7(f). Mat-related features from the Neoproterozoic Tizi n-Taghatine Group, Anti-Atlas belt, Morocco

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In the Anti-Atlas mountains, a variety of mat-related structures is extensively preserved in silicilastic deposits of the Tizi n-Taghatine Group, mainly in peritidal facies associations. This Neoproterozoic Group (~0.8 Ga) is a volcano-sedimentary cover, about 2 km thick, deposited on the northern continental margin of the West African craton (WAC). The group crops out discontinuously in all the Proterozoic inliers along the southern side of the central Anti-Atlas Pan-African suture and has been studied in three separate areas, viz. from west to east: (i) the southern edge of the Siroua massif, (ii) the northern edge of the Zenaga inlier, and (iii) the southern side of the Bouazzer Elgraara inlier (Fig. 7(f)-1). The lithostratigraphic organization of the Tizi n-Taghatine Group reflects a stratigraphic record of large cyclic changes in the depositional system due to relative sea-level variations, the palaeogeographic setting and the tectono-sedimentary evolution of the northern Neoproterozoic WAC passive margin (Bouougri and Saquaque, 2004) (Fig. 7(f)-2). The lower sedimentary package records the first basin-fill stage and reflects the establishment, on a relatively stable margin, of a shallow-water and gently dipping mixed siliciclastic–carbonate ramp facing northwards and attached to a braided alluvial plain in the south. The middle volcanic Tachdamt Formation consists of tholeiitic, alkaline and transitional flood basalts interpreted to represent a widespread extensional event at 788 ±10Ma (Rb/Sr; Clauer, 1976). Cessation of major volcanism was followed by deposition of the upper sedimentary package (Bleïda Formation), which records the late basin-fill stage and reflects a shelf-basin environment filled with thinly bedded and fine-grained turbidite deposits. The Lower sedimentary ensemble (Fig. 7(f)-2) of the Tizi n-Tghatine Group consists of interfingering siliciclastic and carbonate facies associations, ranging from fluvial to siliciclastic and carbonate shallow platform domains. Within this package, occurrences of mat-related structures are found in siliciclastic facies of the Taghdout, Wanimzi, Tamgarda, Imi n-Tizi and Ifarkhs-n-Tirsal Formations.

Mat-related features presented here are documented from three areas: Agoummy (Fig. 7(f)-3B to -3E and Fig. 7(f)-4B, -4C, -4F, -4G), Tirsal (Fig. 7(f)-3A and Fig. 7(f)-4A, -4D, -4E) and Nqob (Fig. 7(f)-3H). The structures are generally related to decimetre- to metre-thick biolaminate horizons and to millimetre- and centimetre-thick organo-sedimentary, laminated layers draping centimetre-thick sandstone beds. The latter reflect distinct stages within microbial mat life cycles (e.g., growth, destruction, overgrowth, biostabilisation, etc.). Most of the structures are found in a heterolithic facies association deposited in the intertidal to supratidal zones of a broadly peritidal coastal environment that experienced episodic emergence, intermittent fluvial sheet-floods and high-energy storm-tide events. The heterolithic deposits occur in decimetre-to metre-thick units and consist of interlaminated and thinly interbedded sandstone, laminated siltstone, and sericitic mudstone. They form rhythmic alternations of 0.5-15 cm thickness, comprising medium- to fine-grained quartzite layers with 0.5-5 cm thick interbeds of laminated siltstone or sericitic argillite. The intervals dominated by siltstone and sericitic argillite display flat internal bedding or wavy and lenticular bedding. They include layers of fine-grained sandstone with

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single sets of cross-lamination and a few centimetre-thick lenticular quartzite beds with symmetrical wave rippled tops. The sandstone intervals preserve a variety of internal structures including wavy to planar lamination, wave and current generated lamination, occasionally with foreset dip directions in bipolar orientation. Additionally, bedding surfaces are flat or wave rippled with interference and oscillation ripples and rare current ripples. A common feature of the heterolithic deposits is the frequent occurrence of shrinkage cracks with various shapes, sizes and densities. Microbial mat structures and additional features, like adhesion warts, normal polygonal desiccation cracks, evaporite pseudomorphs, mud- and sand-chips, together indicate deposition in low-energy coastal shallow marine environments, likely on intertidal to supratidal flats with periodic subaerial exposure.

The Anti-Atlas example shows that peritidal conditions are particularly suitable for the formation and preservation of microbial mat structures. Seaward, in zones above or below storm wave base, establishment of continuous, cohesive microbial mats appears less likely, and only one single horizon (a sandstone storm bed) with Kinneyia structures was found in heterolithic deposits of a storm influenced inner shelf environment (Fig. 7(f)-3E).

Figures

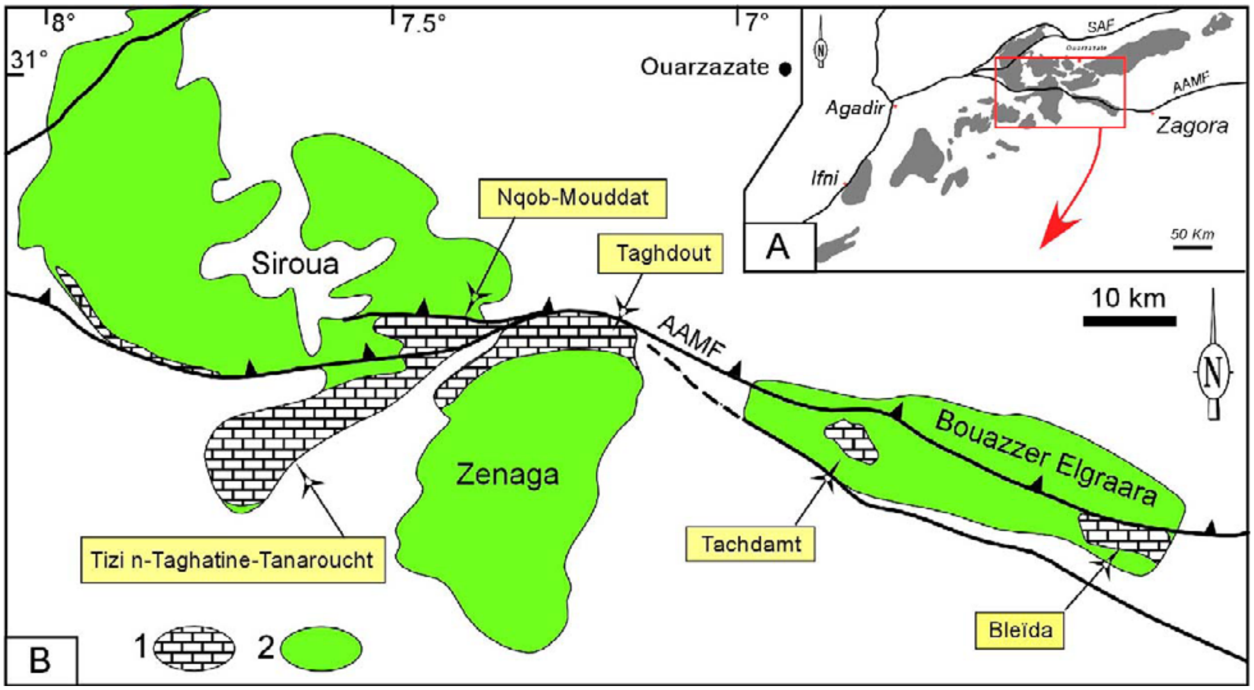

Figure 7(f)-1: Simplified map showing distribution of the Precambrian inliers in the Anti-Atlas mountains (A) and outcrop distribution of the Neoproterozoic Tizi n-Taghatine Group (1) in Proterozoic inliers (2) of the central Anti-Atlas. SAF: South Atlas Fault; AAMF: Anti-Atlas Major Fault.

