Modification of large microbial mat deformation structures before burial: A modern case study

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Abstract

The presence of microorganisms gives remarkable plasticity and flexibility to wet sediments. Under these circumstances, a coherent microbial mat is developed, which is loosely attached to the underlying sediment layer. These thick microbial mats are capable of being lifted from the underlying sediments in response to high-energy events, such as currents and waves forming several types of synsedimentary microbial mat deformation structures. This study analyses excellent examples of these structures developed in Paso Seco (Argentina), a modern coastal flat colonized by microbial mats frequently inundated during storms, and the modifications that affect them before burial. To achieve this, the hydrodynamic conditions in the coastal flat over time were interpreted from water level records obtained with HOBO loggers. Field photographs were obtained to document the microbial structures (such as flipped-overs, tear mats, roll-ups, mat chips, and folds) covering the area after a high-energy event and over the course of the following two years. Specifically, emphasise was put in roll-up structures because of their large size. Sediment samples were extracted to make thin sections for petrography analysis. Once the microbial structures are formed, they show gradual changes caused by the hydrodynamic conditions that control the sedimentary environment, and on several occasions, these changes are preserved in the sedimentary profile. Our observations and measurement of modern sedimentary structures and the in-situ documentation of their evolution may be helpful for the identification and interpretation of analogous sedimentary structures in the fossil record, which could have undergone similar modifications prior to their burial.

Keywords: microbial mats, deformation structures, roll-up structures, erosion, coastal environment

1. Introduction

As long as water is present, sediment is often colonized by microorganisms (cyanobacteria, diatoms and different bacteria) organized into aggregates called biofilms or forming microbial mats attached to the surface (Noffke et al., 2022). In supratidal areas, when seawater inundates sediments during storm events, an epibenthic microbial mat can be formed as a coherent network forming a cohesive and leathery carpet, rich in organic matter and mucilaginous extracellular polymers (EPS) (Decho, 2000; Pan et al., 2013). The filaments of cyanobacteria and the ubiquitous EPS exuded by both, cyanobacteria and diatoms, entangle and glue the sediment grains. That fact modifies the sediment rheology (Pan et al., 2019) producing the increase of the erosional shear stress (Noffke and Paterson, 2008). Hence, that biostabilization leads to the protection of the sedimentary surface against erosion caused by currents or waves. However, if currents or waves are strong enough, the flexible and highly cohesive epibenthic microbial mats are broken and deformed, producing microbial mat deformation structures, which are a type of microbially-induced sedimentary structures (MISS).

In present-day environments, examples of microbial mat deformation structures (e.g. microbial folds, flipped-over edges, and roll-ups) have been documented (Noffke, 2010; Bouougri and Porada, 2012; Cuadrado et al., 2015; Maisano et al., 2019). The possibility of finding microbial mat deformation structures in the fossil record has been proved by the identification of cm-wide roll-up structures in Late Archean sediments of Carawine Dolomite, Australia (Simonson and Carney, 1999), in the Newland Formation in Mid- Proterozoic Belt Supergroup, USA (Schieber, 1986, 1999), in Makgabeng Plateau (c. 2.0-1.8 Ga), Limpopo Province, South Africa (Eriksson et al., 2007), and in the Dresser Formation (ca. 3.48 Ga), Western Australia (Noffke et al., 2013). However, the development of metre-scale microbial structures, as well, in present-day environments (Maisano et al., 2022) suggest that they could also be preserved in the fossil record. Therefore, comprehension of the processes that occur from the deformation of the microbial mat until the MISS is buried based on the study of present-day examples is essential to infer the characteristics that they might show in the fossil record if they are find out.

To achieve this, in the present study, large-scale roll-ups (up to 1 m in length x 0.5 m in width x 0.15 m in height) formed in a confined coastal environment during storm surge events (Maisano et al., 2022) are studied. The aim of the study is to analyse the modifications these large-scale primary sedimentary structures underwent after being formed and before burial for more than two years, and the environmental processes involved in their physical changes during that time. The study emphasizes the distinctive flexibility of the sediment layers due to an epibenthic microbial mat and draw attention to some clues to help in their identification in the ancient record. The study of meter-size roll-up microbial structures in the modern environment can provide answers to the formation process and preservation of some sedimentary structures in the fossil record characterized by sediment layer deformation.

2. Study area

The study area, Paso Seco flat, is located in the south of Buenos Aires Province, Argentina (40°33′S; 62°14′W; Fig. 1). It is an old tidal channel that became disconnected from the daily influence of tides by the formation of a coastal sand spit at its entrance, due to the NE longshore sediment transport along the coast. This progradation caused the present-day semi-confined character of the study area and the subaerial exposure of the bottom of the old tidal channel. The passage of extratropical storms characterized by strong winds, combined with spring tides, causes storm surges that affect the coast (Maisano et al., 2022).

During storm episodes, seawater overpasses the sand spit and generates a rapid flooding of the sedimentary surface of Paso Seco, during which large-size microbial mat deformation structures can be formed (Cuadrado et al., 2015; Maisano et al., 2019).

The study area comprises a surface of 3.5 x 0.4 km, colonized by thick epibenthic microbial mats that are typically cohesive and planar. These microbial mats present plastic and flexible properties caused mainly by cyanobacteria with a gliding motility feature (Cuadrado and Pan, 2018). The two dominant species *Microcoleus chthonoplastes* and *Lyngbya* sp. are the main microorganisms that provide remarkable coherence to the sedimentary flat. In addition, the co-living microbial consortia forming the mats and their metabolic products (i.e., extracellular polymeric substances, EPS) can also significantly alter the rheology of coastal sediments (Pan et al., 2019).

3. Methods

MISS were documented in Paso Seco after a storm characterized by strong winds (up to 47 km h^{-1}) during winter 2018 (June 23rd). To characterize the flooding event produced by the storm and the subsequent evolution of the flat, the hydrology was analysed by obtaining water level records with HOBO loggers (Onset-model U20; 2.5 cm diameter, 15 cm length). One logger was located 40 cm below the tidal flat, in a vertically buried, perforated PVC pipe (the bottom of the pipe was covered by a permeable textile), to record the water level and water temperature every 10 min. The other sensor was placed on the sediment surface of the tidal flat to correct the data by atmospheric pressure. Field photographs were obtained with a camera Nikon (model Coolpix P520 18.1-megapixels) and a UAV (Karma® unmanned aerial vehicle) holding a GoPro 5 camera to document the microbial structures covering the area after the storm of June 2018. MISS such as roll-ups, flip-over edges, and fold structures were examined and measured over a 5500 m^2 area. Special attention was paid to roll-up structures (n=26), which were measured (length, width and height), sampled and crosscut to analyse their structure. Sediment samples were extracted to make thin sections that were obtained after impregnating them with a 4:1 ratio mixture of epoxy resin Dicast 867 and Discure 383 hardener. 35 thin sections of vertical cores were petrographically studied under a Nikon EclipsePOL 50i transmitted-light microscope, coupled with a camera, using lenses with lower and intermediate magnification. Two of the thin sections were selected to describe a roll-up structure in detail.

