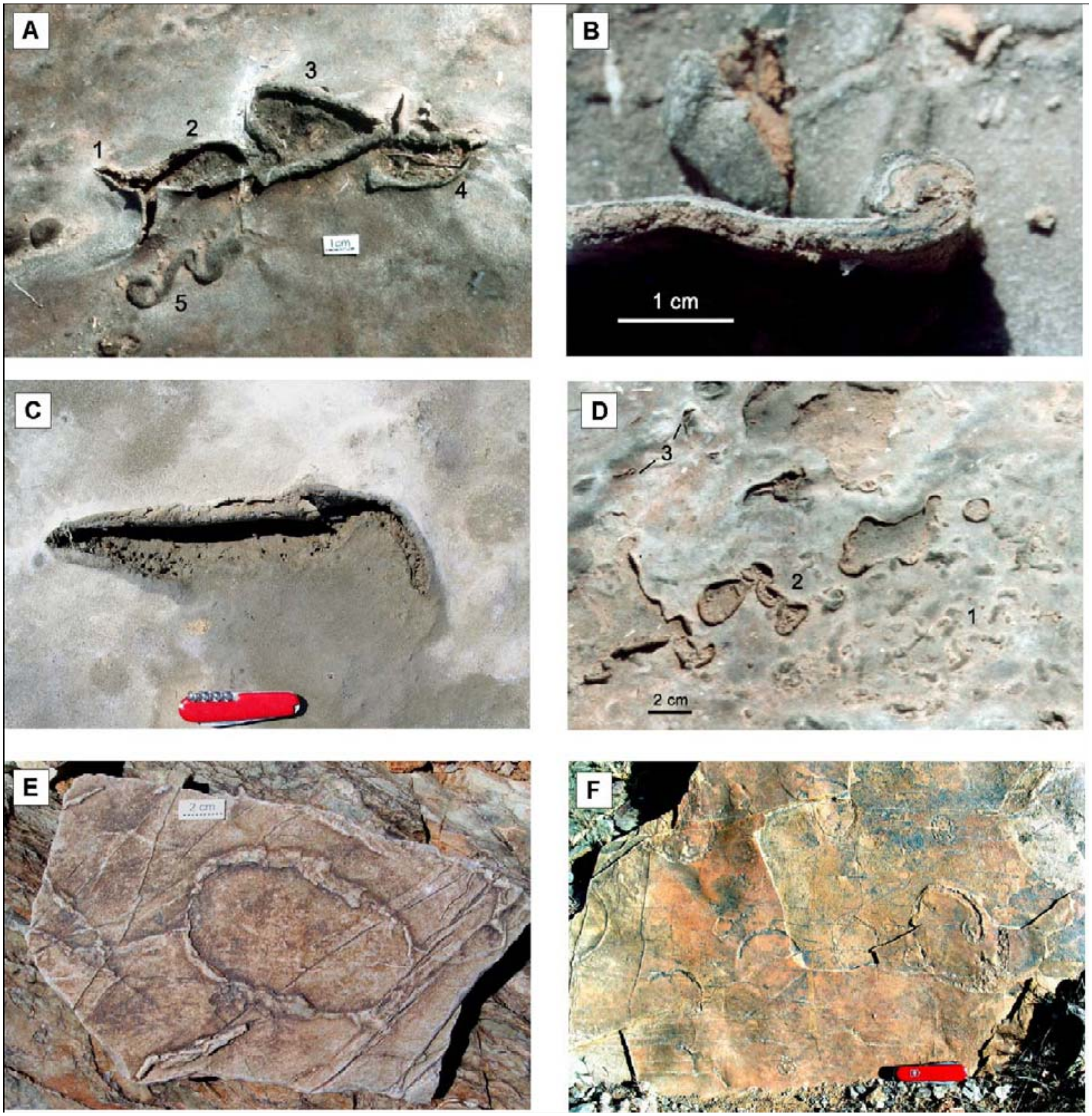

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Fig. 4(c)-5: Curled crack margins:

(A) Modern mat surface with shrinkage cracks. Various stages of crack margin evolution are recognized: (1) incipient crack with simple shape and slightly upturned margins; (2) two opposite margins, one curved and upturned, the other almost straight and curled; (3) three opposing curled margins surround a subcircular opening in the mat surface; (4) old curled margin, partly overgrown by a new mat layer; (5) relic old overgrown curled crack margins. Locality: Bhar Alouane, Mediterranean coast of southern Tunisia; environment: upper intertidal to lower supratidal zones of tidal flat. (B) Section across curled crack margin in modern mat, showing sediment layer below mat to be entangled in the involute margin. Green peripheral band is a new mat layer overgrowing the curled margin. Locality: Bhar Alouane, Mediterranean coast of southern Tunisia; environment: upper intertidal to lower supratidal zones of tidal flat. (C) Modern mat surface with large shrinkage crack showing only one margin to be curled, the other being flat and biostabilized. Locality: Salins du Midi, Réserve Nationale Camargue, southern France; environment: preconcentration basin of 'Salins de Midi' saltern. (D) Mat surface showing several generations of lenticular and irregular to circular, curled margins surrounding cracks and openings in a thin, modern microbial mat: (1) relics of first generation curled margins, completely overgrown; (2) second generation curled margins and openings, partly overgrown by new mat layers; (3) new, third generation, upturned crack margins. Locality: Bhar Alouane, Mediterranean coast of southern Tunisia; environment: upper intertidal to lower supratidal zones of tidal flat. (E) Upper surface of fine-grained quartzite layer showing subcircular and linear, irregular ridges. The subcircular one is distinctly flattened, whereas the linear ridge (near lower side of photo) exhibits a composite structure of two superimposed ridges. The structures are interpreted as curled margins of a narrow linear crack (two ridges) and a subcircular opening in a thin microbial mat that previously covered a sandy sediment surface. Locality: Morocco, Anti-Atlas, Agoummy area; Neoproterozoic Wanimzi Formation, Tizi n-Taghatine Group; palaeoenvironment: peritidal (intertidal to supratidal) coastal plain. (F) Upper quartzite bedding surface with mainly circular to curved ridges, interpreted as curled crack margins partly surrounding circular and subcircular openings in a thin microbial mat that previously covered a sandy sediment surface. Note linear and triradiate ridges at lower left of photo. The diameters of the circular structures vary between 2 cm and 8 cm. Scale (knife): 8 cm. Locality: Morocco, Anti-Atlas, Agoummy area; Neoproterozoic Im n-Tizi Formation, Tizi n-Taghatine Group; palaeoenvironment: peritidal (intertidal to supratidal) coastal plain. All photos: H. Porada and E. Bouougri.

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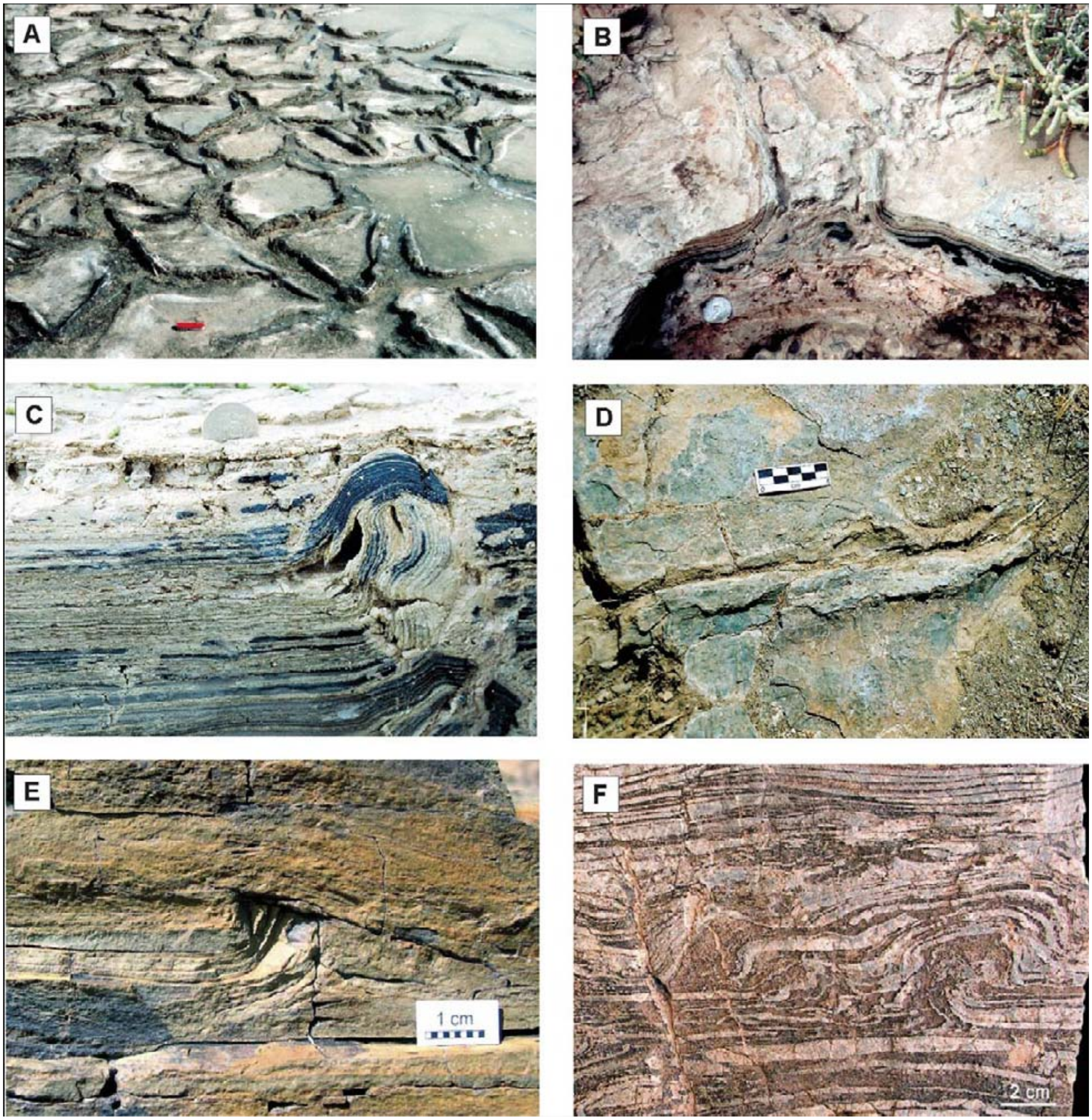