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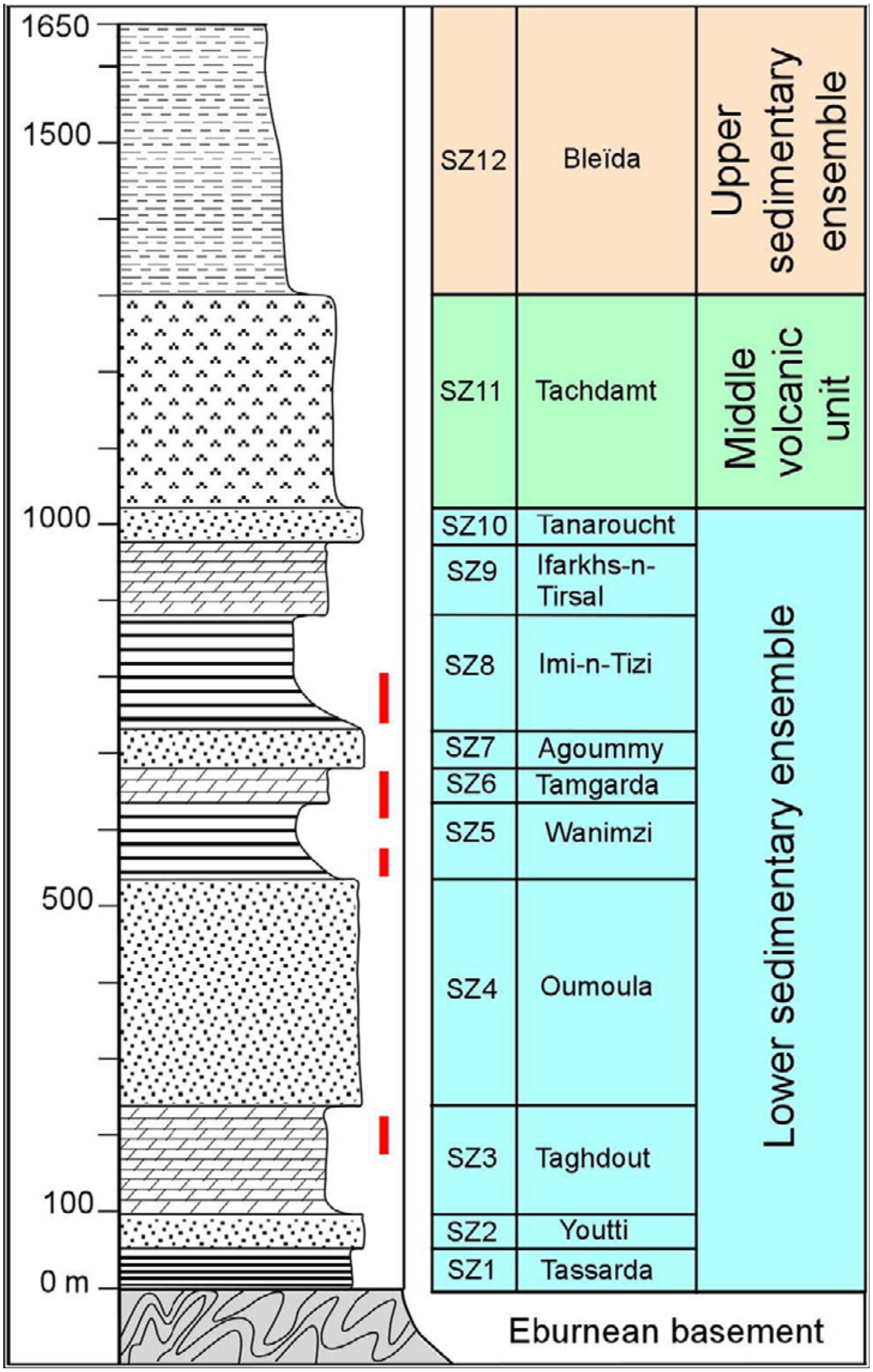

Figure 7(f)-2: Simplified lithostratigraphic column of the Tizi n-Taghatine Group showing (in red) stratigraphic distribution of mat-related features.