4. Results

4.1 Roll-up structures: Development and Characteristics

This section includes a description of the hydrodynamic conditions and the main microbial mat deformation structures in the study area before and during the episodic flooding that occurred on June 2018 (red arrow, Fig. 2a). From March to June 2018, the water level record showed only few inundations of less than 0.2 metres of water level over the flat (blue dashed line, Fig. 2a). Prior to the severe storm that occurred in June 2018, the water level was near the surface (green line, Fig. 2a), and thus, the planar microbial sedimentary surface was wet and only few sedimentary microbial structures were observed, such as levelled mat tears and flipped-over edges, and flattened folds (Fig. 2b).

During the storm in June 2018, which produced a flooding of more than 0.6 m of water column (red arrow, Fig. 2a), meter-sized microbial mat tears, roll-up structures and mat folds were formed on the sedimentary flat over a 3.5×0.4 km area (Fig. 2c, d). The mat tears presented different dimensions, between 3 and 8 m in length and 1-2 m in width (black dashed lines, Fig. 2d). They showed sharp edges produced by the detachment of up to 1 cm of laminated sediment, which corresponds to the surficial microbial mat, and left exposed old mat layers (Fig. 3a-d). Mat tears were commonly associated with flipped-overs (10-50 cm long) along the tear edges, produced by an upturn of 180º of the detached mat (Fig. 3c, red arrow in Fig. 3d).

Roll-ups were formed by the rolling of more than 360º of teared mats by the water current (red arrows, Fig. 2d), which generated a flatten cylinder morphology, commonly oriented perpendicularly to the long axis of the flat and the water current direction (Fig. 4a).

The roll-up structure reached up to 1 m in length (white dashed line in Fig. 4b), 0.5 m in width (red dashed line in Fig. 4b), and more than 0.15 m in height (blue dashed line in Fig. 4 c). In cross-section, the roll-up structures showed an elliptical morphology (Fig. 4 c, d). The structures consisted of a very cohesive and flexible piece of mm-thick (up to 1 cm) microbial mat rolled–up producing a spiral arrangement with several involutions. The number of involutions depended on the length of the microbial mat detached and rolled-up (I, II, III in Fig. 4d). The top of the roll-ups exposed the reverse surface of the overturned microbial mat, which showed a rough appearance that corresponded to the ripped-out sedimentary substrate (old microbial mats; US in Fig. 4c).

Petrographic studies carried out in a piece of roll-up structure (Fig. 5a, b) showed the flexure of several involutions of ~1 cm-thick microbial mat, separated by ~1 cm-thick sand layers. Thin sections reveal that the microbial mats consist of biolaminites composed of repetitively alternating organic matter laminae with mud (~ 100 µm-thick, green arrows in Fig. 5c), very thin micritic laminae (~ 100-200 µm-thick, red arrows in Fig. 5c) and sand laminae (~ 250-400 µm-thick, blue arrows in Fig. 5c). The micritic laminae are composed of carbonate particles smaller than 4 µm. The calcite's high-order interference colour under cross-polarized light makes the identification of these laminae easy. The different laminae have been deformed in a flexible manner and preserve the cohesion between the sediment particles, as well as the original lamination.

4.2. Complex structures related to roll-up structures

Complex structures associated with roll-ups were developed in Paso Seco flat. This is the case of roll-up structures that, instead of showing a spiral internal layout of the folded mat (see Fig. 4c), presented a zig-zag arrangement of the folded mat (red dashed line, Fig. 6a). In addition, this structure was superimposed by thin surficial microbial mats (up to 0.5 cm thick) rolled-up in opposite directions on both sides of the roll-up (yellow arrows, Fig. 6a).

Abundant roll-ups presented accumulations of sediment and cm-sized mat chips on the stoss side of the roll-up structure (red arrow in Fig. 6b). Some roll-up structures were associated with a fold structure at the back of the roll-up (red arrow in Fig. 6c). The length of the fold may be larger than the roll-up length.

Several MISS may co-occur, forming very complex structures, such as the one shown in Fig. 6d. This structure was composed of a tear (2 m in length in Fig. 6d) rolled-up to form a thick roll-up structure with several involutions (red dashed line in Fig. 6d). Moreover, a wider tear with associated flipped-overs was formed around the roll-up (yellow dashed line in Fig. 6d). In addition, a fold was developed at the back of the roll-up (blue arrows in Fig. 6d). Microbial mat chips and sediment were present on the stoss side of the roll-up (green arrows in Fig. 6d).

4.3. Evolution of MISS

The evolution of the deformational MISS through time (more than two years) has been analysed by documenting the changes in the morphology of some of the MISS produced during the flooding of June 2018, in relation to the inundations and subaerial exposure of the sedimentary flat (Fig. 7a). Two days after their creation (June 2018, red arrow in Fig. 7a), a couple of roll-up structures were documented (Fig. 7b). 40 days later, after three subsequent inundations of nearly 30 cm of water column height (P1 in Fig. 7a), the structures were identified with similar morphology (Fig. 7c). The two roll-ups were detected in April 2019 when the morphology of the structures was highly flattened and eroded at the top (Fig. 7d). Prior to this fieldtrip of April 2019, the hydrodynamics during the end of 2018 was characterized by several minor inundations (less than 20 cm) and several days/weeks of subaerial exposure (first part of Period P2 in Fig. 7a). During Austral summer (ending of Period P2 in Fig. 7a) the area was subaerially exposed for most of the time, as the water level was below the sedimentary surface, except for some days at the end of February and beginning of March when an inundation occurred.

Another structure monitored for more than a year was a double flipped-over edge more than 50 cm in length (red arrow in Fig. 7e) associated with a microbial fold (green arrow in Fig. 7e). Both structures presented high flexibility and were subsequently biostabilized over the following weeks after their creation, when the flat remained inundated (P1, Fig. 7e). From August to December 2018, a period in which the sediment surface was repetitively subaerially exposed and affected by inundations of less than 0.2 m of water (first part of P2 in Fig. 7a), the structures were smoothed, the surficial layers were partially eroded, and the microbial fold was flattened (Fig. 7e, f). Since December, the structures suffered an extended period of subaerial exposure due to summer solar radiation (from December 2018 to March 2019, P2 in Fig. 7a), and several floodings during winter 2019 (P3 in Fig. 7A). In August 2019, the upper part of the microbial fold was eroded (white arrow, Fig. 7g, h) and the erosion of the flipped-over mat was more advanced.

In August 2020, the microbial sedimentary surface still exhibited roll-up structures formed during the storm in June 2018, although significantly eroded (Fig. 8a). The partial erosion caused the truncation of the microbial roll-ups, which produced the disappearance of the upper part of the structures and the preservation of only the lower part and the mat bent edges, perpendicular to the sedimentary surface (red arrow in Fig. 8b- c). In transversal cross-section, the eroded roll-up structures consist of up to 50 cm-long segments of planar microbial mats parallel to the sedimentary surface and curved in their extremes, with sand sediment between them (Fig. 8 d, e). The hydrologic record during the previous 10 months indicates that the sedimentary surface was affected by several inundations and long periods of subaerial exposure (nearly 60 days in March-April 2020, Fig. 8f).