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Fig. 4(c)-6: Overgrown, upturned crack margins:

(A) View of surface of decimetre-scale polygonal network of shrinkage cracks within modern biolaminite. The edges of the polygons are upturned, overturned and partly overfolded. In the crack openings, a new thin mat has formed, partly overgrowing the polygons' edges. Note high tide water flooding the polygonal network from the right side. Scale (Swiss army knife): 8 cm. (B) Section across two symmetrical upturned crack margins in thin layer of modern biolaminite. The margins are upturned into a vertical attitude and have a thickness of 2 cm. On the bedding surface, they are slightly sinuous or curved. The crack opening is filled with sediment which is partly trapped beneath the upturned margins. Scale (coin): 24 mm. (C) Section across a single upturned crack margin developed on one side of a shrinkage crack in modern biolaminite. The margin is upturned into a vertical attitude and partly overgrown by new mat layers. Sand- to silt-sized sediment is accumulated on both sides of the overgrown upturned crack margin, thus fossilizing the structure. Scale (coin): 25 mm. Photos (A) to (C) from the intertidal zone, Bhar Alouane, Mediterranean coast of southern Tunisia; environment: intertidal zone. (D) Upper sandstone bedding surface showing upturned crack margins forming inverted 'V' or antiformal structures along both sides of a shrinkage crack. Upturned margins are up to 3 cm high. Locality: Namibia, Haruchas area; Vingerbreek Member, Nudaus Formation, Schwarzrand Subgroup, Nama Group; Terminal Proterozoic; palaeoenvironment: intertidal to supratidal shallow back-barrier setting, with small tidal channels and few high energy storm deposits. (E) Cross-sectional view of an asymmetric upturned crack margin formed at one side of a shrinkage crack preserved within sandstone; laminae are upturned into a vertical attitude. Locality and palaeoenvironment, as for (D). (F) Section across an upturned margin of a shrinkage crack preserved in sandstone. The margin is overturned and completely overgrown. Towards the top of the photo, the structure is fossilized by continuous, normal lamination. Locality: Morocco, Anti-Atlas, Nqob area; Neoproterozoic Wanimzi Formation, Tizi n-Taghatine Group; palaeoenvironment: intertidal zone of a peritidal coastal plain. All photos: H. Porada and E. Bouougri.

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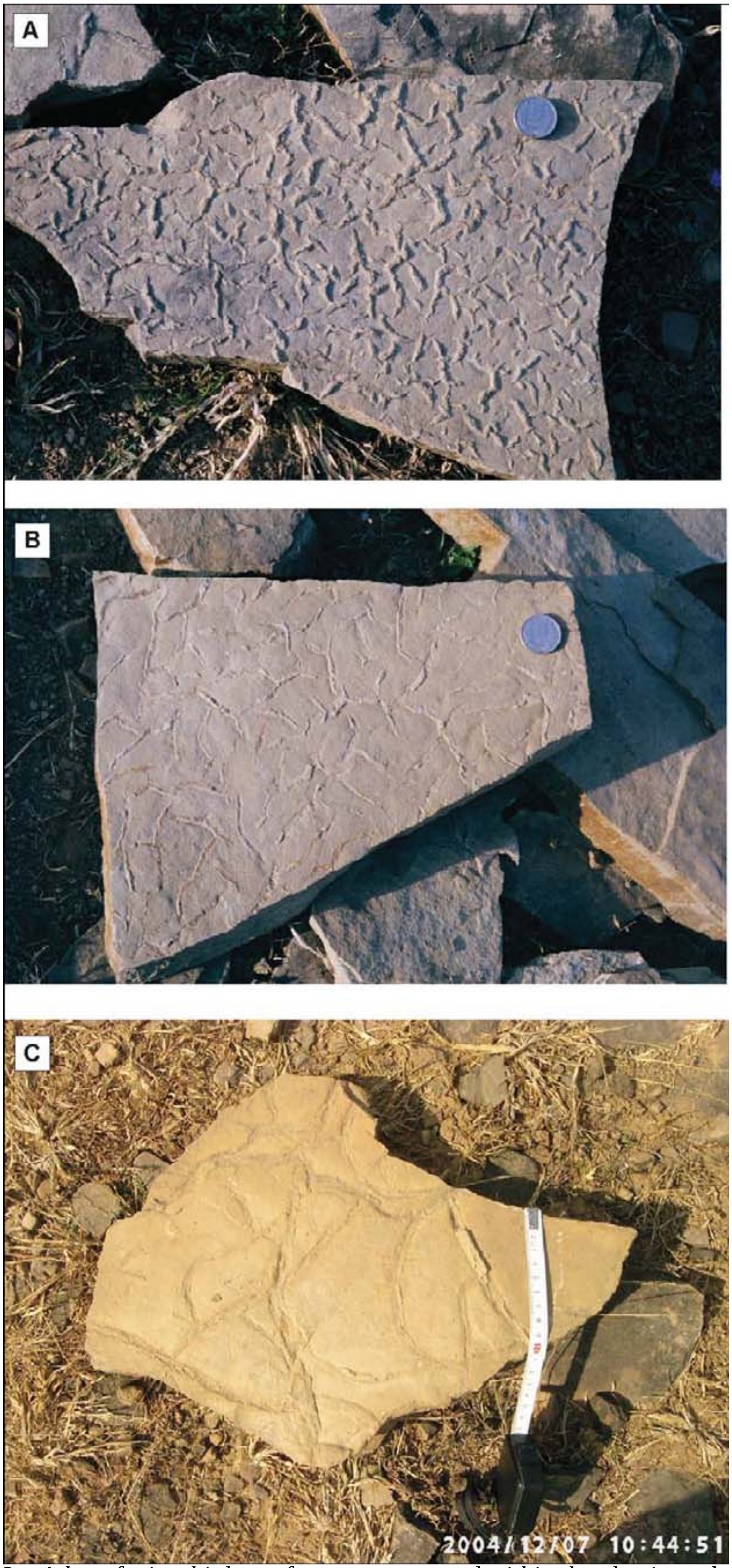

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Fig. 4(c)-7: Filled sand cracks:

(A) Positive ridges on bed upper surface, which have a cross-cutting pattern (including 'triple junctions') and form an incipient network. Note also, weak development of second-order ridges between well-developed first-order features. Resemble analogous sets of (negative) sand cracks with very similar geometrical pattern (compare with Fig. 4(c)-2), but their positive nature is analogous to petee ridges. However, the latter generally comprise sandstone from the lower bed, are related to disturbance of laminated sands in lower bed and are separated by concave-upward segments between the ridges. In the example illustrated (and in B and C), none of these criteria are met and the composition of the ridges is that of the overlying sandstone bed. (B) Positive ridges on bed upper surface, which have a cross-cutting pattern (including 'triple junctions') and form an incipient network (first-order features only). Note also that many of these ridges are partially flattened, including a few that appear to have been pushed sideways and then flattened (see broader flattened ridge to left of coin). Resemble analogous sets of (negative) sand cracks with very similar geometrical pattern (compare with Fig. 4(c)-2), but their positive nature is analogous to petee ridges. Note that some of these reticulate features change from being ridges to being shallow (negative) cracks, in the bottom left part of the slab. It must be emphasized, however, that a cracked mud layer, between the two sand layers in A and B may also have produced these crack-fill features, and these two examples cannot thus be taken as unequivocal evidence for desiccation of a mat growing on a sandy substrate. (C) Sinuous cracks which form irregular curved patterns, and which are filled by a later (coarser and more granular) sandy material, different to the underlying sandstone bed; much of this secondary crack-fill material has been erosively removed, the largest remnant being situated to the left of the measuring tape. The negative nature of the original sand cracks in the bed's top surface is clear. These crack-fills would thus appear not to be petee ridges, as also evidenced by undisturbed sandstone laminae in the upper part of the underlying sandstone bed (as seen in section) and the lack of concave-upwards segments between the crack features. For all three photos, locality: Chorhat Sandstone Member (Kheinjua Formation, Semri Group) (c. 1600 Ma), Vindhyan Supergroup, central India, at Chopan; palaeoenvironment: intertidal setting. All photos: S. Banerjee.