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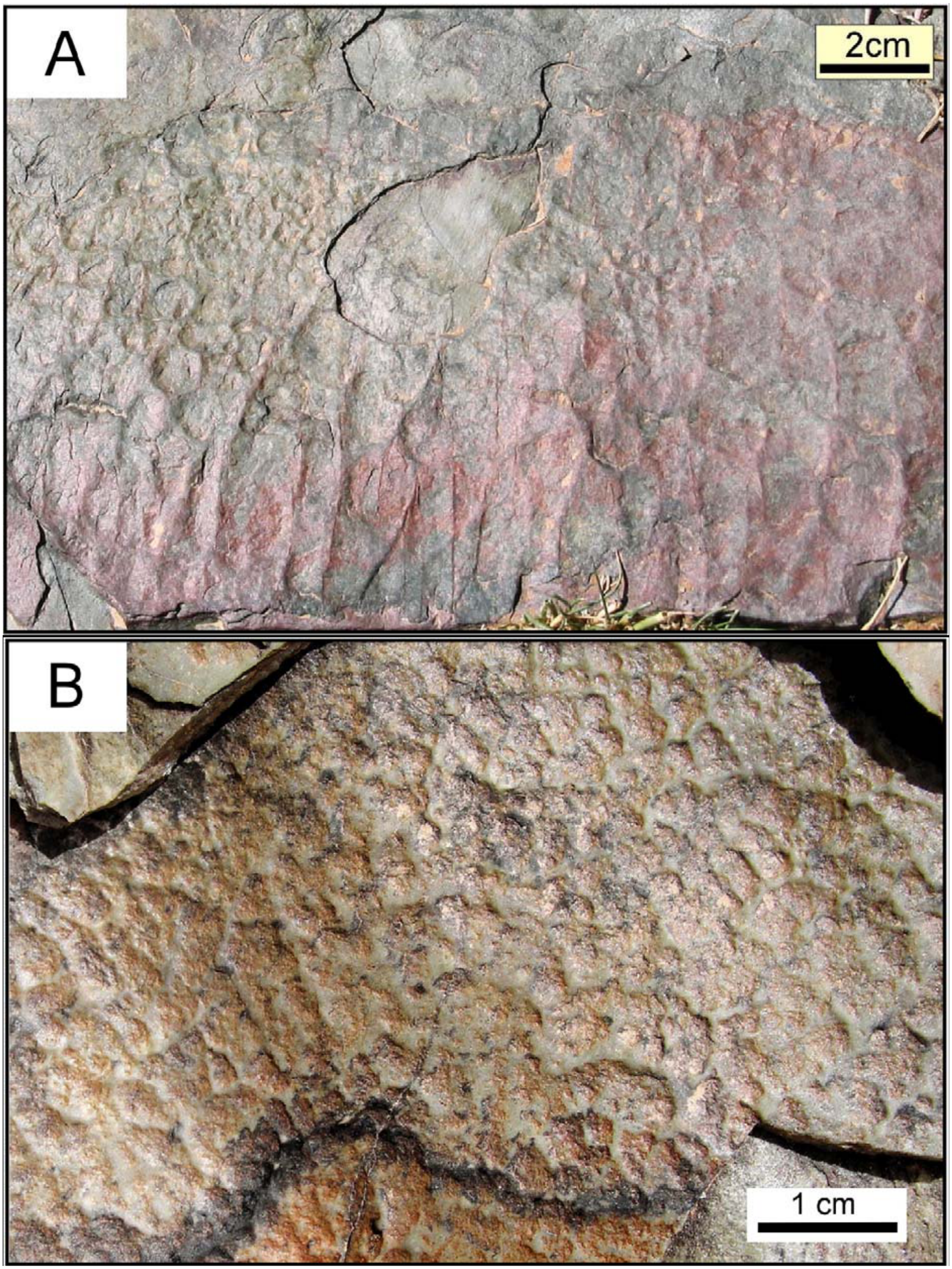

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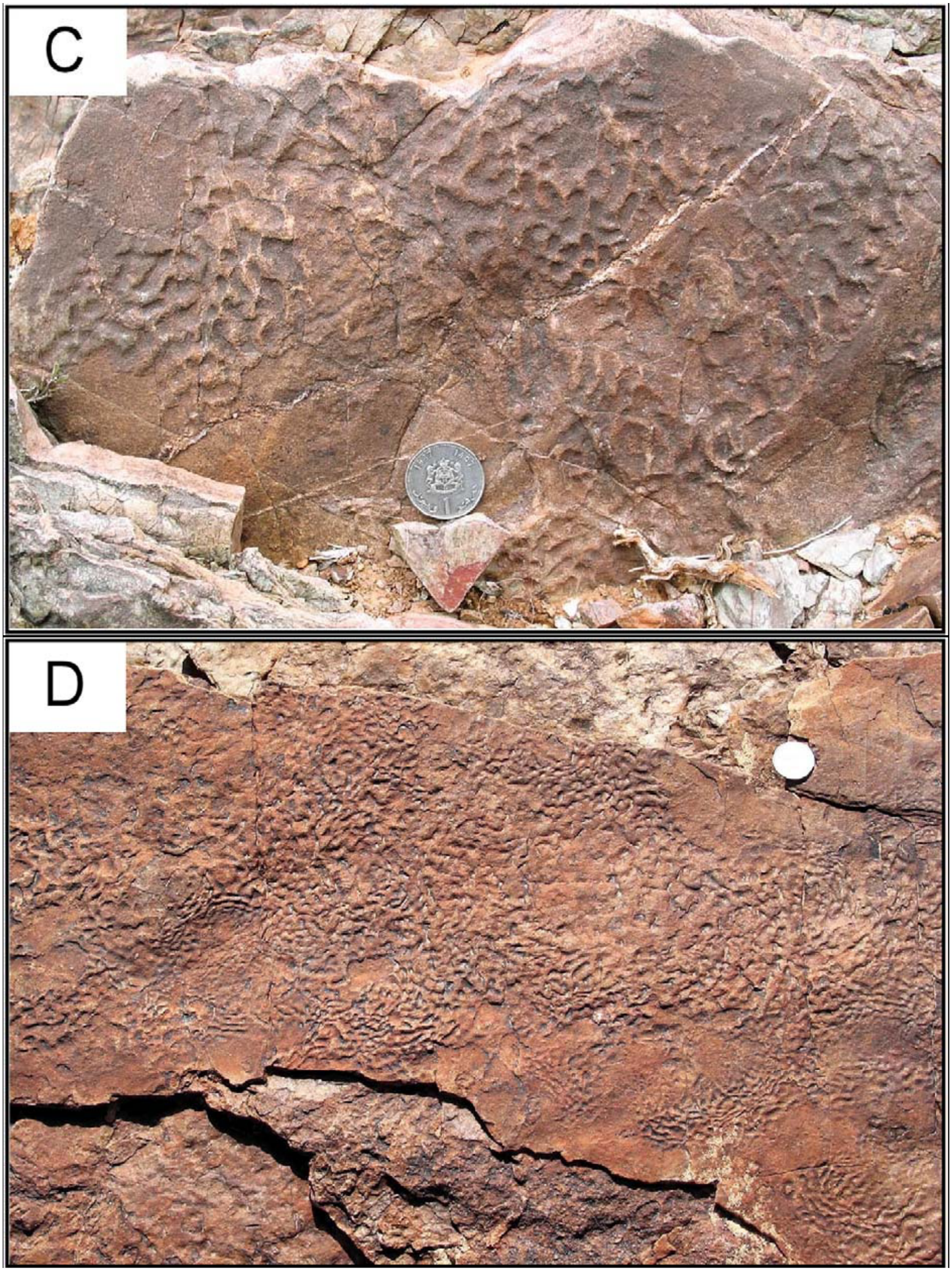