During prolonged periods of subaerial exposure, especially in summer, the intense wind typical in Paso Seco would provoke the deflation of the most surficial layers of the dried roll-ups (video 1).

5. Discussion

Paso Seco provides an excellent modern example of the changes that microorganisms can cause to the sediment in terms of flexibility, and allows the study of the modifications to which microbial deformation structures are subject after their creation and before burial. The epibenthic microbial mats developed in Paso Seco present ~1 cm in thickness and consist on a biolaminated structure composed of mm to cm-thick layers of cohesive material (organic matter and mud) separated by sandy layers, where older mat generations are overgrown by younger ones (definition of biolaminites by Gerdes and Krumbein, 1987). An important feature of these epibenthic mats is that their microbial assemblages are characterized by a large number of filamentous cyanobacteria that weave the sediment secreting high amounts of EPS, which favors their gliding motility (Stal, 2001) and forming an effective protection against desiccation during long exposure to solar radiation. Moreover, the EPS generates adhesion between sediment particles and has high viscoelastic properties, conferring physical flexibility and mechanical resiliency to the microbial mats (Peterson et al., 2015). The remarkable plasticity of the mats in wet conditions due to the presence of EPS (Decho and Gutierrez, 2017) is crucial to mat deformation when a water current is applied to the microbial mats.

When this coherent microbial mat is overpressed by a water column, it is loosely attached to the underlying sandy layer. As a result, the surficial microbial mat may be lifted from the underlying sediments in response to high-energy events, such as currents and waves (Maisano et al., 2022). The detached microbial mat is pushed by the currents and reacts in a flexible mode due to its high cohesion, forming different MISS. The plastic behaviour during deformation varies on the amount of organic matter and humidity of the microbial mat (Pan et al., 2019). Thus, when they are wet, they present higher plastic performance than when they are dry.

In the study area, the development of microbial structures is influenced by geomorphology. Towards the coast, a narrow mouth (Fig. 1b) yields the acceleration of flood currents entering from the sea and generates high-velocity currents. These currents enter the old tidal channel and act on the microbial mats (Maisano et al., 2022), and one of the largest MISS, the roll-ups, might be created. They are of remarkable dimensions because of the tearing of the cohesive microbial mat over long distances (up to eight meters). In cross-section, roll-ups present generally an elliptical shape probably because they were flattened by the weight of their own structure (Fig. 4c). On some occasions, a microbial fold may form at the back of a roll-up structure when the structure becomes so heavy that the water current cannot continue rolling it. Then, all the roll-up structure is pushed a bit further by the current, sliding over the underlying sedimentary surface and forming a fold at the back of the roll-up (Fig. 6c). Even more complex structures may be formed when the microbial mat is ripped producing a wider tear around a roll-up structure (Fig. 6d). Furthermore, subsequent inundations may produce modifications to previous microbial structures (Fig. 6a).

In addition, roll-up structures behave as an obstacle to the sand and mat chips that are transported by the current. Therefore, these sediments are deposited on the stoss side of the roll-up (Fig. 6d). The association of a fold at the back of a roll-up structure and the accumulation of sand and microbial mat chips on the stoss side are hints to infer the current direction that produced the MISS.

After their formation, MISS may show gradual flattening (Fig. 7d, f) due to the weight of the structure, and can be affected by erosional events, such as aeolian deflation during subaerial exposure and water currents during subsequent lower-energy inundations (less than 30 cm of water column, Fig. 7b-d, g-h, 8a-d). The erosion is promoted by the desiccation of the roll-ups due to solar radiation and by subsequent blowing out of the desiccated surficial fragments (see video 1). The repetitive erosional processes end up truncating the structures (Fig. 8c, e) but the lower part of them can be preserved. The truncated roll-ups may be identified in cross-sections due to the presence of flexible microbial mats with curved ends oriented perpendicularly to the sediment surface (Fig. 8c, e).

Deformation features have been described in thinly-laminated, muddy-sandy, ancient sediments and have been interpreted as caused by the flexible behaviour of microbial mats. Roll-ups of few millimetres to centimetres were documented by Eriksson et al. (2000, 2007) in deposits interpreted as formed in a desert environment (Makgabeng Formation, South Africa, c. 2.0-1.8 Ga). They have an excellent preservation of the whole structure in the rock. The inferred genesis proposed by the authors to the observed structures is different from the roll-ups documented here, but still they ascribed them to deformation of cohesive microbial mats. Noffke et al. (2013) described small (~ 3 cm in width), rolled-up fragments of sediments in early Archean intertidal deposits of Australia, and interpreted them as pieces of microbial mats with flexible behaviour that were ripped off, transported and re-deposited. Such structures presented a zig-zag arrangement (see Fig.7b in Noffke et al., 2013) like the morphology shown by some of the roll-ups described in Paso Seco (red dashed line, Fig. 6a). Besides, in late Archean to Paleoproterozoic carbonate sediments of Western Australia, Simonson and Carney (1999) documented small (up to ~ 2 cm in width) roll-up structures closely associated with other types of structures, such as folds. Although the authors were not able to offer a full explanation of the genesis of the structure, they related them with the occurrence of cohesive microbial mats.

The above ancient examples show many morphologic similarities with the structures described in the current study, suggesting that microbial deformation structures may be preserved in the fossil record. However, all the microbial deformation structures described in the aforementioned ancient successions are much smaller than the ones formed in Paso Seco and they are entirely preserved. This is probably because smaller structures may be buried faster. Nevertheless, larger deformation structures, such as the roll-ups of Paso Seco, might potentially occur in the fossil record but truncated because their large height makes them more prone to erosion. The characteristics that would allow to recognize entirely preserved roll-ups in cross-section of ancient successions would be the identification of discrete structures that have no lateral continuity and consist of an up to 1 cm-thick set of fine-grained laminae that are overturned more than 360° creating a spiral shape. In the case that the roll-up had been partially truncated before burial, its identification in the geological record would be more difficult. The presence of the same up to 1 cm-thick set of laminae stacked on top of each other multiple times at a specific location and with upwards curled edges would allow the recognition of truncated roll-ups in cross sections of ancient successions.

Considering that microbial deformation structures may be preserved in the fossil record, the possibility that the presence of soft-sediment deformation structures might be related with microbial mat development and deformation should be considered when interpreting ancient successions. In this sense, Varejão et al. (2022), studying, mixed carbonate-siliciclastic successions deposited in lacustrine settings with sea incursions (Early Cretaceous, Araripe Basin, Brazil) that contain abundant soft-sediment deformation structures (SSDS), interpreted some SSDS as the result of the deformation of microbial mats, caused by periodic flooding and desiccation. The SSDS ascribed by Varejão et al. (2022) to a microbial origin have similar dimensions and characteristics to the microbial deformation structures present in Paso Seco. Thus, despite the difficulties for interpreting the triggering agent that produced SSDS in the fossil record, the studies that document the plastic and flexible characteristics of microbial mats in the modern counterparts should be considered when trying to interpret this type of structures. These studies might provide clues for understand the sedimentary processes involved in their formation in the past.