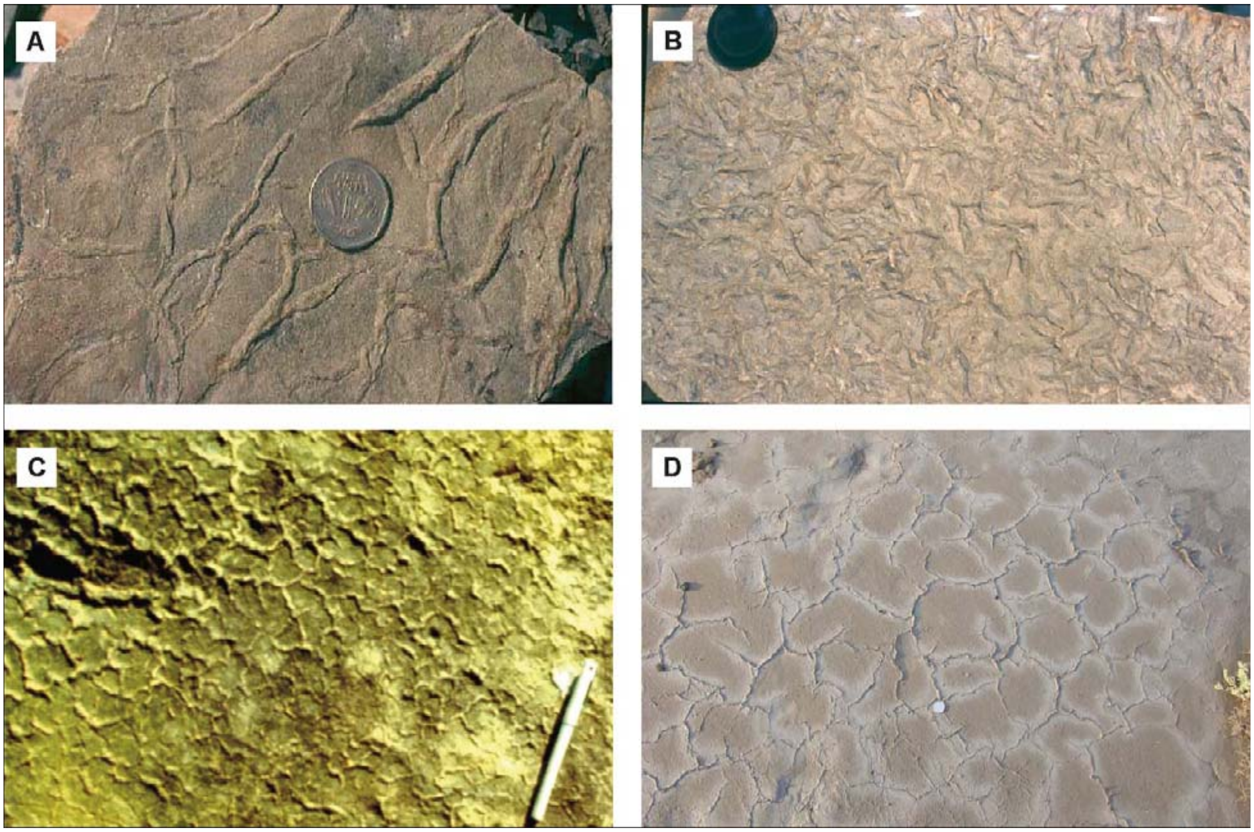

Fig. 4(c)-8: Petees/petee ridges:

(A) Petee ridges showing both spindle-shaped forms and longer, more sinuous shapes. Presumably these formed initially as incipient tears and sinuous cracks in a mat covering a sandstone bed, and were then filled from below by that same sandstone to form the positive petee ridges. Locality: Chorhat Sandstone Member (Kheinjua Formation, Semri Group) (c. 1600 Ma), Vindhyan Supergroup, central India, at Amjhore; palaeoenvironment: intertidal setting. (B) Dense pattern of at least two orders of petee ridges (filled by same sandstone as that comprising underlying bed, with deformation of sandstone laminae in that sandstone, and with upward-concave segments between petees). An impression is gained from this photo, that the densely packed petee ridges may have been deformed, possibly owing to a still-living mat between them which was subject to shortening, due to something like movement of mat and petees under the influence of a strong current. Locality and palaeoenvironment: as for (A). (C) More pervasive, reticulate-polygonal pattern of petee ridges; note ridges cutting across each other in several places, suggesting pervasive development, probably by synaeresis origin. Locality and palaeoenvironment: intertidal-supratidal zone of the 0.6 Ga Sonia Sandstone, Jodhpur Group, Rajasthan, India. (D) Reticulate, polygonal pattern of petee ridges, from modern sands along the Indian coast at Mumbai, in the intertidal zone. Note incomplete connection of many of the ridges; also, locally, sand cracks can be observed passing laterally into petee ridges – left of the coin, and in the middle of the top margin of the photo. Photos A, B and D: S. Banerjee. Photo C: S. Sarkar.

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Fig. 4(c)-9: Petee ridges and related sand cracks:

Irregular network of petee ridges, composed of the same sandstone as the bed in whose top they occur; this underlying bed also has sandstone laminae which are disturbed, when seen in section, and the ridges are separated by concave-upward segments. Note, however, the presence of negative cracks in parts of this bed upper surface: particularly the two clearly negative features (which resemble incipient mat-tears – see Fig. 4(c)-2) immediately above the two prominent ridges adjacent to the coin, and also several, more sinuous cracks in the right-lower part of the field of view. This suggests that the cracks were likely primary and were later filled from underneath by liquefied sand which, under pressure (gas expulsion or dewatering; or from overlying beds or due to loading with changes in tidal height) formed the petee ridges (see also Fig. 4(c)-8D). Locality: Chorhat Sandstone Member (Kheinjua Formation, Semri Group) (c. 1600 Ma), Vindhyan Supergroup, central India, at Amjhore; palaeoenvironment: intertidal setting. Photo: S. Banerjee.

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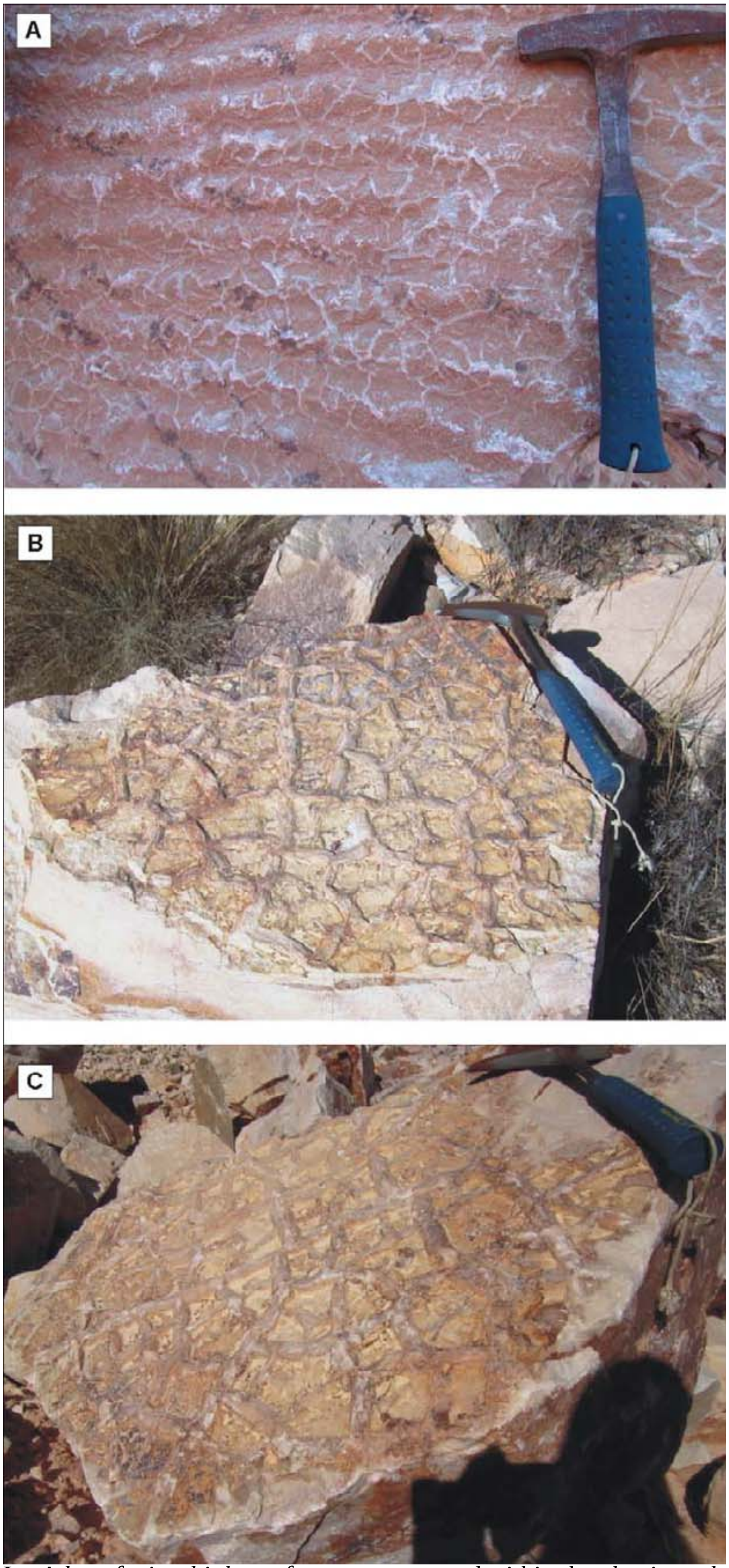