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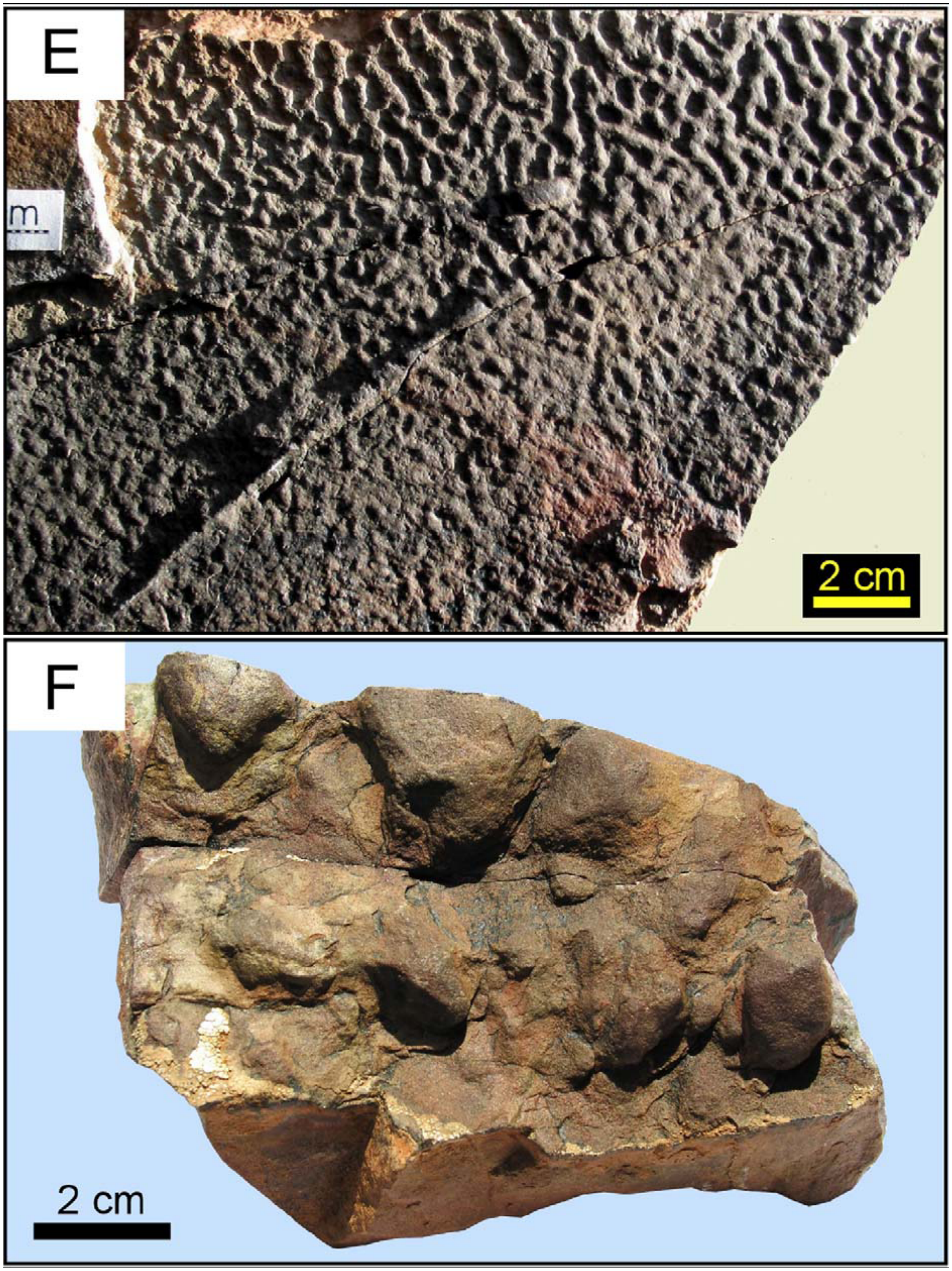

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Figure 7(f)-3: Mat-growth features (A, B), subsurface *Kinneyia* structures (C–E) and subsurface sand protrusions (F).
(A) Reticulate 'elephant skin' pattern on upper bedding surface of siltstone. The surface shows a polygonal to hexagonal arrangement of sharp-crested ridges of variable size, partly evolving into a more linear pattern. In the centre of the photo, the underlying layer is flat indicating that the structure is restricted to the upper millimetre-thick siltstone lamina. (B) Close-up view of small-scale reticulate 'elephant skin' pattern on upper bedding surface of thinly laminated siltstone layer. The smooth-crested ridges are arranged in a subcircular to hexagonal pattern with hollows of 2–5 mm in diameter. According to the size and shape of this growth pattern, the term 'net structures' or 'honeycomb growth structures' may be more appropriate. For both A and B: *Locality*: Agoummy area, Anti-Atlas; Wanimzi Formation; *Genesis*: the two examples show the diversity in size and shape of reticulate growth patterns developed on thin microbial mats. Similar structures have been described from a modern tidal flat environment in Tunisia (e.g., Gerdes et al., 2000a) and attributed to vertical growth of cyanobacterial filaments (e.g., of *Microcoleus chthonoplastes*, *Lyngbya aestuarii*) forming tufts, pinnacles and ridges; *Associated structures*: desiccation cracks, current and wave ripple cross-laminations, oscillation and interference ripples, small-scale load structures, millimetre- to centimetre-scale alternation of sedimentary sandstone event layers of storm or fluvial origin, and organosedimentary laminated layers of siltstone and sericitic argillite; *Palaeoenvironment*: intertidal to lower supratidal zones of a peritidal coastal plain. (C) Upper flat surface of 5 cm thick fine-grained sandstone layer showing typical *Kinneyia* structures. The structures consist of flat-topped crests arranged in a honeycomb-like pattern. Depressions and pits vary from subcircular to hexagonal or elongate and gently curved. Coin for scale is 24 mm in diameter. Locality: Agoummy area, Anti-Atlas; Wanimzi Formation. Associated sedimentary structures: interference and oscillation ripples, wave ripple cross-laminations, shrinkage cracks, few hummocky cross-stratification (HCS) structures, heteroliths, and thickening-up parasequences. Palaeoenvironment: wave and storm influenced shoreface to intertidal coastal plain of a braid-delta environment. (D) Upper surface of 2 cm thick quartzite layer with *Kinneyia* structures. *Kinneyia* crests are irregularly distributed and partly curved, forming large elongate and subcircular structures with diameters ranging from 10 to 15 cm. The central flat parts of these structures exhibit sparse and short crests and depressions. Depressions between crests form isolated, subrounded to elongate pits, 8 to 15 mm long. Coin for scale is 24 mm in diameter. Locality: Agoummy area, Anti-Atlas, Imi n-Tizi Formation. Associated sedimentary structures: shrinkage cracks, interference and oscillation ripples, heteroliths with wavy bedding, biolaminites, wave induced structures, mud chips, sand clasts, and fluvial/tidal channels. Palaeoenvironment: peritidal coastal plain. (E) Upper surface of 4.5 cm thick quartzite layer (storm deposit) showing well developed *Kinneyia* structure. The structure consists of meandering and partly interfering, flat-topped to rounded crests and intervening troughs or pits. Inter-crest distance is 4–5 mm. Locality: Agoummy area, Anti-Atlas, Wanimzi Formation. Genesis: *Kinneyia*-type wrinkle structures are considered here as a category of 'subsurface structures' developed on a flat sandy surface underneath a mat (see Chapter 6(a)). Similar modern examples have not been described yet. Some modern growth structures with honeycomb-like patterns, developed on the upper sides of 2 mm thick microbial mats, induce nodular structures with intervening pits and grooves, resembling *Kinneyia* in size and shape, on the lower side of the mat (e.g., from Tunisia). Associated sedimentary structures: heterolithic deposits with alternation of sericitic mudstone and centimetre- to decimetre-thick quartzite beds, HCS, wave ripple crosslaminations, interference and oscillation ripples, gutter and groove casts, and thickening-upward parasequences. Palaeoenvironment: inner shelf environment influenced by storms. (F) Upper surface of 4 cm thick quartzite bed with rounded to elongate upward protrusions of sand. The blister- or dome-shaped sand protrusions are separated from each other by relics of thinly laminated sericitic mudstone with lenses of siltstone and sparse isolated grains of quartz. The sand protrusions cross-cut the lower laminae of the overlying drapes, indicating that their formation postdates deposition of the layer above, which itself preserves lenticular shrinkage cracks. Locality: Agoummy area, Anti-Atlas, Imi n-Tizi Formation. Genesis: the structure is developed on a sediment surface beneath a mat and reflects mat surface morphological details, like blisters and domes. Preservation of mat morphological details is due to upward protrusion of sediment, partly or completely filling bulges and domes developed in the mat. Modern examples (e.g., Tunisia) show that bulges or domes developed in the mat are partially or completely filled with sediment rising up from below (see Chapter 8(d)). Upward protrusion of sediment may be induced by hydraulic upward pressure in confined groundwater below mat or by 'evaporative pumping' (Hsü and Siegenthaler, 1969). Associated sedimentary structures: oscillation, interference and current ripples, desiccation cracks, mud clasts, few small fluvial/tidal channels, heterolithic deposits with centimetre-scale interbedded sandstone and organosedimentary sericitic layers, and a few event deposits related to fluvial sheet floods or storms. Palaeoenvironment: intertidal to lower supratidal zones of a coastal plain. All photographs (A to F): E. Bouougri and H. Porada.