6. Conclusion

The present study evidences the cohesiveness and great flexibility that microbial mats confer to sediment, allowing the development of deformational MISS in a siliciclastic environment due to high-energy currents. The hydrodynamic characteristics of Paso Seco flat provide the proper conditions for the development of metre-scale microbial roll-up structures, which are the most striking deformational MISS in the study area due to their size, and other related complex microbial structures. These characteristics are: alternation of calm periods, during which microbial mats biostabilise the sediment, and flooding episodes during storm surges, during which the microbial mats can be deformed. This research explains the physical changes of the microbial structures over time once they are formed and before burial. After the structures are created they remain inundated for an extended period (days), during which they are recolonised and biostabilised by a new mat. Afterwards, the flat is repetitively affected by minor inundations and subaerially exposed, which cause the smoothing of the structures and the erosion of the surficial layers by solar radiation and wind effect. This fact generates the truncation of the structures. However, the lower part can be preserved, which might be observable in a vertical section of the flat as planar microbial mats curved at their extremes. Similar sedimentary structures characterized by sediment layer deformation are recognized in the fossil record, evidencing the preservation potential of deformational MISS and highlighting the possible application of the observations in present-day microbial settings to interpret ancient successions.

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Data availability

Datasets related to this article can be found at http://dx.doi.org/10.17632/b6wdr3phnr.1, an open-source online data repository hosted at Mendeley Data (Cuadrado Diana, 2021).

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Captions

Figure 1. Location of Paso Seco flat. (a) Satellite image showing the study area behind a sand spit (blue square). (b) Close-up view of the study area (blue square in a). The orange mark indicates the location of the water level sensor. Image extracted from Google Earth

Figure 2. Hydrodynamics and aerial images of the study area. (a) Water level record from March 2018 to July 2018 (green line) relative to the microbial mat surface (red line). Water level above the microbial mats indicates inundations and below the red line indicates groundwater variations and exposing of mat surface. Red arrow indicates the flooding of June 2018. (b) Appearance of the study area before the storm episode in June 2018. (c-d) Aerial images of the study site two days after the flooding in June 2018. (c) Meter-sized roll-ups formed at the end of the ripped microbial mats (red arrows). Black circle points to a person for scale. (d) An orthogonal aerial photograph showing long microbial tears (black dashed

lines) that are rolled up in the direction of the flood current (red arrows). 1-2 m-long microbial folds (yellow dashed line) were created in random directions.

Figure 3. Mat tears and associated flipped-over edges. (a) View of an exposed mat layer (old mat layer) after a ripped mat tear. There is a sharp edge (~ 1cm) at the tear margin. (b) Close-up view of a desiccated tear. The biolamination in the tear edge can be observed (arrow). (c) Irregular edges at the margin of a tear that leave exposed several layers of microbial mats underneath. (d) Close view of c). Old mat layers are exposed (mat I is the oldest and mat V the youngest). Part of the tear edge is flipped over (white dashed line), exposing the underlying sediment (red arrow).

Figure 4. (a) Roll-up schematic diagram. (b) Roll-up acting as a barrier for landward transport of sediment and microbial mat chips. The direction of the water current is pointed (red arrow). The structure showed 0.7 m in length (yellow dashed line) and 0.3 m in width (red dashed line). (c) Vertical section of a roll-up structure composed of several involutions of mm-thick, very cohesive and flexible microbial mat. The uppermost surface of the structure shows the sediment attached to the lower surface of the overturned mat (US). (d) Drawing of B indicating the subsequent involutions (I, II, III).

Figure 5. Petrography of a roll-up structure. (a) Sample of a roll-up structure from which a thin section was prepared. The yellow dashed rectangle shows the location of the thin section. (b) A magnifying glass image of the thin section from (A). The yellow dashed square shows the area shown in c). (c) Thin section photomicrograph under cross-polarized light of the rolled-up microbial mat shown in (b), which consists of alternating sand (blue arrows), mud + organic matter (green arrows) and micritic laminae (red arrows).

Figure 6. Characteristics of roll-ups structures. (a) Vertical section of a roll-up structure showing a zig-zag arrangement (red dashed line). Surficial thin microbial mats are turned to opposite directions by subsequent currents (yellow arrows). (b) A roll-up structure acting as an obstacle for the transport of sand and microbial mat chips (red arrows). mm indicates microbial mat; us indicates the reverse of the overturned mat. (c) A roll-up developed over the flat. The structure is associated with a fold developed in the back the roll-up (red arrow). (d) A complex structure formed in two stages: i) a tear of 2 m in length forming a roll-up structure (RU) with several involutions (red dashed line); ii) a fold developed in the back of the roll-up (F, blue arrows) due to the slip of the surficial mat over which the roll-up was transported. The current (black arrow) made the tear wider (yellow arrows) around the roll-up. Flipped-over edges (FO, yellow dashed line and yellow curved arrow) were developed at the sides of the roll-up structure. The roll-up structure acted as an obstacle for the sediment transport and microbial mat chips (SS, MC, green arrow). UMM indicates underlying microbial mat.

Figure 7. Evolution of MISS. (a) Water level record from June 2018 to November 2019 (green line) relative to the sedimentary surface (red line). The great inundation in June 2018 (more than 0.7 m of column water) is indicated by a red arrow. Yellow circles indicate the field trips. P1, P2, and P3 indicate periods between field trips when different structures were monitored. The blue dashed line indicates inundations of 0.2 m. (b) A couple of roll-up structures created by the inundation of June 2018. (c) Same structures shown in b) 40 days after the inundation. (d) Structures shown in b) ten months after the inundation. (e) A flipped-over edge (red arrow) and a microbial fold (green arrow) created during

the inundation in June 2018. (f) The MISS showed in e) six months after their creation. (g) The MISS showed in e) 14 months after their creation. The white arrow indicates the truncated fold. (h) Close view of g).

Figure 8. Identification of MISS in a vertical section. (a) Roll-up structure formed in June 2018 progressively eroded. (b) Close view of a). The red arrow indicates the bent edges of the previous roll-up structure perpendicularly oriented to the tidal flat. (c, d, e) Cross-sections of eroded roll-ups showing bended extremes of microbial mats, truncated at the surface. Microbial mats are the mud layers (light colour) that are intercalated with sand layers (dark colour). (f) Water level record from November 2019 to August 2020 (green line). The red line indicates the sediment surface, and the blue dashed line indicates seawater inundations of 0.2 m. The orange line shows a long period when the flat was subaerially exposed.