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Fig. 4(c)-10: Petees/petee ridges:

(A) Reticulate pattern of flattened petee ridges (mainly first-order with few second-order ridges) developed on earlier wave ripples. (B) and (C) Note three orders of petee ridges in both examples. Both are from loose blocks of partially recrystallised quartzites quarried in a small opencast working. Thin sections through these petee ridges showed clearly a lower medium-grained sandstone, overlain along an irregular contact (soft sediment deformation) by an upper fine-grained sandstone layer; the latter also makes up the petee ridges (detailed discussion in Parizot et al., 2005). For all three photos, locality: c. 2.1 Ga Magaliesberg Formation (Pretoria Group, Transvaal Supergroup), B and E Silica Mine, c. 50 km east of Pretoria, South Africa; palaeoenvironment: tidal flat – braid-delta setting on an epeiric sea coastline. All photos: M. Parizot.

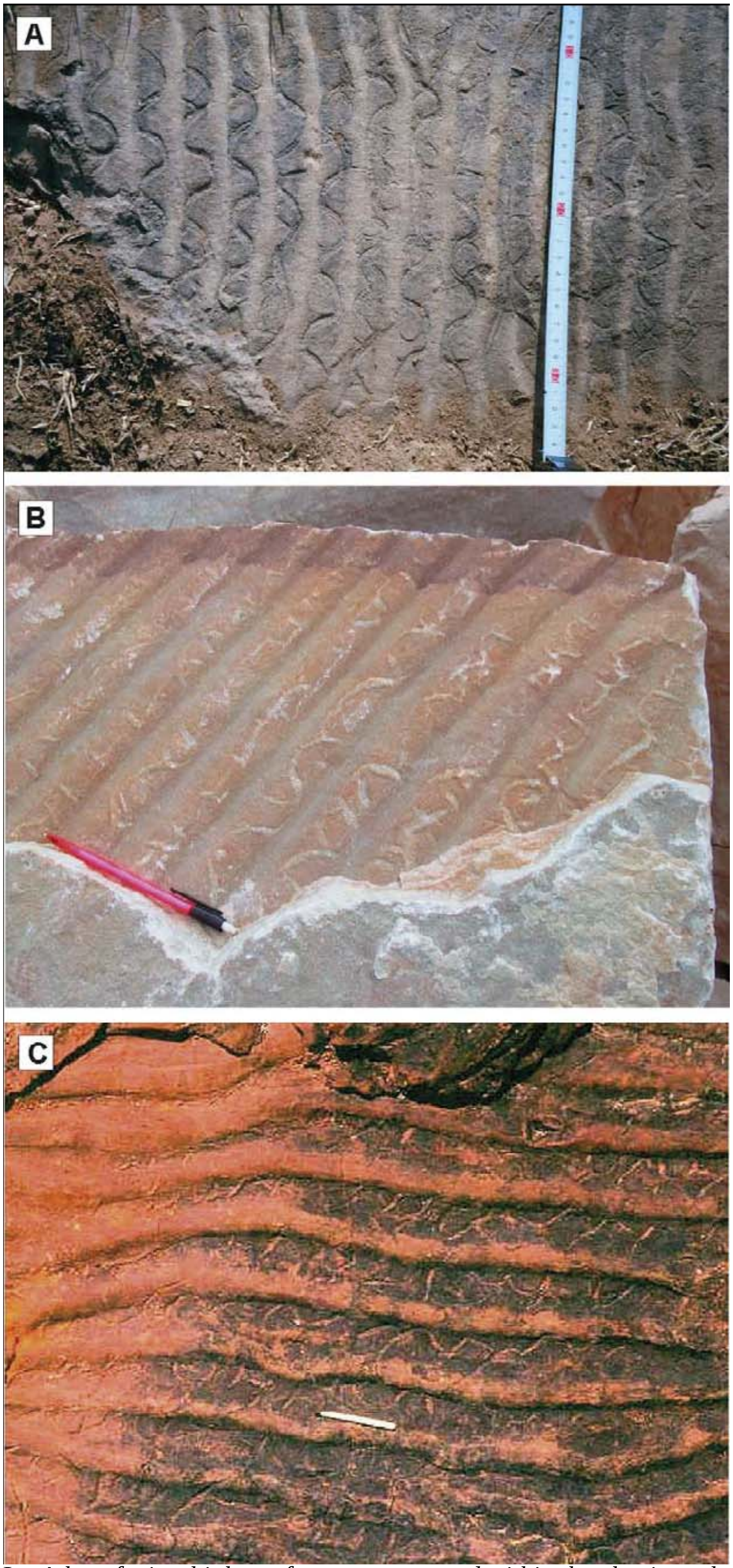

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Fig. 4(c)-11: '*Manchuriophycus*':

(A) Sinuous cracks confined to troughs between wave ripples ('*Manchuriophycus*') on sandstone bed upper surface; note uncommon, smaller connecting cracks which do cross ripple crests. Locality: Chorhat Sandstone Member (Kheinjua Formation, Semri Group) (c. 1600 Ma), Vindhyan Supergroup, central India, at Chorhat; environment: intertidal setting. Photo: S. Banerjee. (B) '*Manchuriophycus*' structures preserved on the sole of a sandstone bed overlying that on which they originally formed. Note that inverted wave ripple crests between these cracks are flattened off, most probably due to tidal reworking (detailed discussion in Parizot et al., 2005). Pen is 8 mm wide. Locality: c. 2.1 Ga Magaliesberg Formation (Pretoria Group, Transvaal Supergroup), B and E Silica Mine, c. 50 km east of Pretoria, South Africa; palaeoenvironment: tidal flat – braid-delta setting on an epeiric sea coastline. Photo: M. Parizot. (C) Sinuous cracks confined to troughs between wave ripples in sandstone ('*Manchuriophycus*'). Note that ripples bifurcate at left of photograph, and that the cracks grow in dimension as spacing between ripple crests widens. Note also a later generation of cracks (long cracks below and above pencil; also lower left of photograph) which cut across ripple crests and cracked troughs at an orientation approximately perpendicular to the ripple crests. Locality and palaeoenvironment: as in (A). Photo: S. Banerjee.

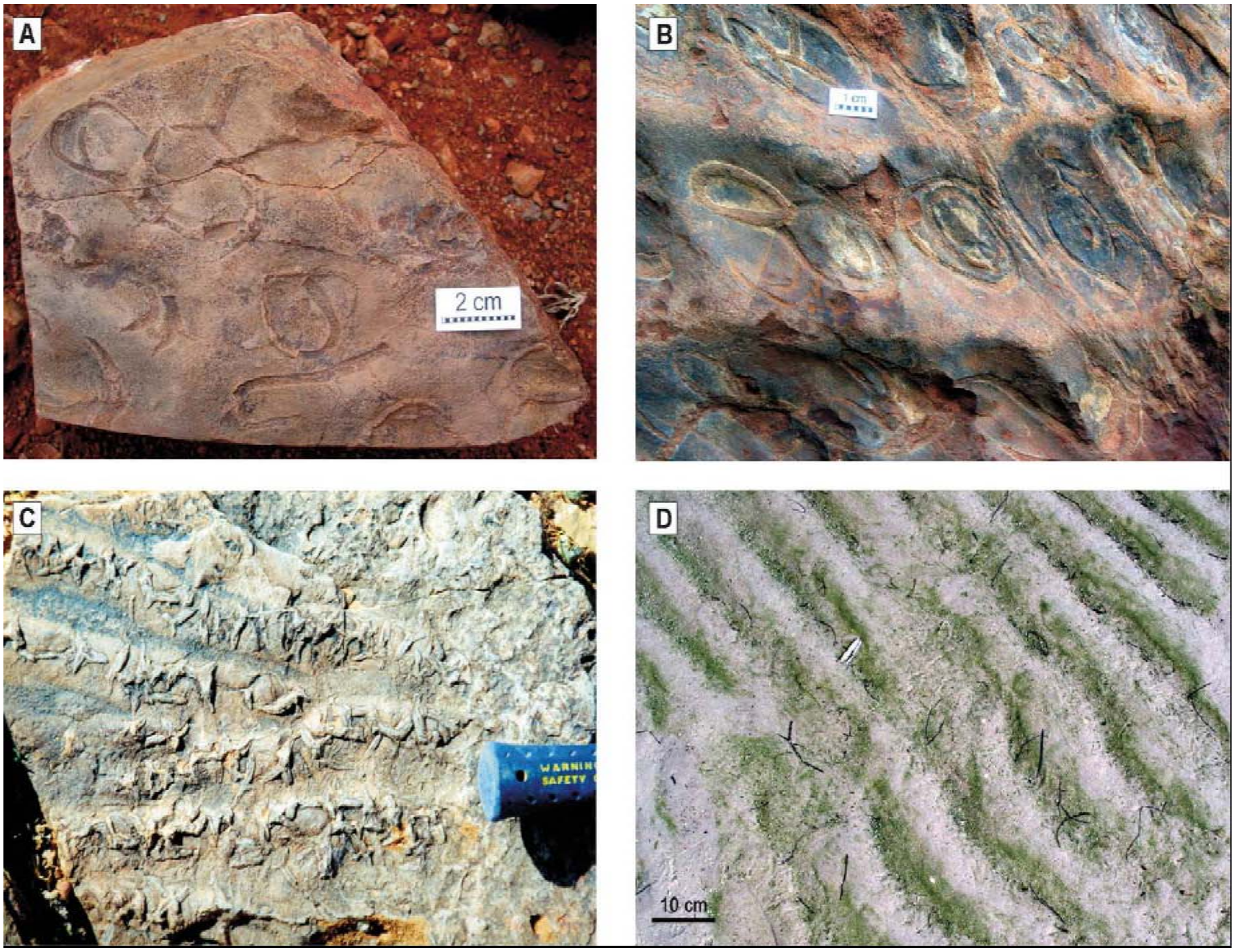

Fig. 4(c)-12: '*Manchuriophycus*':

(A) Sandstone upper bedding surface with interference ripples. In troughs, sinuous, circular and triradiate cracks ('*Manchuriophycus'*) are developed. Note that cracks largely follow the edges of the troughs. Locality: Morocco, Anti-Atlas, Ifni inlier, Larbâa n-Sahel area; Neoproterozoic Tizi n-Taghatine Group; palaeoenvironment: coastal plain of lacustrine or shallow marine environment, fringing alluvial braid-delta system. (B) Upper bedding surface of sandstone with interference ripples and shrinkage cracks. In the troughs, figure-8 - like cracks ('*Manchuriophycus'*) occur. Locality and environment: as for A. (C) Lower bedding surface of sandstone with spindle-shaped, lenticular and triradiate microbial shrinkage cracks in troughs of oscillation ripples. Locality: Morocco, Anti-Atlas, Agoummy area; Neoproterozoic Imi n-Tizi formation, Tizi n-Taghatine Group; palaeoenvironment: intertidal to lower supratidal zones of a peritidal coastal plain. (D) Modern sediment surface with current ripples and concentration of cyanobacteria in troughs and on lee sides of ripples. Locality and environment: shallow outlet of temporary pond in upper intertidal zone of tidal flat, Amrum island, North Sea coast of Germany. All photos: H. Porada and E. Bouougri.

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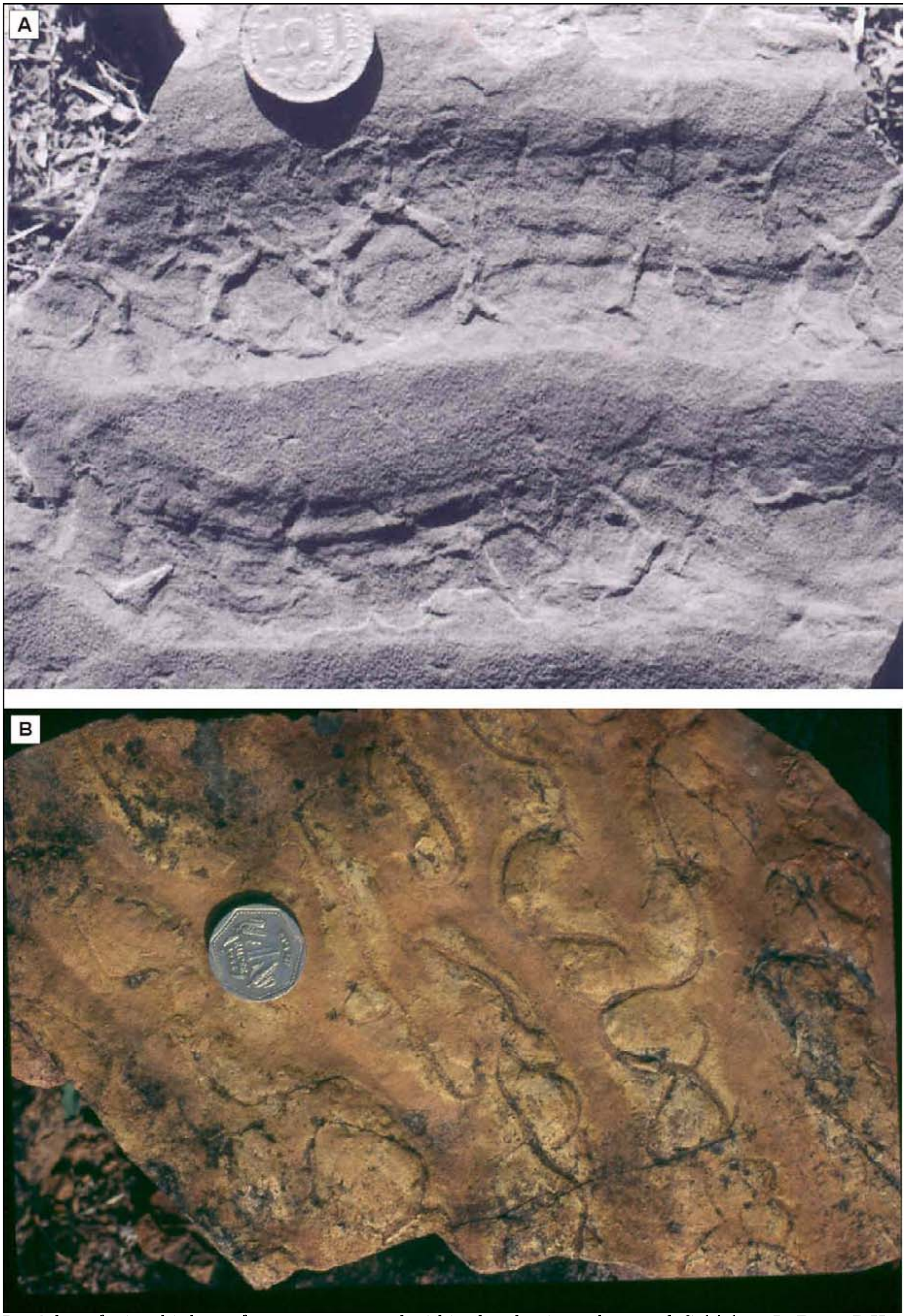

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Fig. 4(c)-13: '*Manchuriophycus*' oddities:

(A) Reticulate pattern of ridges, reflecting petee-type crack fills, where the primary cracks formed in the troughs between slightly sinuous ripples within sandstone. An origin similar to '*Manchuriophycus*' may thus be assumed, with thicker mat within ripple troughs cracking, but instead of the sinuous patterns typical of '*Manchuriophycus*', a reticulate assemblage of short, straight cracks formed, later filled from below by liquefied sand to form petee-type ridges. Locality: Chorhat Sandstone Member (Kheinjua Formation, Semri Group) (c. 1600 Ma), Vindhyan Supergroup, central India, at Chopan; palaeoenvironment: intertidal setting. (B) Top surface of a rippled sandstone bed, with sinuous cracks developed only on ripple crests. Note that ripples form complex bifurcating patterns; also note the very well-developed sinuous crack which follows one such ripple crest subdivision in the top right part of the photograph. This pattern is effectively the opposite of that shown in Figure 4(c)-11 and can be described as an 'inverse *Manchuriophycus* feature'. Locality: Chorhat Sandstone Member (Kheinjua Formation, Semri Group) (c. 1600 Ma), Vindhyan Supergroup, central India, at Amjhore; palaeoenvironment: intertidal setting. Both photos: S. Banerjee.

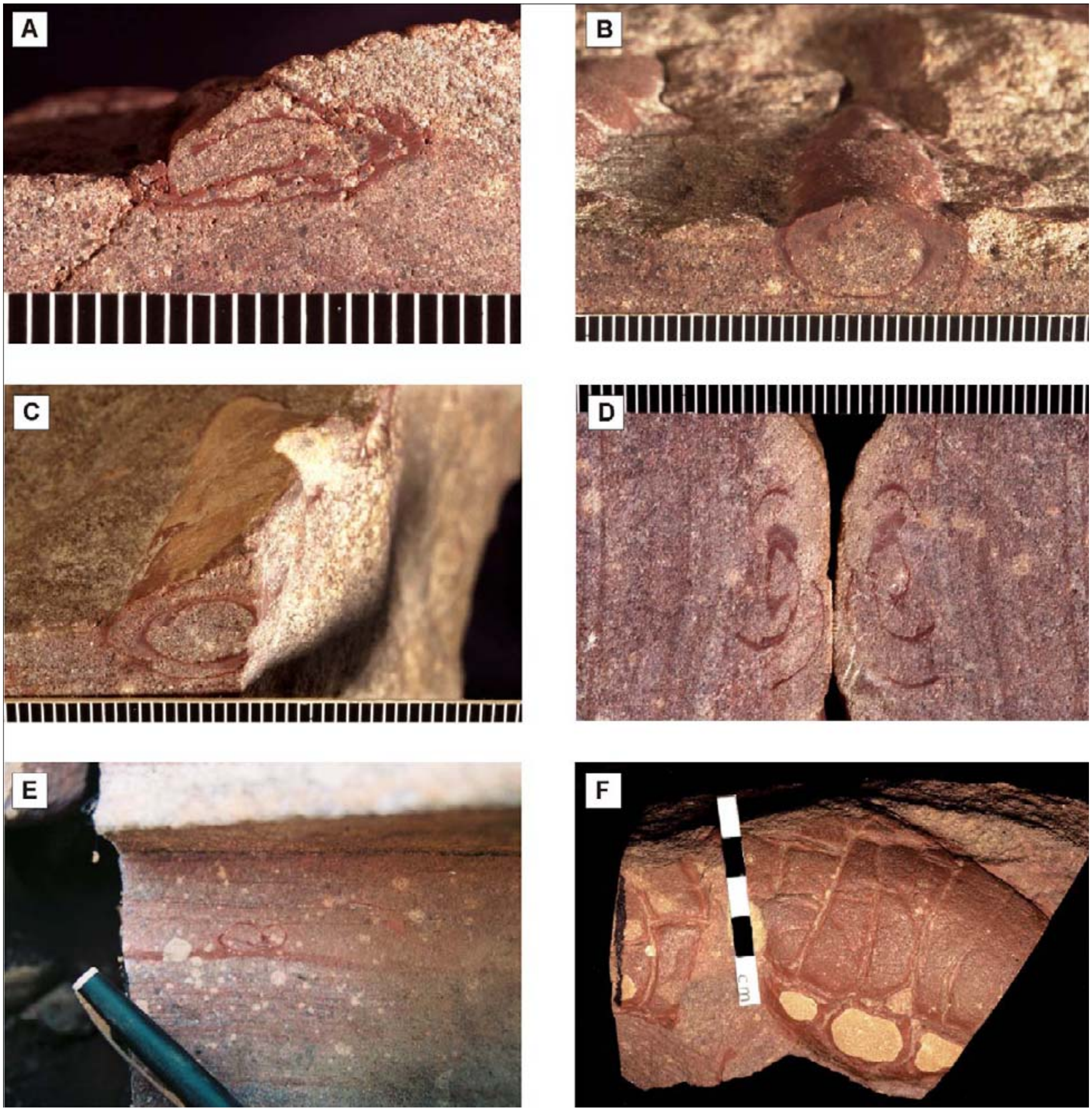

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Fig. 4(c)-14: Rolled-up mat fragments:

Various ‘roll-up’ structures from sandstones from a playa lake lens within predominant aeolian sandstones of the Makgabeng Formation (c. 2.0-1.8 Ga), Makgabeng Plateau, Limpopo Province, South Africa. In all cases the roll-ups consist of strongly ferruginous mudrock, rolled up within thinly bedded (upper flow regime), flash-flood reworked playa and/or aeolian fine-grained sands. The individual roll-ups occur either within a part of or within the full thickness of a single such upper flow regime plane bed. (A) Slightly flattened concentric roll-up, shown in cross-section – roll-up extends several centimetres into the rock, having thus a cigar-like overall geometry. Millimetric scale. (B) Unflattened concentric roll-up, illustrating three-dimensional cigar-like geometry; almost two full concentric circles are preserved in the roll-up. Millimetric scale. (C) Unflattened concentric roll-up, with elongated cigar-like geometry and more than two full concentric revolutions preserved; right edge of roll-up partly destroyed in sampling. Millimetric scale. (D) Section sliced through a cigar-like roll-up, showing mirror-image geometry; note almost three complete concentric circles. Millimetric scale. (E) Two roll-ups, with opposite sense of rotation, forming a scroll-like feature. Note that the large light coloured spots within the sandstone are reduction spots, not coarse-grained sand particles. (F) Close-up detail of outer wall of a ferruginous rolled-up mat fragment. Note cracks in the mudrock forming the preserved roll-up, analogous to mud cracks. Under the microscope, such cracks have a typical V-shaped sectional geometry, and are filled with secondary, fine sand grains. The mud was thus able to form the roll-ups due to an inferred microbial mat providing cohesion for several concentric rotations to form a ‘cigar’, and then, upon desiccation (of inferred mat and mud), the rolled-up mud dried and cracked. Centimetric scale. All photos: A.J. Bumby; material collected in field by A.J. Bumby, I. Tonzetic and P.G. Eriksson.

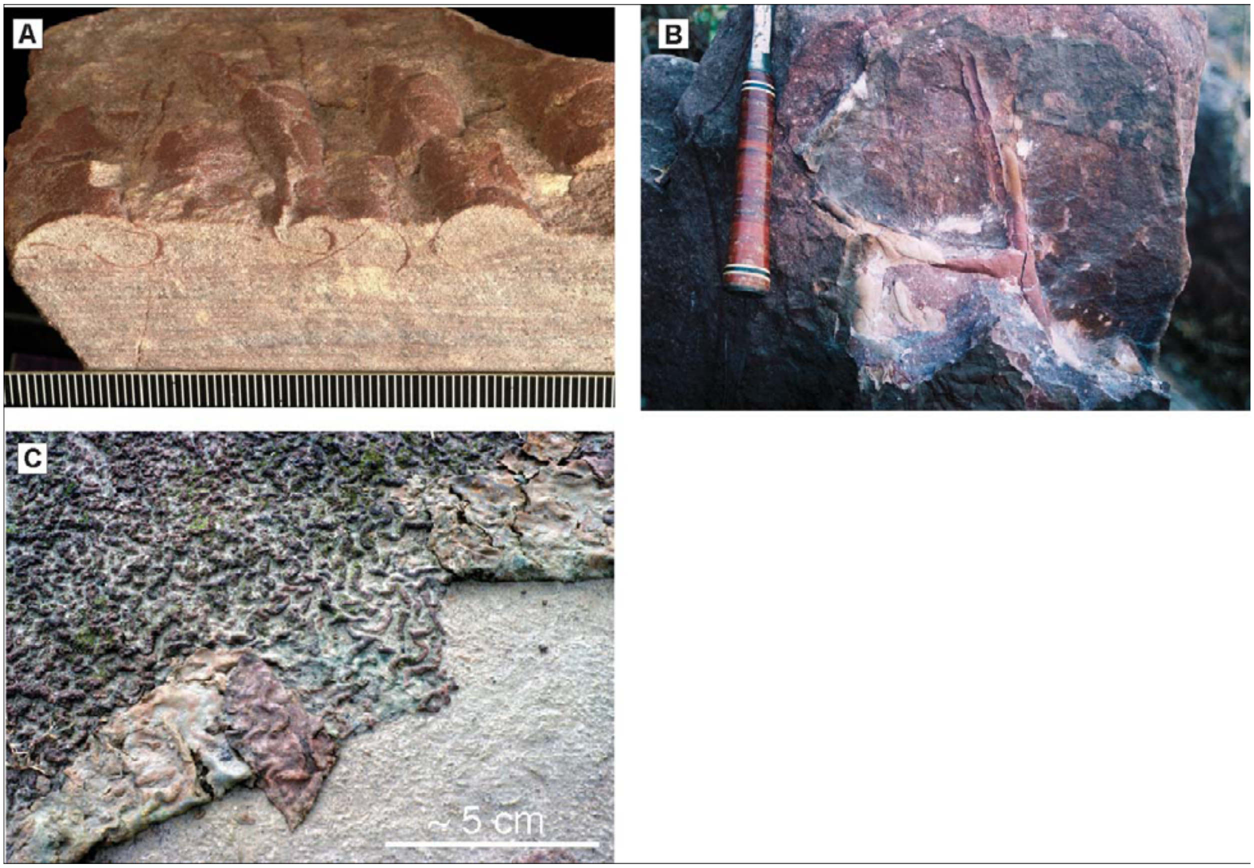

Fig. 4(c)-15: Rolled-up mat fragments and flipped-over mat fragments:

(A) Large cut sandstone slab showing several preserved rolled-up mat fragments (comprised of ferruginous mudrock), each with cigar-like three-dimensional geometry; note parallel orientation of long axes of ‘cigars’, possibly due to high energy flash-flood fluvial current action. Millimetric scale. Locality: Makgabeng Formation (c. 2.0-1.8 Ga), Makgabeng Plateau, Limpopo Province, South Africa; palaeoenvironment: playa lake lens within predominant aeolian sandstones, all subject to flash-flood reworking. (B) Upper surface of sandstone bed containing several large, linked rolled-up and flipped-over mat fragments. These suggest localized physical destruction of a microbial mat and formation of flip-over and roll-up features without complete detachment of the mat from its sandy substrate. Locality and palaeoenvironment: as for A. Photos A and B: A.J. Bumby. (C) Modern, wrinkled microbial mat, developed on loose quartz sand, showing segment of mat flipped over by wind when the area was flooded during a rainstorm, and subsequently dried up. Location: transient excavation, Ottawa, Canada. Photo: J.A. Donaldson.

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Fig. 4(c)-16: Microbial mat chips:

Upper surface of sandstone bed containing numerous smaller to larger mat fragments and mat chips. Note that some of these have curled up to form roll-ups, while others are curved microbial mat chips. Some of the larger fragments have cracked surfaces; presumably, these became desiccated and cracked after becoming fragmented from a primary mat. All these mat destruction features consist of iron-pigmented mudrocks. Lens-cap for scale. Locality: Makgabeng Formation, Waterberg Group (c. 2.0-1.8 Ga), Makgabeng Plateau, Limpopo Province, South Africa; palaeoenvironment: flash-flood deposited sandstones which reworked interdune-playa lacustrine deposits within an overall palaeodesert setting. Photo: A.J. Bumby.

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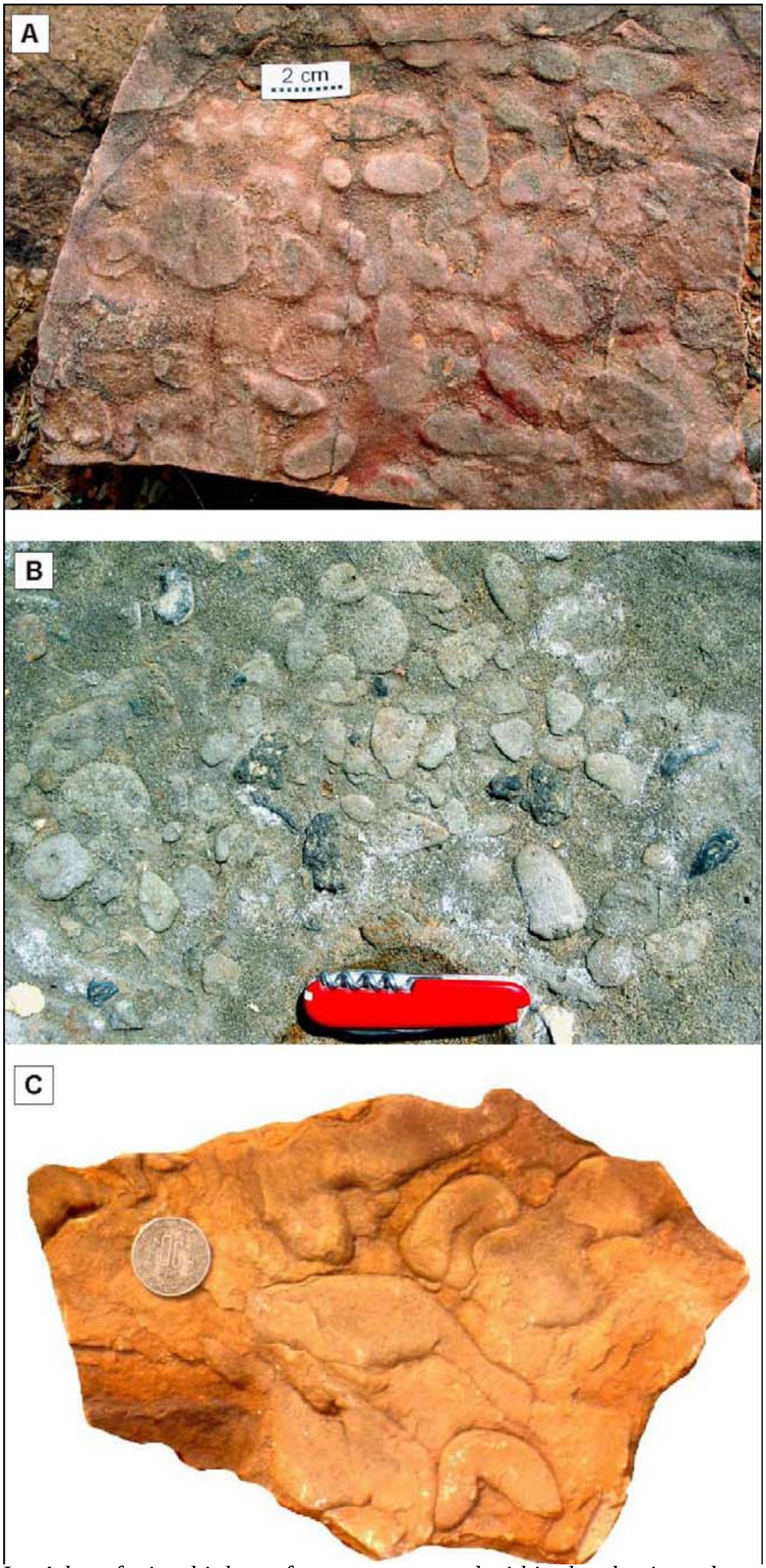

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Fig. 4(c)-17: Microbial sand chips:

(A) Upper surface of fine-grained sandstone layer, about 5 cm thick, showing rounded and elongate, flat sand clasts. Size of clasts varies between 1 and 2 cm (long axis); thickness is less than 2 mm. Clasts are slightly oriented and some of them overlap. Locality: Morocco, Anti-Atlas, Agoummy area; Neoproterozoic Wanimzi Formation, Tizi n-Taghatine Group; palaeoenvironment: intertidal zone of a peritidal coastal plain. (B) Modern sandy-pebbly sediment surface with subrounded to rounded microbial sand chips. The chips consist of black organic material with enclosed fine-grained sand- to silt-sized grains, vary in size between 1 and 2 cm (long axis), are up to 3 mm thick, and partly show overlapping relationships. Surrounding sediment is biostabilized. Scale (knife): 8 cm. Locality: Salins du Midi, Réserve Nationale Camargue, Southern France; environment: shoreline of preconcentration basin of 'Salins du Midi' saltern. (C) Sand chips with obvious deformation, indicating flexible binding between sand grains. Extracellular polymeric substances and microbial filaments presumably provided the cohesion needed to produce the chips from granular sand. Locality: 0.6 Ga Lower Bhander Sandstone, Vindhyan Supergroup, central India; palaeoenvironment: coastal playa. Photos A and B: H. Porada and E. Bouougri; photo C: S. Sarkar.

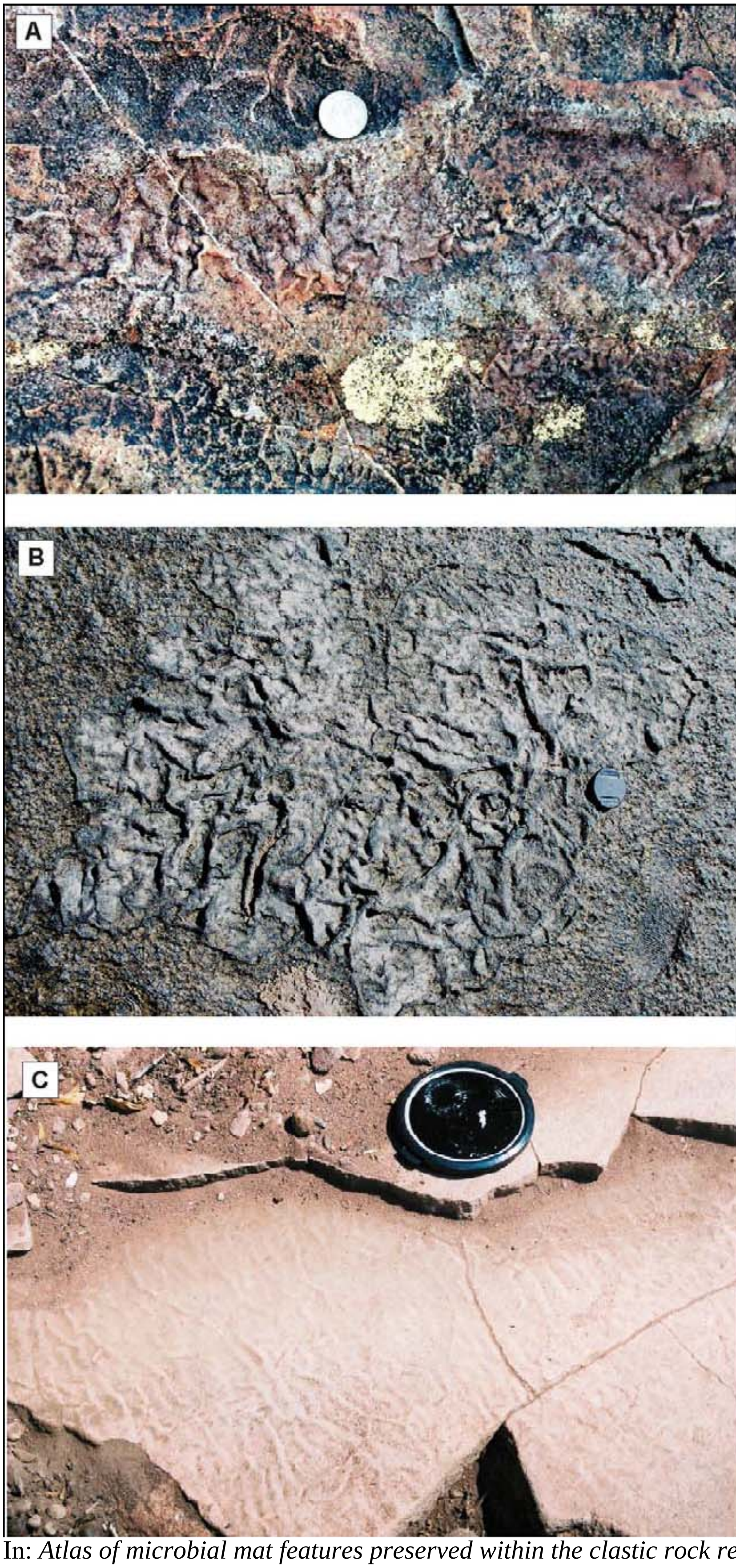

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Fig. 4(c)-18: Wrinkle structures (destructive):

Upper sandstone bedding surface with centimetre-sized, sinuous to curved, irregular, round to sharp-crested bulges (wrinkles). The deformation is restricted to a thin sandy layer. The underlying, undeformed sandstone layer exhibits a reticulate pattern of 'elephant skin' (see Figs. 4(a)-5, -6, -7) type (lower left part of the photo), developed on a surface from which the mat has apparently been removed by tractional forces. Scale (coin): 24 mm. Locality: Morocco, Anti-Atlas, Tirsal area; Neoproterozoic Wanimzi Formation, Tizi n-Taghatine Group; palaeoenvironment: intertidal zone of a peritidal coastal plain. (B) Detached and previously floating mat fragment which has come to rest on sandy bed; note irregular, round to sharp-crested bulges (wrinkle structures), induced by successive tractional events affecting a thin, loosely attached microbial mat. The mat fragment underwent local cracking after a new mat had formed on the exposed sandy surrounding surface. Locality: Mediterranean coast of southern Tunisia, between Gabes and Skhirat; environment: upper intertidal zone surrounding a wide tidal channel plain. (C) Inferred wrinkle marks developed on a sandstone bed upper surface, presumably due to shortening of partially loose mat under the influence of a current. Found associated spatially and temporally with many mat destruction features such as flip-overs, roll-ups, and sand cracks. Note approximately parallel orientation of wrinkles in upper right part of photograph, contrasting with irregular patterns in lower foreground – these suggest the possibility that shortening of a loose mat was greater in the latter part of the sand bed upper surface. This photo illustrates the inherent problems associated with a continuum of wrinkle structures developed within both mat-growth and mat-destruction frameworks (see discussion in Chapter 6(a)). Locality: Makgabeng Formation, Waterberg Group (c. 2.0-1.8 Ga), Makgabeng Plateau, Limpopo Province, South Africa; palaeoenvironment: flash-flood reworked interdune-playa lake lenticular deposit contained within aeolianites. Photos A and B: H. Porada and E. Bouougri; Photo C: A.J. Bumby.

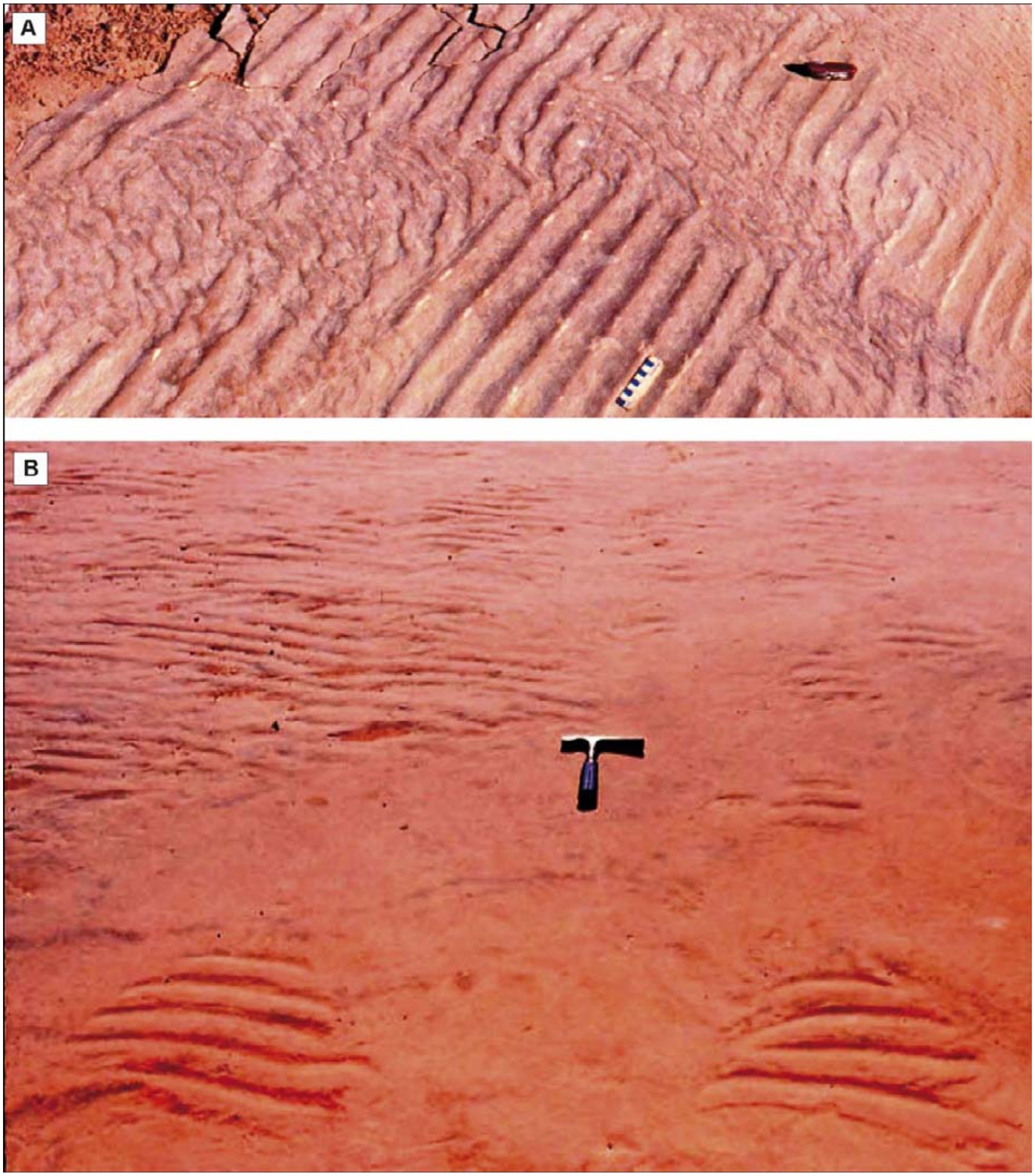

Fig. 4(c)-19: Ripple patches:
(A) A first generation of ripples on a sandstone bed has been reworked only in certain places by a second generation of ripples, but is perfectly retained where it was presumably protected by a microbial mat cover. (B) Ripples preserved only in patches, where an inferred microbial mat providing the necessary protection from erosion had been removed locally. Note gradational contacts between ripple patches and surrounding smooth sandstone. Locality: 0.6 Ga Sonia Sandstone, Jodhpur Group, Rajasthan, India; palaeoenvironment: intertidal-supratidal zone. Photos: S. Sarkar.

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