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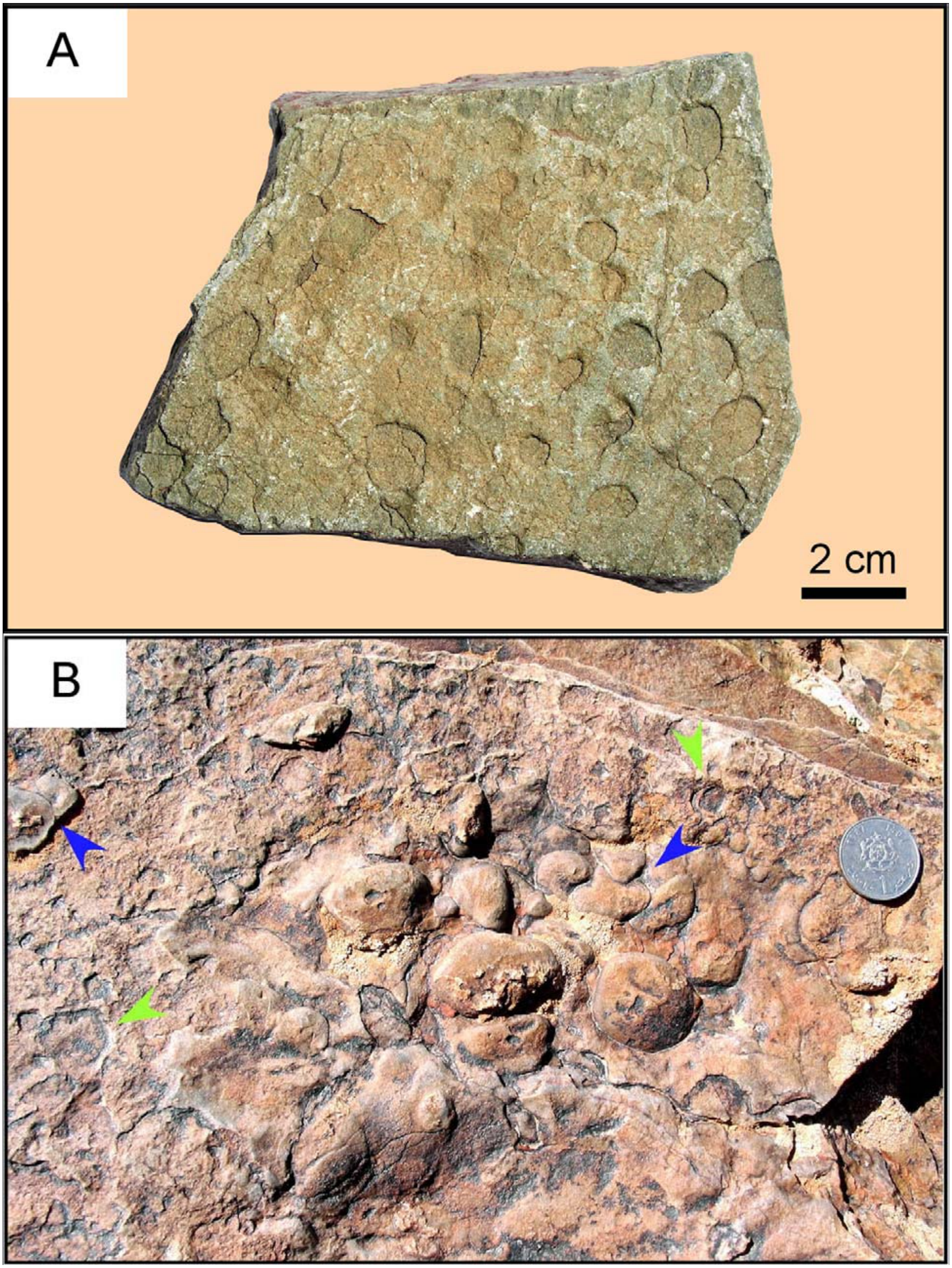

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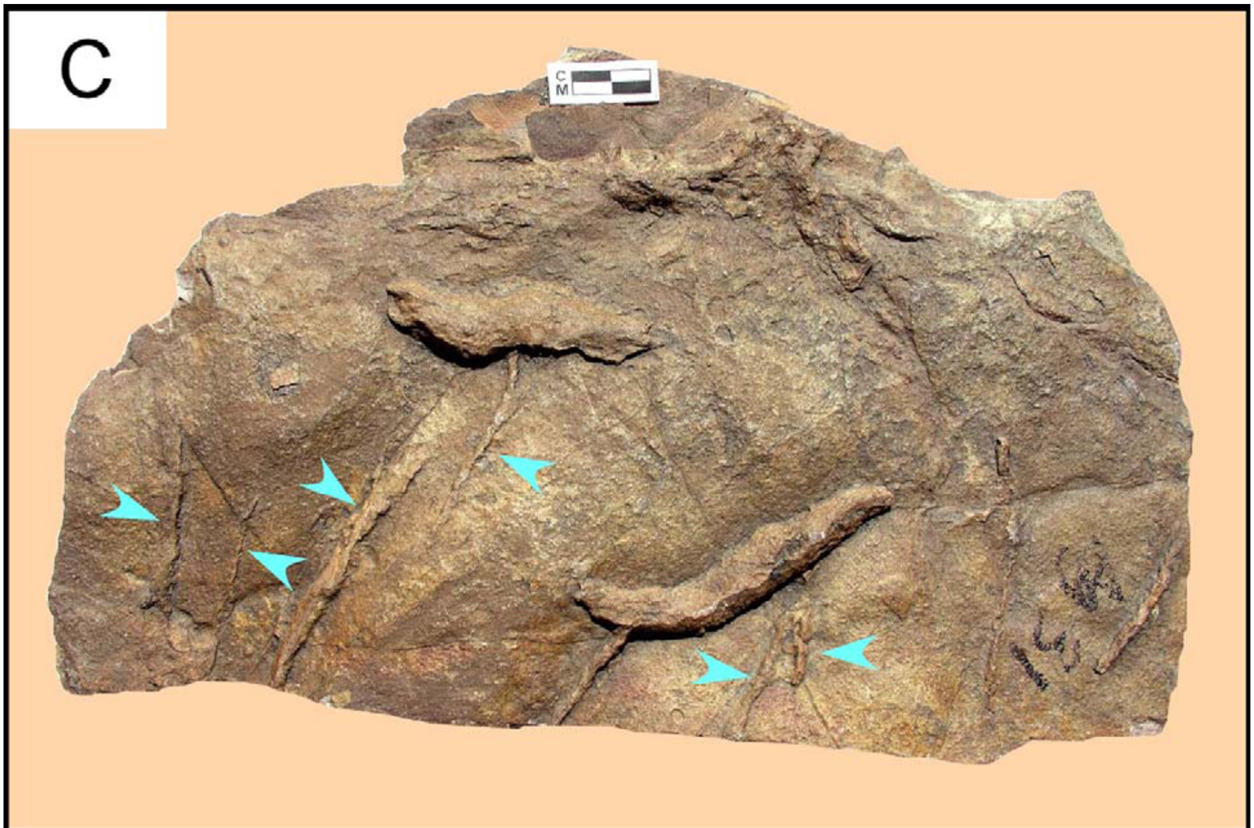

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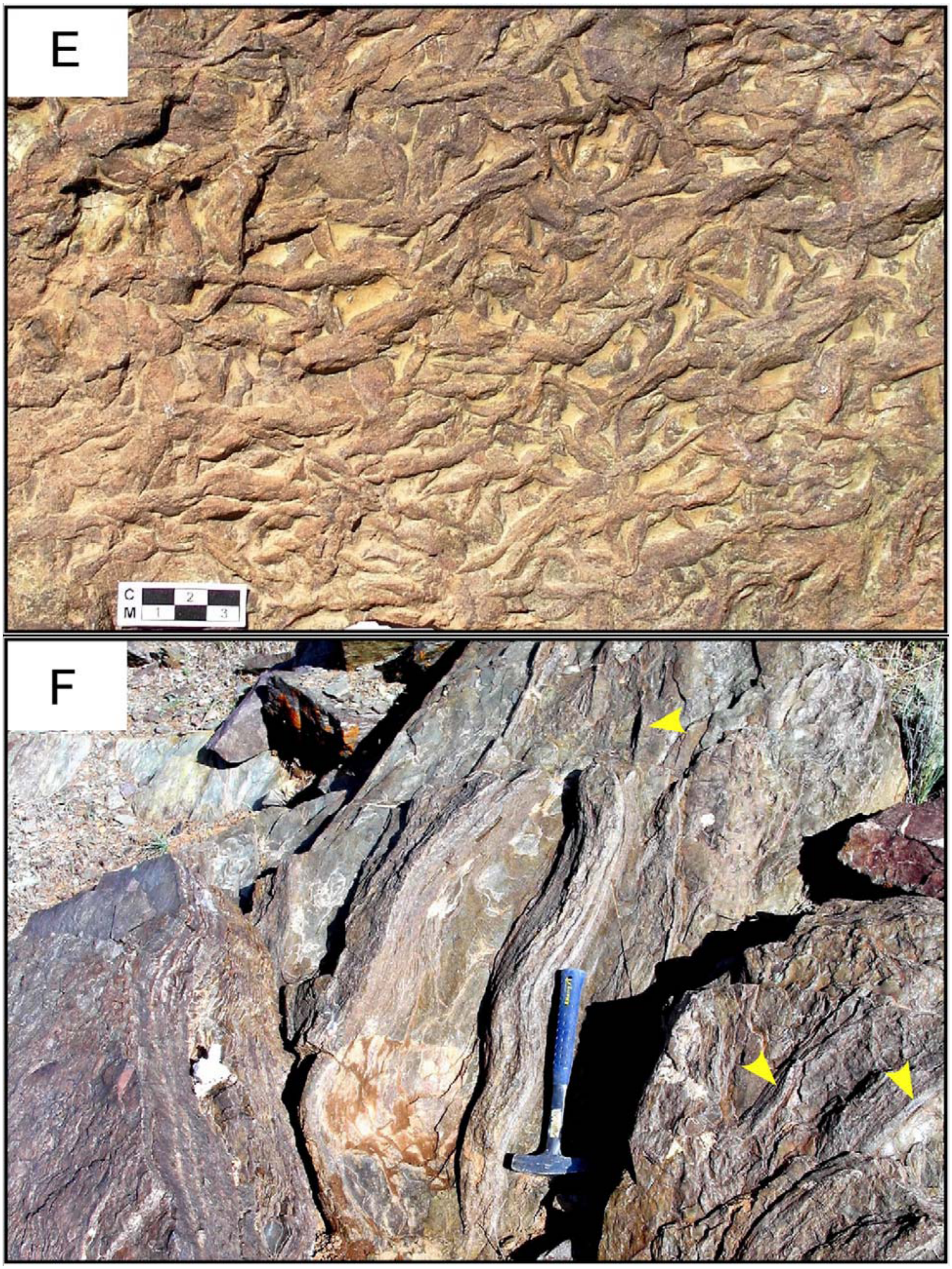

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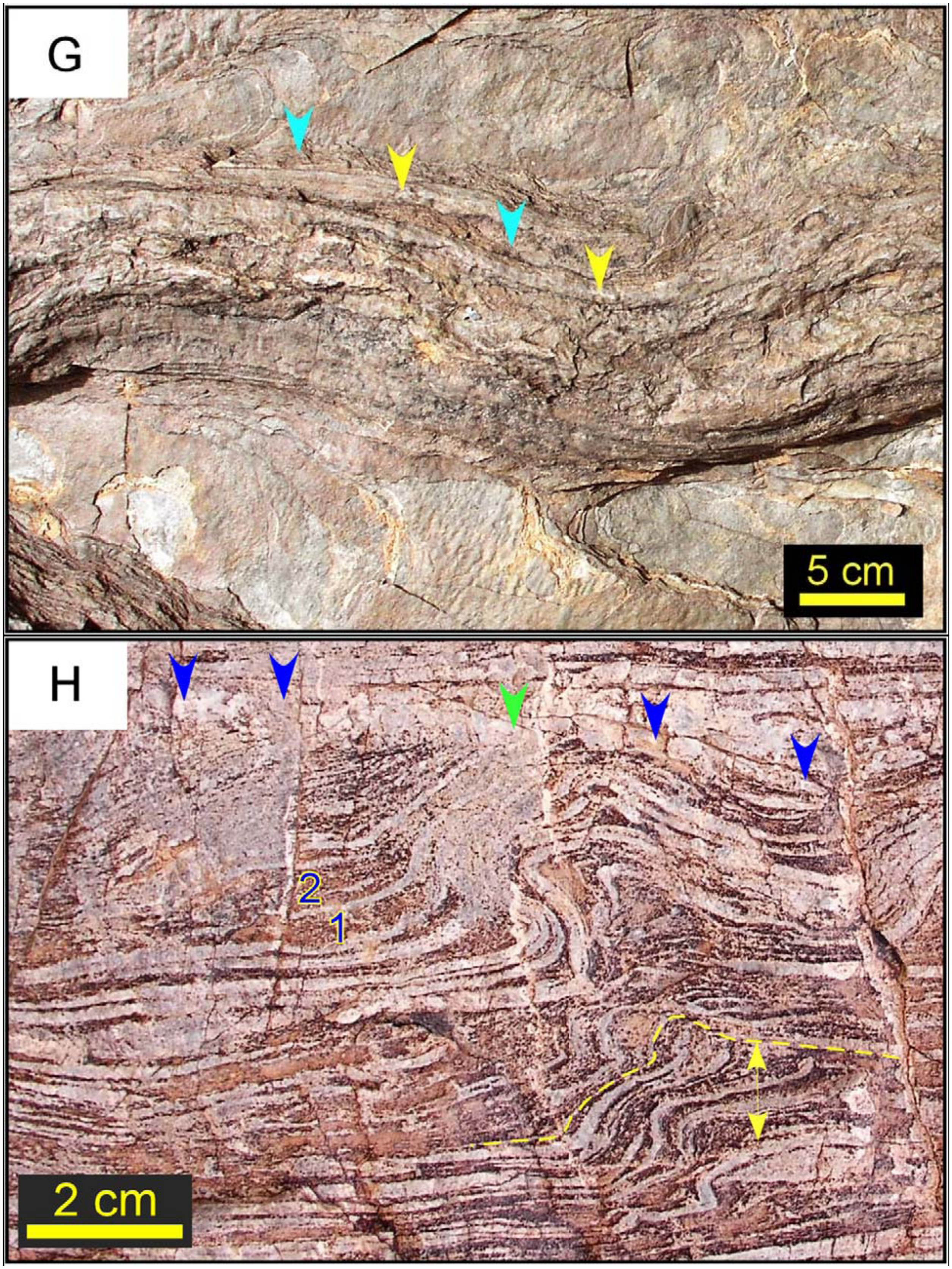

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Figure 7(f)-4: Mat destruction-growth features: erosion marks (A), microbial sand/silt clasts (B), microbial shrinkage/sand cracks (C–E), large desiccation polygons in biolaminites (F, G) and shrinkage and overgrown upturned crack margin in biolaminite (H).
(A) Upper surface of 3 cmthick fine-grained quartzite layer with flat-bottomed, round to elliptical depressions in the upper millimetre-thick lamina. The structures are 0.5–1.2 cm in diameter, with long axes between 0.8 and 1.3 cm and short axes between 0.4 and 0.8 cm, and are usually aligned. The margins of the depressions are remarkably regular and sharp, the bottoms are flat and expose the underlying lamina. Locality: Tirsal section, Anti-Atlas, Wanimzi Formation. Genesis: the flat bottoms and sharp margins of the structures suggest that pieces of an upper fine-grained cohesive veneer have been removed by tractional currents and reworked as platy rounded 'microbial chips'. The structures are considered to represent erosion marks of a fine-grained and millimetre-thick biostabilised veneer. In modern environments, e.g., the tidal-flats of the North Sea coast, erosion marks have been recognised in the middle to upper intertidal zones (Gerdes et al., 1993, 2000a). These and some ancient examples (see Reineck, 1979) usually have greater dimensions than those presented here, which are rather of the size of raindrop impacts. An interpretation as raindrop impacts or mud-chip imprints is, however, excluded mainly due to the flat bottoms and sharp and regular margins and, less stringently, due to the varying sizes, elliptical forms and preferred orientation of the structures. Associated sedimentary structures: oscillation, interference and current ripples, desiccation cracks, mud clasts, few small fluvial/tidal channels, heterolithic deposits with centimetre-scale interbedded sandstone and organo-sedimentary sericitic layers, and a few event deposits related to fluvial sheet floods or storms. Palaeoenvironment: intertidal to lower supratidal zones of a coastal plain. (B) Upper surface of 5 cm thick fine-grained sandstone layer with subrounded and elongate, platy sand clasts. Size of the clasts varies between 1 and 3.5 cm (long axis), whereas thickness varies from 2 to 5 mm. Clasts are slightly oriented and some of them are clustered closely together, partly with overlapping relationships (blue arrows). The sand chips are preserved either as compacted intraclasts or weathered-out moulds (green arrows). The contact between sand chips and adjoining sediment is sharp and usually enhanced by limonitic staining. The clasts are finer-grained and more sericitic than the underlying sediment layer. The texture of the sand chips is matrix-supported with 'coated grains'; a sericitic component fills the pore spaces and coats individual sediment grains. Coin for scale is 24 mm in diameter. Locality: Agoummy area, Anti-Atlas, Imi n-Tizi Formation. Genesis: the clasts of sand- to silt-sized sediment are considered to result from physical erosion of a thin microbially-bound layer and subsequent reworking of the chips by wave and current action. Imbrication of clasts may indicate transport by currents. In modern environments, microbial mat chips preferably occur in the intertidal to lower supratidal range (e.g., Gerdes et al., 2000a). Ancient examples are reported from the upper intertidal zone (Gehling, 2000) and nearshore environment (Gehling, 2000) where a mat could grow unimpeded to form a resistant cohesive layer, and nevertheless be destroyed by wave action and strong currents during a storm. Associated sedimentary structures: oscillation, interference and current ripples, desiccation cracks, mud clasts, few small fluvial/tidal channels, heterolithic deposits with centimetre-scale interbedded sandstone and organo-sedimentary sericitic layers, and a few event deposits related to fluvial sheet floods or storms. Palaeoenvironment: intertidal zone of a peritidal coastal plain. (C) Upper surface of 2.5 cm thick quartzite bed with isolated, lenticular and spindle-shaped sand-filled cracks. The surface shows two types of cracks forming two superimposed generations. The first one consists of narrow cracks (0.5 cm maximum width) preserved as isolated or subparallel and slightly curved ridges which frequently meet at the ends (blue arrows), thus surrounding lenticular structures up to 2 cm wide. The second generation consists of isolated platy sand ridges, 1.5 cm high and a few millimetres thick, with a length of up to 10 cm. Scale is 2 cm. Locality: Agoummy area, Anti-Atlas; Imi n-Tizi Formation. Associated sedimentary structures: heterolithic deposits with centimetre-scale interbedded sandstone and organo-sedimentary sericitic layers, event deposits related to fluvial sheet floods or storms, few small fluvial/tidal channels, mud clasts, oscillation ripples, interference and current ripples, desiccation cracks, and adhesion warts. Palaeoenvironment: intertidal to lower supratidal zones of a peritidal coastal plain. (D) Upper surface of 10 cm thick quartzite bed with spindle-shaped, curved, sinuously curved, circular and 'wriggly' microbial sand cracks. The surface shows impressions of removed sandy crack-fills with tapering ends and crack-fillings preserved as flat sand ridges (indicated by arrows). The length of the cracks varies from 2 to 17 cm and the average width is 0.8 cm. The cracks may merge together but do not show any cross-cutting relationship. Scale is 2 cm. (E) Upper surface of 3 cm thick quartzite bed exhibiting high density of filled sand cracks. The fills are lenticular, straight, spindle-shaped to sinuously curved and form a network of differently oriented bodies, which usually meet at high angles. Some of the fills are juxtaposed or arranged in two opposite ridges. Length of individual bodies varies from 2 to 8 cm, average width is between 0.5 and 1 cm. The crack-fills form superimposed bodies with tapering ends and overlapping relationships. They occur in distinct thin, laminated sericitic layers preserved between the cracks (yellow layers). Distinction of generations is based on the criterion that in a shrinking layer cracks do not develop

cross-cutting relationships. Rather propagating cracks merge if meeting at low angles, or form high angle junctions if laterally arriving at existing ones. Due to high rate of compaction, the crack-fills appear as a single generation on the bedding surface. The sericitic layers hosting the cracks display a laminated fabric with matrix-supported grains, lenticular lenses of isolated and aligned grains, and black carbonaceous laminae. Scale is 3 cm. For both D and E: *Locality*: Tirsal area, Anti-Atlas; Wanimzi Formation; *Genesis*: the sand cracks illustrated here are examples of a variety of shrinkage cracks developed in organo-sedimentary microbial layers that underwent subaerial desiccation in the intertidal to lower supratidal range of peritidal environments (e.g., Porada and Löffler, 2000; Bouougri and Porada, 2002). Similar cracks have previously been documented as synaeresis cracks, *Manchuriophycus*, *Rhysonetron*, etc. The term ‘microbial shrinkage cracks’ proposed by Porada and Löffler (2000) is genetic and refers to an association of cracks related to shrinkage of microbial mats or, more generally, organo-sedimentary material. Such cracks may develop in millimetre- to centimetre-thick organo-sedimentary argillaceous layers draping sand surfaces (photos C, E). The observation that cracks may be isolated from sand layers above and below, and may be preserved as casts and moulds on bedding surfaces indicates that filling occurs mainly during tidal floods and before deposition of the event sand layer above (photo D). The development of subparallel opposing cracks which seem to surround openings (photo C), is one of the typical shrinkage features associated with thin and still living microbial mats, as observed in modern examples in Tunisia (personal observation). In the example of photo D, the thin microbial mat that underwent shrinkage was not preserved during burial. The superimposed crack generations (photo E) formed in a stack of organo-sedimentary layers which underwent repeated events of subaerial exposure and flooding during buildup; *Associated sedimentary structures*: 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, wave and current ripple cross-lamination, oscillation and interference ripples, small-scale load structures, and polygonal desiccation cracks; *Palaeoenvironment*: intertidal to lower supratidal zones of a peritidal coastal plain. (F) Large desiccation polygon, seen in plan view, preserved in planar laminated siliciclastic biolaminite. The large cracks extending 4 cm upwards, cut across several layers in which small isolated lenticular and spindle-shaped cracks are preserved (indicated by arrows). In detail, each large crack cuts through a multilayered structure of millimetre-thick alternating siltstone and laminated sericitic layers. The isolated spindleshaped cracks are V-shaped, tapering downward, and are filled with fine-grained sandstone material. (G) Close-up view of a large, sinuously curved crack showing laminated structure. Blue arrows indicate sericitic–organic layers; yellow arrows indicate siltstone layers. Locality: Agoummy area, Anti-Atlas; Imi n-Tizi Formation. Genesis: the large cracks forming polygonal networks are interpreted as the upturned margins of major polygonal cracks formed during shrinkage of biolaminite. Such upturned crack edges are typical of biolaminite deposits in the intertidal zone and have been observed in the modern tidal flats at Bhar Aloune, Tunisia (see Figure 4(c)-6). The small spindle-shaped cracks filled by sandy material constitute another aspect of desiccation, with limited opening of cracks and rapid subsequent filling by sediment during tidal flood events. Associated sedimentary structures: oscillation, interference and current ripples, desiccation cracks, mud clasts, few small fluvial/tidal channels, heterolithic deposits with centimetre-scale interbedded sandstone and organo-sedimentary sericitic layers, and a few event deposits related to fluvial sheet floods or storms. Palaeoenvironment: upper intertidal to lower supratidal zones, periodically submerged and regularly flooded by tides or during storm events. (H) Simple structure developed by overgrowth of an upturned crack margin in biolaminites that underwent subaerial shrinkage. The laminae of the upturned margin are very thin and are mainly of microbial origin, whereas behind the overgrown edge, lamination consists of a millimetre-scale alternation of continuous white laminae and discontinuous brown sedimentary laminae (1 and 2 as examples). The white laminae consist mainly of laminated sericitic layers including floating sand- to silt-sized quartz grains and lenses of silt-sized quartz. The brown layers consist of alternations of sericitic laminae and fine-grained siltstone laminae with a few flakes of mica. The whole structure is sealed by a horizontal and continuous white quartzitic layer (indicated by blue arrows). Behind the edge (on the left side of the green arrow), laminae of the polygon are discontinuous and slightly upturned. To the right side of the green arrow, laminae continuously overgrow the upturned edge. Yellow arrows indicate initial upturned margin laminae, whereas the yellow dashed line indicates the first overgrowing laminae. Locality: Nqob area, Anti-Atlas; Tamgarda Formation. Associated sedimentary structures: centimetre-thick quartzite beds with wave and current ripple cross-lamination, few centimetre-thick sandstone layers of storm or sheet flood events, desiccation cracks, interference and oscillation ripples, and planar biolaminites with shrinkage cracks. Palaeoenvironment: intertidal zone regularly flooded during high tides. All photographs (A to H): E. Bouougri and H. Porada.

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