Video 1. A video shows the flat's behavior when it is exposed to prolonged periods of solar radiation and subaerial exposure, especially in summer. Note the intense wind which provoke the deflation of the most surficial layers of the dried roll-ups.

Highlights:

Meter-sized roll-up structures were formed on a sedimentary flat during storms

MISS evidence the high flexibility of the microbial mats

Repetitive erosional processes end up truncating the microbial structures

Figure 1

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Figure 2

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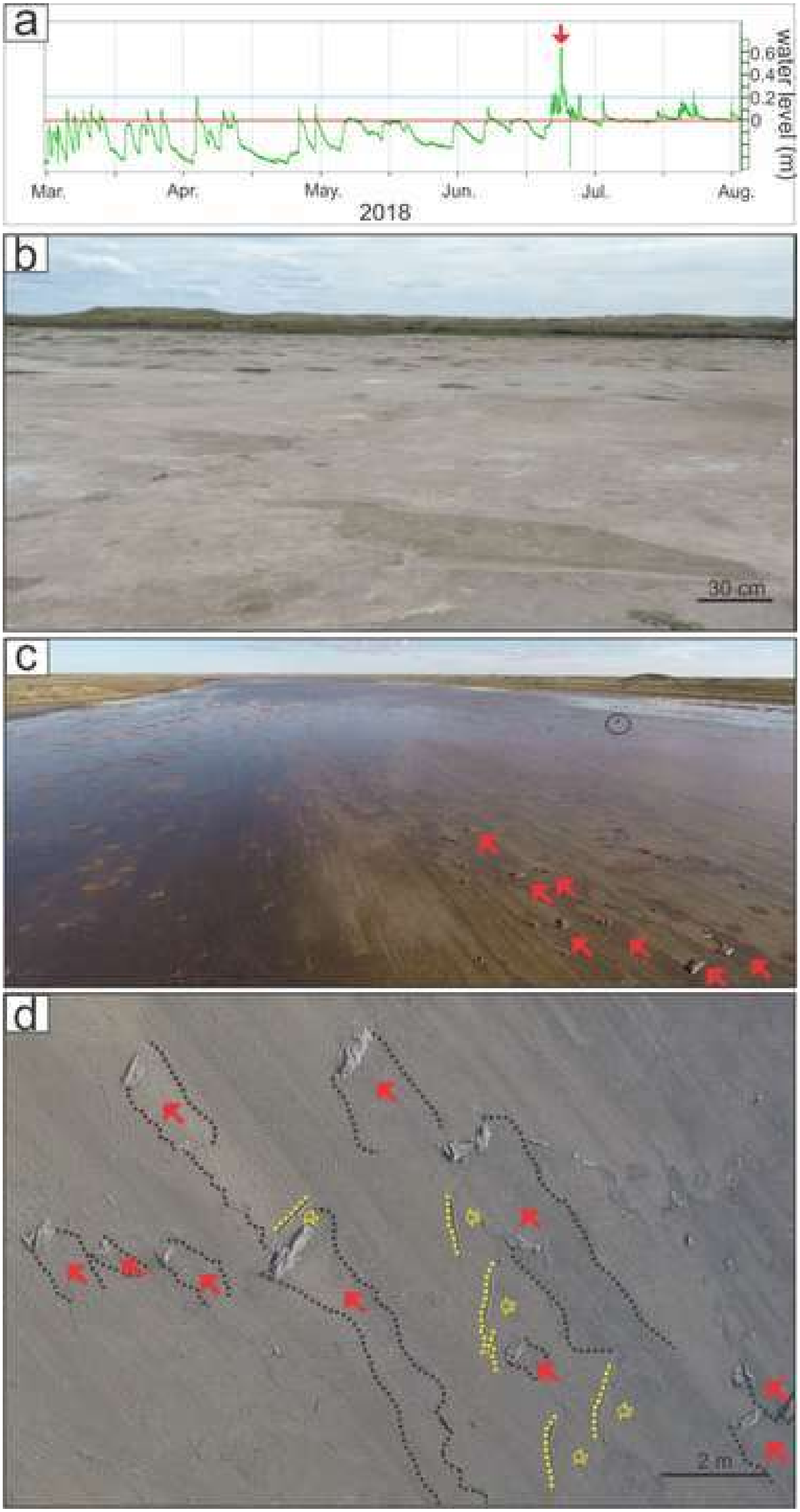

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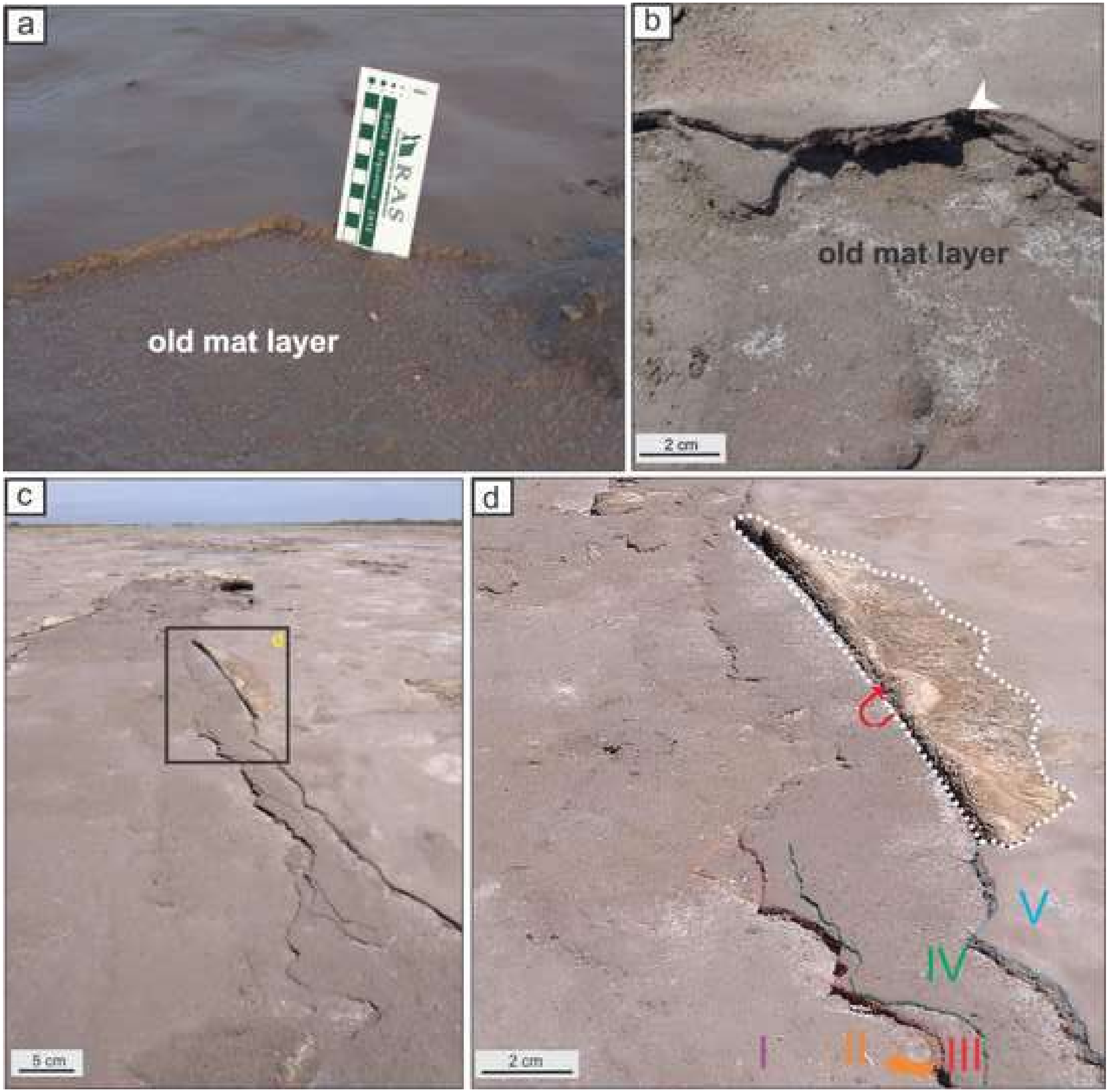

Figure 4

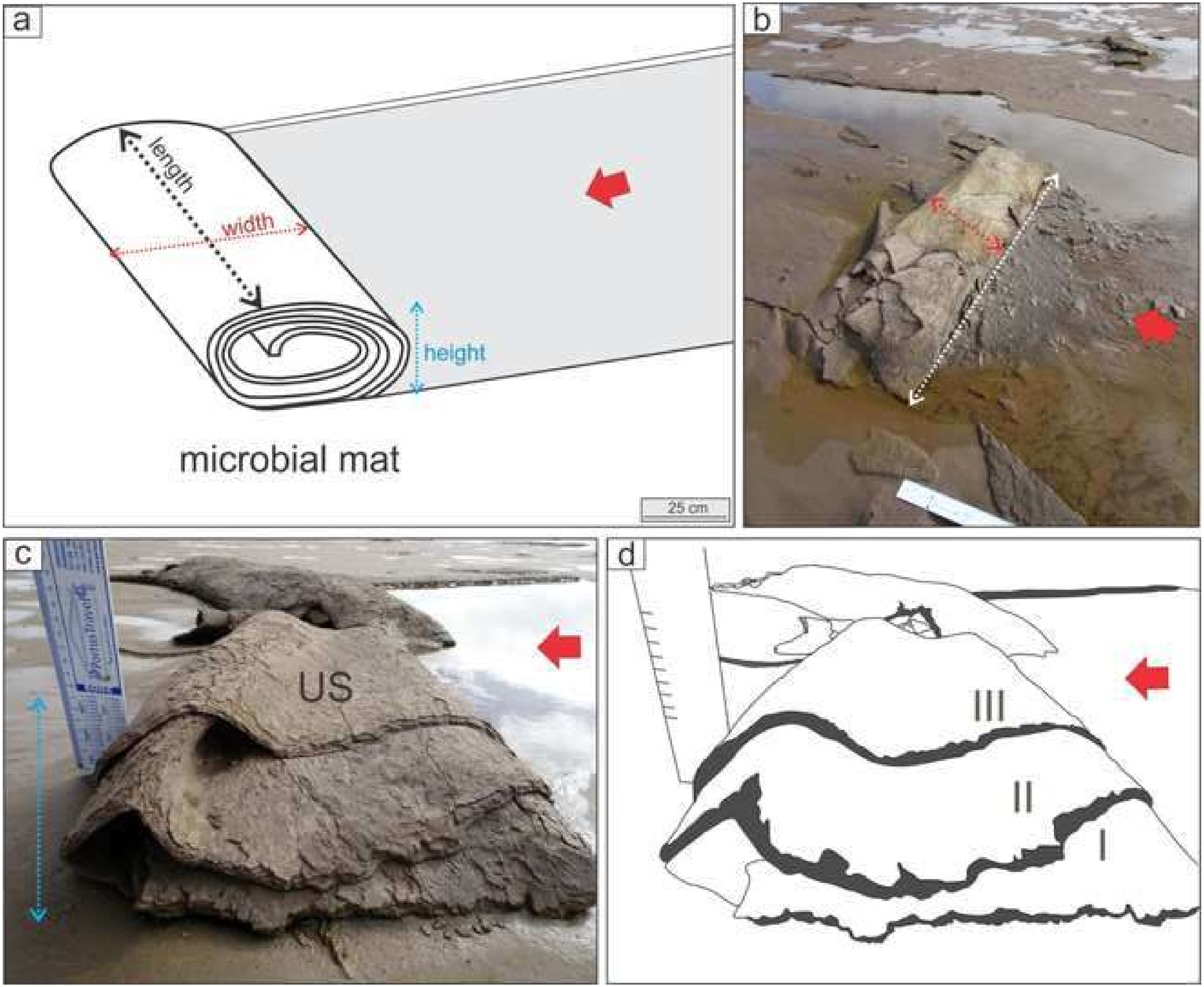

Figure 5

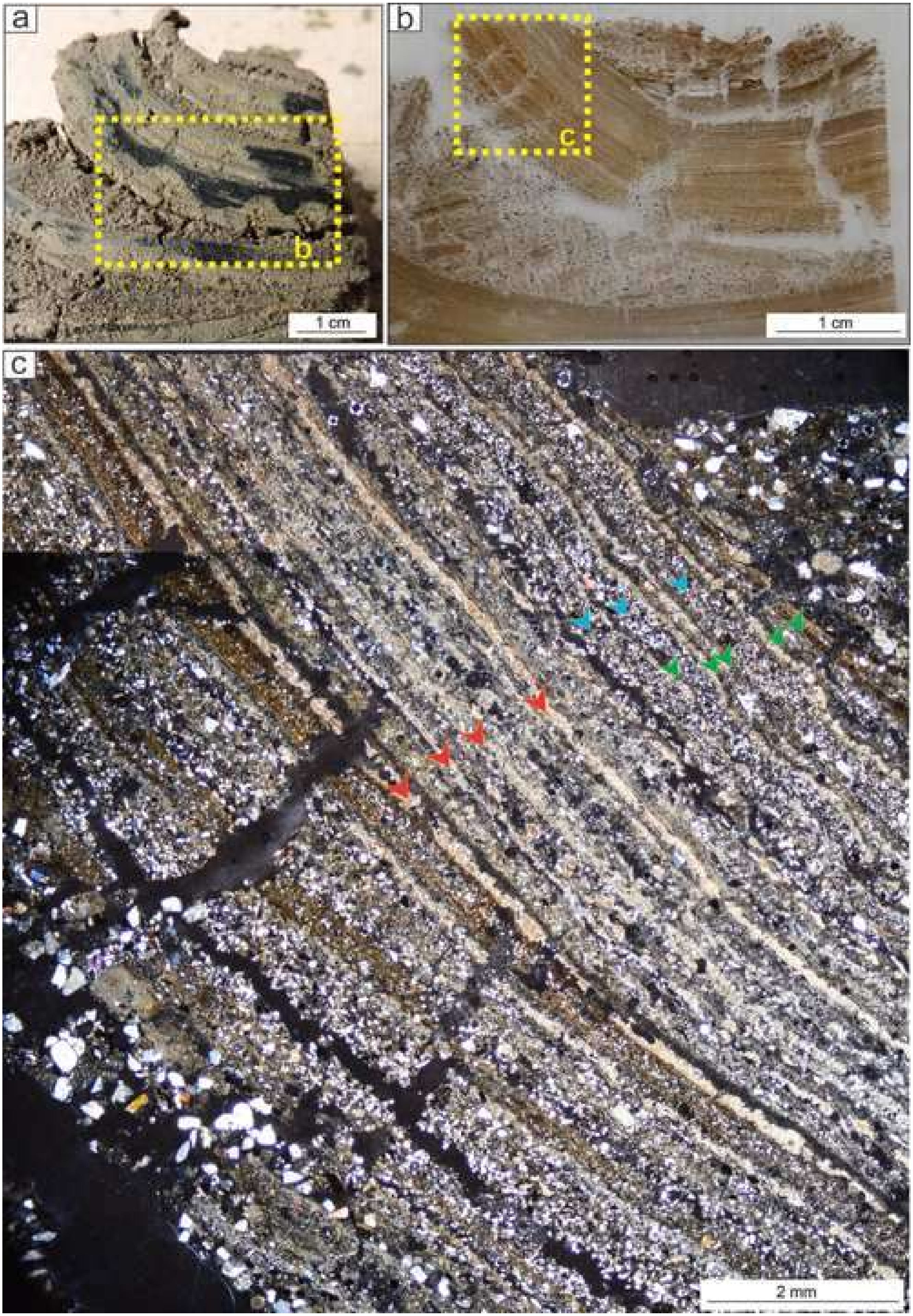

Figure 6

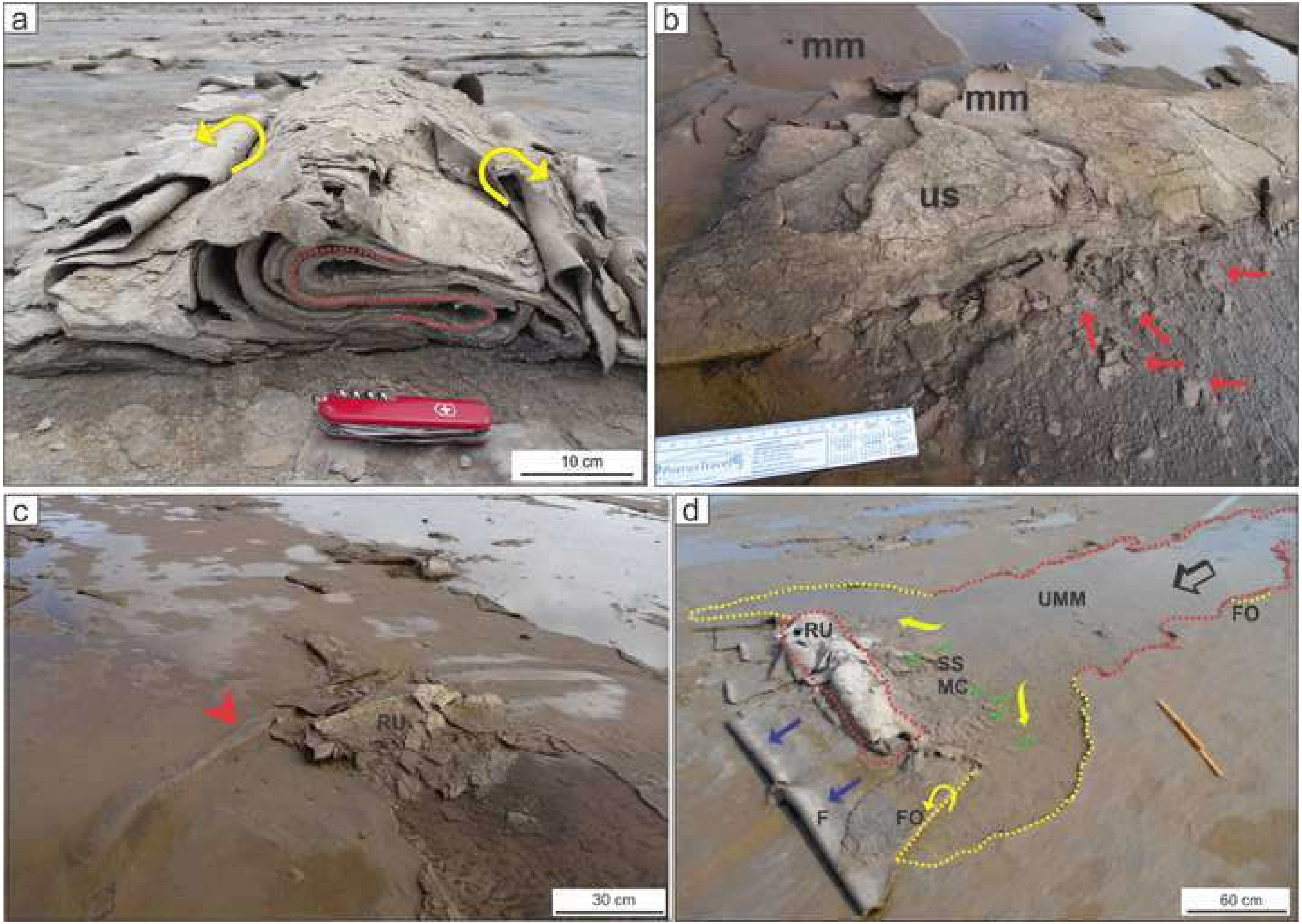

Figure 7

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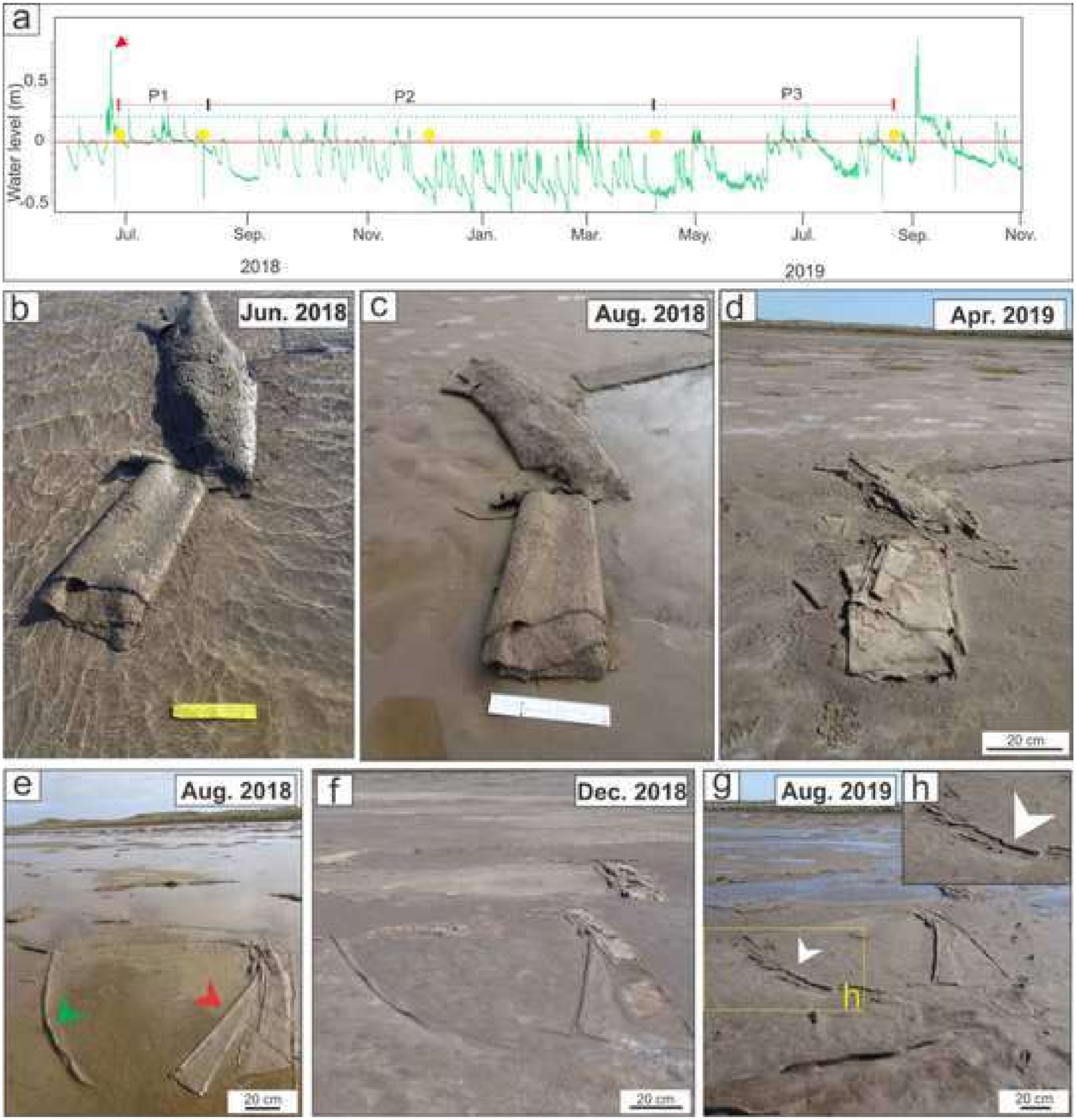
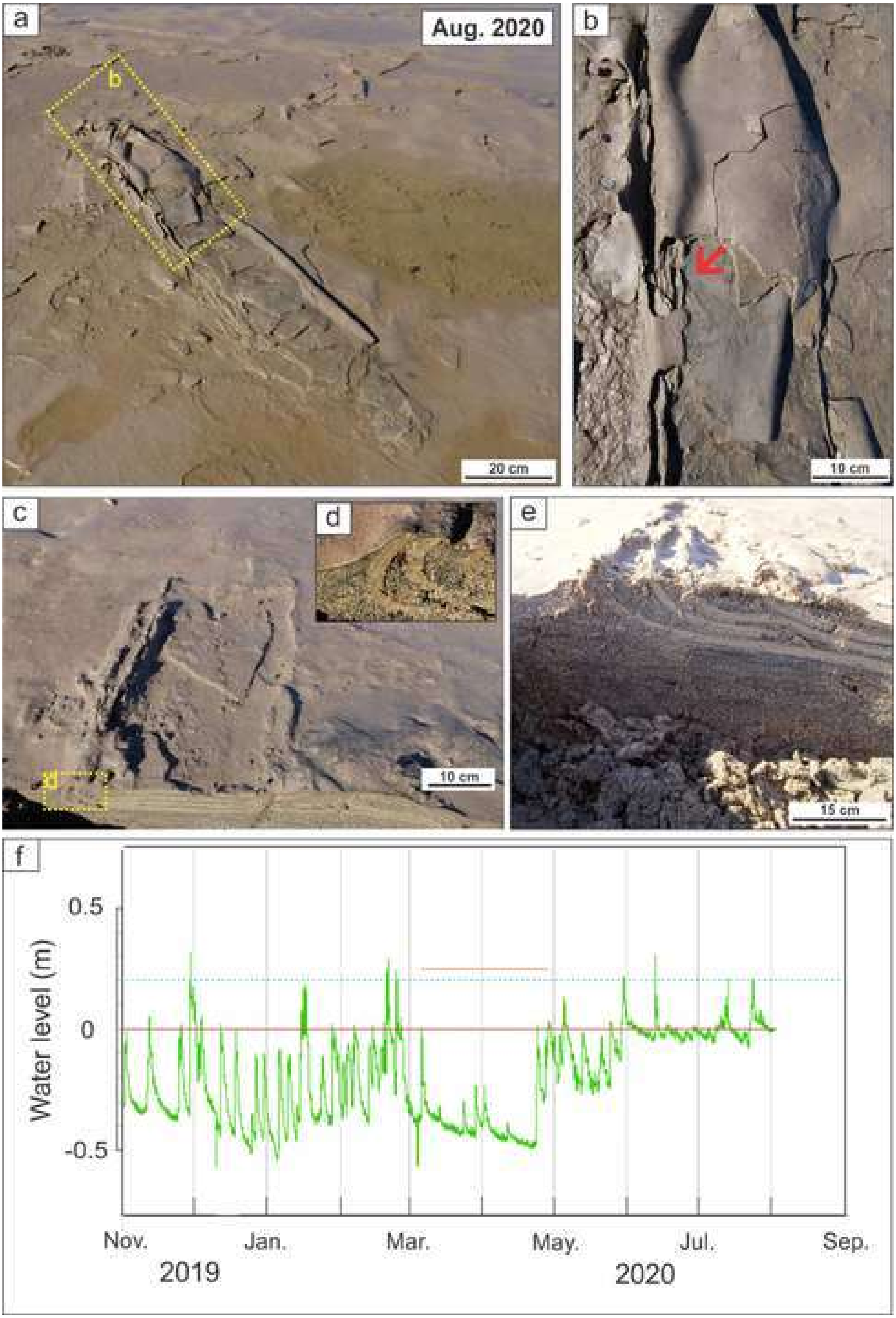


Figure 8


a
Aug. 2020
b
20 cm
b
10 cm
c
d
d
10 cm
e
15 cm
f
Water level (m)
0.5
0
-0.5
Nov.
Jan.
Mar.
May.
Jul.
Sep.
2019
2020

Video 1

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Supplementary material for on-line publication only
video1_F.mp4

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: