Microbial shrinkage cracks in siliciclastic rocks of the Neoproterozoic Nosib Group (Damara Supergroup) of central Namibia

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Fossil shrinkage cracks occurring on bedding surfaces of fine-grained siliciclastic rocks are characterized by sinuously curved, sub-circular and subordinately sigmoidal cracks and networks of cracks. They are described from shallow marine deposits of Proterozoic age but not from the Recent. The crack infillings are usually easily separated from both lower and upper bedding surfaces. Such cracks, preserved in fine-grained quartzitic rocks of the Duruchaus Formation (Nosib Group) of the Damara Supergroup in central Namibia, are described. A relationship to shrinkage and cracking of a microbial mat that underwent partial desiccation during temporary aerial exposure is suggested and the name "microbial shrinkage cracks" is proposed. Evidence favouring microbial participation in the development of the cracks includes: (a) the complete absence of a shrinkable argillaceous or otherwise suitable interlayer; (b) the ready separability of the crack infillings from adjoining lower and upper bedding surfaces and accordingly their independance from the beds above and below; (c) the presence of pseudomorphs after pyrite and possibly ferroan carbonate on and close to the adjoining bedding surfaces; (d) the predominance of curved and sub-circular cracks, sometimes forming loops and 8-shaped marks; (e) the smoothened ripple morphology of the upper bedding surface below the cracks. The genetic model suggests the following sequence of events: (a) biostabilization of the siliciclastic sediment surface and successive growth of a microbial mat in a shallow marine, tidal environment; (b) aerial exposure of the mat leading to progressive dewatering and to crack initiation of the surface layer; (c) infilling of the cracks with siliciclastic detritus during renewed flooding; (d) recovery and continued growth of the mat, overgrowing the crack infillings; (e) burial of the mat under sediments with a subsequent aquatic event.

Introduction

It was in 1987 that Henno Martin, during one of his last field campaigns in Namibia, introduced to the authors an outcrop on the farm Haakdoorn 300, Gobabis District (Haakdoorn, Fig. 1) exhibiting a network of irregular linear and subordinately curvilinear patterns, forming positive as well as negative features (casts and moulds) on upper bedding surfaces of sandstone layers. The sandstone layers are overlain by thin mudstone horizons or drapes. The structures are developed in a low-grade metamorphic terrestrial sequence of the Neoproterozoic Nosib Group and have been interpreted as marine trace fossils of the *Planolites* and *Treptichnus* types by Killick (1983). Martin (pers. comm, 1987) suggested that they might be shrinkage or "syneresis" cracks and of inorganic origin.

Another exposure of alleged trace fossils occurs on the southwestern slope of Koedoeberg mountain on farm Hatsamas 92, near Dorbabis ("Hatsamas", Fig.1). The subtle structures occur in rippled, fine-grained, thinly bedded sandstones of a facies transitional from the arkosic Kamtsas Formation to the silty to pelitic Duruchaus Formation (Nosib Group) and delineate incomplete polygonal to subcircular networks of sinuously curved segments. Occasionally, isolated short, fusiform structures are developed. Junctions at angles of 90 and 120° are frequent, the latter form typical triple junctions. An isolated slab of ripple-marked sandstone with similar structures was recovered from the Gurumanas Evaporite Member of the upper Duruchaus Formation (Heins, 1991) ("Gurumanas", Fig. 1) in the eastern Geelkop dome (GD on Fig.1).

This article restricts itself to a description, discussion and interpretation of the excellently preserved, fusiform or curved, crack-like structures in the Neoproterozoic
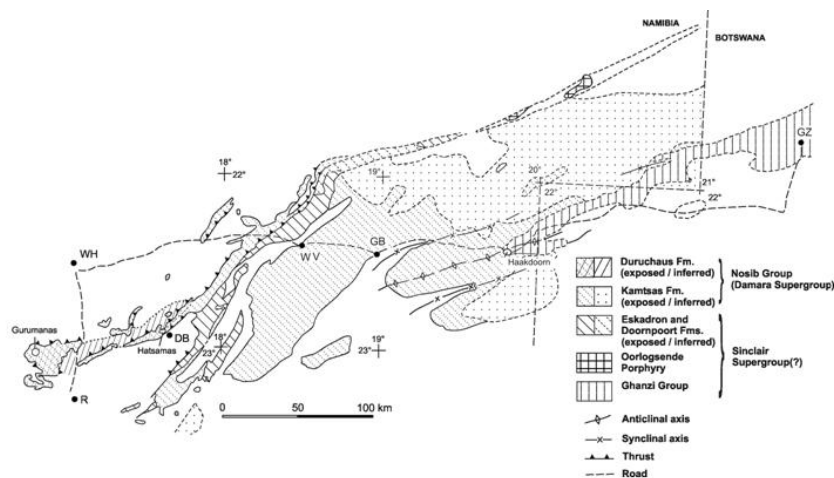
Figure 1: Generalized geological map of the area between Windhoek (Namibia) and Ghanzi (Botswana) showing deposits of the Nosib Group (Damara Supergroup). DB = Dordabis; GB = Gobabis; GZ = Ghanzi; WH = Windhoek; WV = Witvlei. Gurumanas, Hatsamas and Haakdoorn are localities at which networks of cracks are preserved. (After Schalk, 1970; Geological Map of S.W. Africa/Namibia, 1980; Hegenberger and Burger, 1985).

siliciclastic sediments of the Nosib Group on farm Hatsamas 92.

The same type of "exotic" cracks has been described from numerous localities around the world, from the Palaeoproterozoic Huronian Supergroup (Faul, 1950; Frarey and McLaren, 1963; Hofmann, 1967) and Cambrian Potsdam Sandstone (Dawson, 1890) of Canada, the Neoproterozoic of South Manchuria and Japan (Endo, 1933; Yabe, 1939), the Neoproterozoic Belt Series and Eocene Green River Formation of North America (Wheeler and Quinlan, 1951; Barnes and Smith, 1964; Picard, 1966), the Neoproterozoic Umberatana Group of Australia (Plummer and Gostin, 1981), the Neoproterozoic Dalradian Supergroup of Scotland (Tanner, 1998) and the Upper Triassic of East Greenland (Stauber, 1942). Further examples occur in Triassic siliciclastic rocks in the epicontinental German basin (e.g. Detfurth and Exter Formations). In all instances the structures occur on ripple-marked surfaces of plane-bedded psammitic beds, preferentially in the ripple troughs where they form incomplete polygonal to sub-circular networks. Thin metamorphosed mudstone or mudrock layers may or may not be included in the succession which is usually attributed to a shallow to marginal marine or lacustrine facies. They have, however, not been observed in the Recent (Seilacher, 1997) and have not been produced yet by experiments (Jüngst, 1934; White, 1961; Burst, 1965).

The sinuous to sub-circular structures were originally interpreted as some kind of *Lebensspuren*, specifically worm casts or worm burrows (e.g. Dawson 1890; Faul 1950; Frarey and McLaren, 1963) and the generic name *Rhysonetron* was applied to them by Hofmann (1967). Alternatively, they were considered to be remains of algae and were named *Manchuriophycus* by Endo (1933) and Yabe (1939). There has been doubt and discussion about their biogenic origin. Häntzschel (1949) suggested that they are unusual mud cracks developed in the double-wedged mud fillings of ripple troughs (Meyer, 1966). Wheeler and Quinlan (1951) presented an example showing that the sinuous structures in the ripple troughs merge with polygonal mudcracks towards the ripple crests, the latter possibly forming a second crack generation. Glaessner (1969) claimed that there is "no reason for postulating a biogenic origin" for the fusiform, sinuous and sub-circular structures. However, he left open considerations of whether they formed subaerially by normal dessication, under water by "synaeretic shrinkage of mud" (e.g. Jüngst, 1934; White, 1961), intrastratally by dessication/shrinkage at very shallow depth (Richter, 1941), or by compaction during deeper burial.

Tanner (1998) suggested that layer-parallel contraction caused by compaction of mudstone layers during burial is the main crack-forming mechanism which is followed by intrastratal intrusion of water-saturated sand from above or below into the cracks resulting in the formation of more or less complete polygonal patterns. Kidder (1990) invoked expulsion of pore-water during compaction to explain the fusiform (spindle-shaped) crack geometries. These mechanisms require burial depths of at least several hundred metres (Cartwright and Lonergan 1996; Bethke, 1986) and would thus widely disconnect the formation of the structures from the depositional environment of the host rock. In this case the structures could not be used as environmental indicators.

Astin and Rogers (1991) suggested that many of the fusiform (lenticular) structures represent pseudomorphs after gypsum crystals that formed on desiccating surfaces and may have initiated the subaerial development of incipient to more complete desiccation polygons.

Microbial communities are well known from Proterozoic carbonate environments, where they produced stromatolites, but have rarely been described from siliciclastic environments (e.g. Schieber, 1986, 1998, 1999; Garlick, 1988; Pflüger and Gresse, 1996; Hagadorn and Bottjer, 1997, 1999; Gehling, 1999). Microbial mats today are typically found in stressed nonmarine or shallow to marginal marine environments where bioturbating or grazing organisms are restricted (Garret, 1970). In the Proterozoic, however, when such organisms were largely non existent, it may be expected that microbial communities "very likely colonized any conceivable environment where their light and nutrient requirements were met" (Schieber, 1998, p. 105), including siliciclastic, shallow marine domains.

Compared to carbonate environments where early cementation supports preservation of the biogenic structure and organic matter, preservation potential is generally poor in siliciclastic settings. Decomposition of organic matter, concomitant fabric collapse and subsequent burial compaction will destroy all remnants of the biogenic construction within a short period of time. Park (1977) and Krumbein and Cohen (1977) estimated that this happens in modern microbial mats within the first hundred years of burial. Nevertheless, Schieber (1998, 1999) discussed sedimentary structures and textural features that may be indicative of the former existence of microbial mats in ancient siliciclastic sediments. These include: (1) domal buildups resembling stromatolites in carbonates (Schwarz *et al.*, 1975; Garlick, 1988); (2) cohesive behaviour of laminae and silty to sandy substrata during soft-sediment deformation, erosion and transport allowing formation of lamina intraclasts (Garlick, 1988) and sand intraclasts ("microbial sand chips", Pflüger and Gresse, 1996); (3) rippled patches on otherwise smooth surfaces (see Noffke, 1999 for modern examples); (4) irregular curved-wrinkled impressions on bedding planes interpreted as impressions of disturbed thin microbial mats (Horodyski, 1993); and (5) lamina-specific distribution of certain early diagenetic minerals, e.g. dolomite, ferran carbonate, pyrite (Pflüger and Gresse, 1996). Attention has further been drawn to so-called "wrinkle structures" (wrinkle marks; runzelmarken; "elephant skin" after

Gehling (1991); Kinneyia ripples) which occur as irregular features on the tops of fine-grained quartzite or siltstone beds, frequently of Neoproterozoic-Cambrian age. They are occasionally associated with "trace fossils" (resembling the structures at Hatsamas) and are now believed to have been formed by microbial processes (Hagadorn and Bottjer, 1997, 1999).

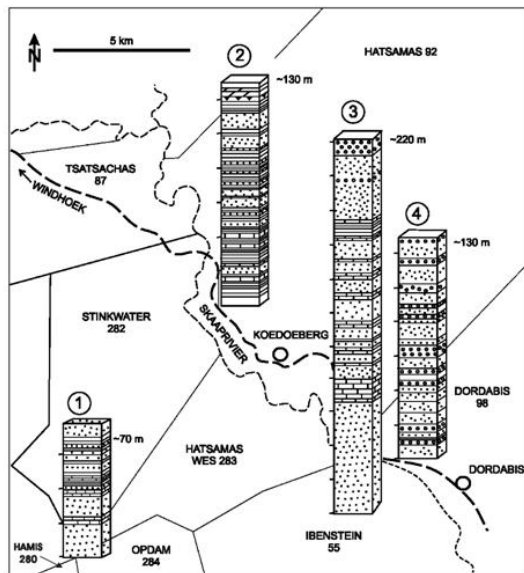## Observations on farm Hatsamas 92, SW slope of Koedoeberg mountain

Detailed lithostratigraphic sections 3-10 km from locality "Hatsamas" in the Duruchaus Formation are presented in Figure 2. Section 1 (farm Hamis 280) is mainly siltstone with frequent quartzitic interbeds and some metapelitic units with associated carbonate layers and lenses. Quartzitic interbeds increase in number upwards. The section ends with a unit of medium- to coarse-grained fluvial quartzite of the Kamtsas Formation. Section 2 (Lübbertberg mountain, farm Coas, portion of Hatsamas 92) exhibits dominantly metapelitic rocks with siltstone units, 2-8 m thick, and a few quartzitic interbeds (up to 0.5 m). Carbonate layers, associated with the metapelites and siltstones, occur predominantly in the lower portion of the section. The section is terminated by grey marble of the Corona Formation above a thrust horizon. Section 3 (Wit Koei mountain, farm Ibenstein 55) starts with micaceous siltstone with a few interbeds of fine-grained quartzite. Ripple marks occur throughout and "dewatering structures" (Uhlig,

Figure 2: Simplified geographic map of the area 5 km NW of Dordabis, showing position of Koedoeberg mountain (farm Hatsamas 92). Lithostratigraphic columns (after Uhlig, 1987) indicate fine-grained lithological successions of the Duruchaus Formation, as exposed at (1) farm Hamis 280; (2) Lübbertberg mountain, farm Coas, part of Hatsamas 92; (3) Wit Koei mountain, farm Ibenstein 55; (4) farm Dordabis 98. Legend to columns: Heavy dots = medium- to coarse-grained quartzite (Kamtsas Formation); light dots = fine-grained quartzite and subarkose; bricks = carbonate; lines = siltstone and mudstone; barbed line = thrust.

1987) have been observed at the top of this part. The middle portion of the section (*ca.* 100 m) contains numerous thin carbonate layers intercalated in siltstones and subordinate metapelites. The upper siltstone is abruptly overlain by coarse- to medium-grained quartzite typical of the Kamtsas Formation. Section 4 (farm Dordabis 98) is made up of thinly bedded siltstone and fine- to medium-grained quartzite of the Kamtsas type in almost equal proportions. Pseudomorphs of Fe-oxides after pyrite are usually associated with the siltstone beds in the lower and middle portion of the section.

The Duruchaus Formation was laid down in rift-related basins during the initial stages of the Damaran deposition. The predominance of fine-grained lithologies (metapelites, siltstones) and carbonates in the Duruchaus Formation contrast with the coarser grained and siliciclastic sediments throughout the coeval Kamtsas Formation which was deposited in fluvial settings. Section 4 has been interpreted as interfingering of the two depositional domains in a marginal lacustrine (or marine?) setting. The other sections are considered to represent more fully developed lake environments where deposition of mudstones and carbonates occurred (Uhlig, 1987; Löffler and Porada, 1987).

Lithologies recorded at "Hatsamas" represent an overall coarsening and thickening upward cycle starting with a siltsone unit and terminating with massive and coarse-grained, locally pebbly, arkosic lithologies. The crack horizon is located in a transition zone with fine- to medium-grained sandstones and minor "mudrock" intercalations. Locality "Hatsamas" likely represents a shoreline environment of a permanent lacustrine (or marine?) water body (see chapter "Environmental implications"). This is supported by small- to medium-scale sedimentary structures: (1) low-angle and locally curved "hummocky-like" cross-stratification; (2) tabular to finely laminated stratification; (3) well developed small-scale asymmetrical to lingoid current ripples (10 cm wave length, 2-3 cm amplitude); and (4) symmetrical wave ripples (1-2 cm wave length, <1 cm amplitude). Incomplete rectangular to polygonal networks of clearly subaerial desiccation cracks are preserved on bedding surfaces of some thicker layers (8-12 cm).

The sinuous to sub-circular structures (Figs. 3a-d) occur in an interval of thinly bedded, very fine-grained sandstone to siltstone with Fe-oxide-rich partings (0.5 to 1 mm) between individual layers. The layer below the surface on which the structures are developed is *ca.* 3 cm thick (Fig. 4a) and consists of medium-grained, reddish-brown sandstone grading upwards into fine- to very fine-grained grey sandstone. The coarser grained bottom part shows small-scale current ripple bedding on a cm scale, while the upper part is characterized by symmetrical flaser to ripple bedding indicating wave action in very shallow water. The layers above the structures are 2-8 mm in thickness and also show small-scale symmetrical ripple bedding forming ripples of 7-8 cm wavelength and 2-5 mm amplitude. The first of

these beds is separated from the thick layer below and the next thin layer above by Fe-oxide horizons. There is no trace of mudstone between the beds. The structures occur at the contact of the first thin bed with the underlying thicker layer and leave, if removed, impressions in both of them.

Under the microscope, cross sections of the structures exhibit lensoid, elliptic or convex-up half-elliptic shapes with acute ends. The structures are located in the plane of Fe-oxide enrichment, in a way that the plane splits at their ends and continues uninterruptedly above and below (Fig. 4b). The structures are not connected with the layers above and below and are thus made up of individual bodies situated between the adjoining beds. Fe-oxide infiltration has occurred from the surrounding plane into the bodies so that they either show an Fe-oxide-enriched rim or are fully empregnated by Fe-oxide. Otherwise there is no difference with respect to composition and grain size between the bodies and the siltstone layers below and above. In the siltstone beds adjoining the plane of Fe-oxide enrichment, a faint relic microlamination (0.1 mm-scale) defined by varying amounts of Fe-oxide and possibly by phyllosilicates and extending less than 1 mm into the beds appears to be developed (closely spaced lines on Fig. 4b). If not entirely related to diffusion processes during Fe-oxide infiltration, the microlamination may indicate original bedding.

The bedding surface on which the structures are developed exhibits slightly sinuous and occasionally bifurcated symmetrical ripples (3-5 cm wave lengths, 3-5 mm amplitudes). The pattern is transversed, at 30° to the ripple trend, by an irregular undulation manifested in *ca.* 10 cm wide low ridges and shallow depressions (Fig. 3a). Both ripples and ridges are remarkably flat and smooth and rather vague, in contrast to the much more sculptured ripple marks developed on bedding surfaces in the same succession above and below. However, these do not carry the sinuous and sub-circular structures under consideration.

Numerous brownish pseudomorphs after pyrite and euhedral (ferroan?) carbonates from 1-3 mm across are randomly distributed on the bedding surface. Both presumed relics of pyrite and carbonate are closely related to bedding surfaces, but are largely absent from inside the beds themselves. They are also absent from inside the bodies.

On the bedding surface, the sinuous and sub-circular structures are preferentially developed in ripple troughs and depressions and tend to peter out towards ripple crests and ridges (Figs. 3a-c). The structures are formed by smooth bodies, slightly flattened in cross-section and gently tapering in width and thickness towards each end (Fig. 3d). They can easily be removed from the adjoining beds above and below and then leave distinct impressions on both upper and lower bedding surfaces. However, in places, the impressions are very flat and faint and are only discovered at low-angle illumination. Isolated from the beds, the bodies resemble casts of some tubiform cavities. Most of the bodies are curved but almost straight forms or segments also occur. A few are singular; these exhibit a crescent-shaped or sigmoidal form, 2-3 cm long, with tapering ends. Most of the casts are linked up with others to form partly incomplete chains of connected elliptic to sub-circular structures in the ripple troughs. Locally, more angular to polygonal patterns resembling normal desiccation cracks may be developed.

The maximum observed width of the bodies is 5 mm, whereas their maximum vertical thickness is in the range of 2-3 mm. It should be noted, however, that these proportions may have been reversed before compaction. Many of the bodies bear a median longitudinal depression, *ca.* 1 mm wide, on both their lower and upper surfaces (Fig. 3d). That on the lower surface is less well developed. Occasionally, two depressions, separated by a shallow central ridge, are developed (Fig. 3d). The longitudinal depression has hitherto only been described from virtually identical bodies of the Lower Proterozoic Huronian by Frarey and McLaren (1963). Glaessner (1969) suggests that it is produced by compaction of an originally prismatic crack filling. Rarely,
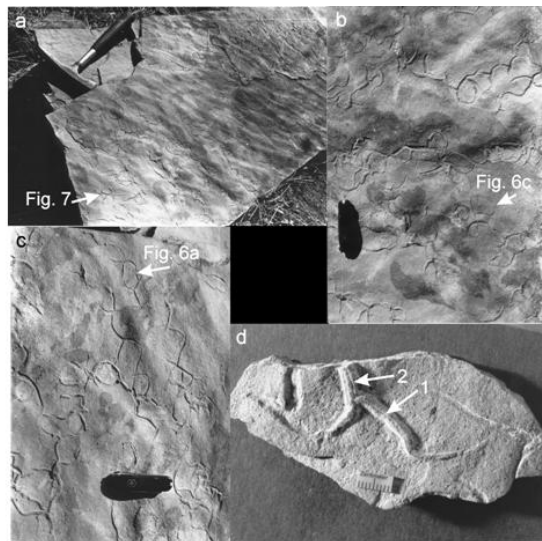
Figure 3: Microbial shrinkage cracks from locality Hatsamas. References to Figs. 6a, c and 7 mean that details indicated by arrows are shown in these figures. (a) Upper bedding surface of fine-grained quartzite, exhibiting smoothed ripple morphology and carrying incomplete networks of sinuous and sub-circular cracks preferentially developed in ripple troughs. Scale (hammer) is *ca.* 30 cm. Locality: Koedoeberg mountain, farm Hatsamas 92. (b) Upper bedding surface with incomplete networks of sub-circular cracks, partly forming loops. Scale is *ca.* 5 cm. Locality: Koedoeberg mountain, farm Hatsamas. (c) Upper bedding surface with sinuously curved, interfering, cracks and sub-circular to 8-shaped marks. Incomplete networks of curved cracks are related to ripple troughs. Scale is *ca.* 5 cm. Locality: Koedoeberg mountain, farm Hatsamas 92. (d) Initial triple junction from which cracks propagate. Note single (arrow 1) or double (arrow 2) longitudinal depression on crack infillings. Lower bedding surface of fine-grained quartzite. Locality: Koedoeberg mountain, farm Hatsamas.
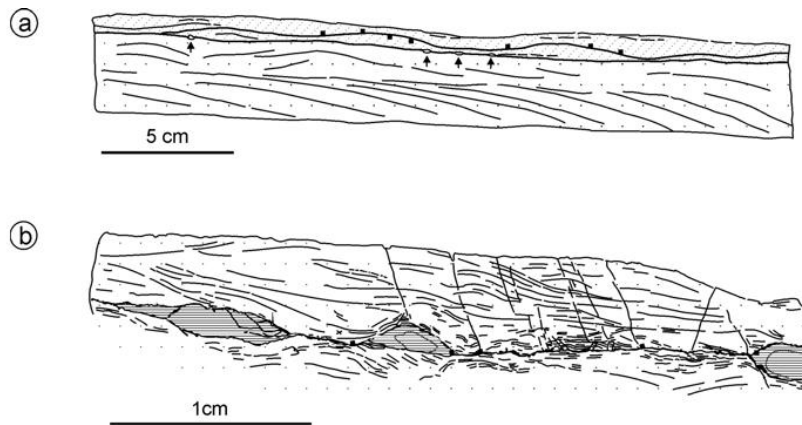
Figure 4: Drawings from polished section (a) and thin section (b), both perpendicular to bedding, showing simplified internal fabric of fine-grained quartzite layers above and below horizon containing crack infillings. Arrows in (a) indicate positions of crack infillings; black cubes are pseudomorphs after pyrite. In (b), crack infillings are marked by hatching. Irregular (heavy) black line indicates Fe-oxide horizon developed at interface of lower and upper bed and enveloping crack infillings. Dotted line in crack infillings indicates limit of Fe-oxide infiltration. Note steeply dipping microfaults in upper bed, terminating at lower bedding surface.

bifurcation of the bodies by splitting along the median depression has been observed (see Fig. 6a). This seems to indicate that the bodies are basically composite symmetric entities, laterally attached to some adjoining material and less resistant or possibly widening and infilled in the centre. Similar structures may develop in subaerial desiccation cracks when, during progressive desiccation, filled cracks re-open and second generation cracks start propagating from them.

The earliest elements to develop are triple junctions, crescent-shaped to sigmoidal bodies and, possibly, sub-circular ring structures (Figs. 5a-c). Structures with blind tapering ends may remain single and isolated from a network. Usually, however, more evolved structures (Figs. 5d-f) and eventually networks (Fig. 5g) developed when the ends of initial structures propagated and subsequently interfered and joined up with simultaneously propagating structures starting from other nucleation points. Figures 6a and b show examples of interfering branches that have propagated towards each other from triple junctions in ripple troughs. Due to different starting points (e.g. A and B on Fig. 6a) and, possibly, rates of propagation, prograding branches inevitably meet existing ones. This appears to happen usually after 4-6 cm of propagation and the resulting junction generally is at a near 90o angle due to the curved courses of both the interfering branches. As a result, more or less regular and complete chains of elliptic rings, 2-4 cm in diameter, develop. They tend to spread along ripple troughs, with right angle and triple junctions in the trough centre and curvature of individual segments increasing towards the margins. The growth pattern of the networks appears thus to be controlled by ripple morphology, however, in a subtle manner as the ripples are very flat and smooth.

Overlap of bodies without mutually affecting the other's form, as described from the Huronian by Frarey and McLaren (1963), has not unequivocally been observed. However, 90° junctions situated oppositely

at the two sides of a branch are not unusual and may simulate overlap (see Figs. 6 a and b).

A rather complex structure involving propagation, strong curving, triple junctions and 90° junctions of branches, differing in relative age, is presented on Figure 6c (see also Fig. 3b). It shows, on an upper bedding surface, the imprints of bodies curved into closed sub-circular loops and linking up with others to form a network. Circular to elliptic rings, constantly 2 ± 0.5 cm in diameter, may occur independant of or attached to a network (Fig. 7; drawn from Fig. 3a). Occasionally, two rings occur in conjunction to form 8-shaped marks (Barnes and Smith, 1964; Plummer and Gostin, 1981) (Fig. 5e). In some rings, branch-offs start from the outer margin and terminate again after 2-3 cm (Fig. 7), whereas other branch-offs may develop into or join up with a network. It thus appears possible that some of the networks may have started from ring structures. Circular features dominate by far relative to straight el-
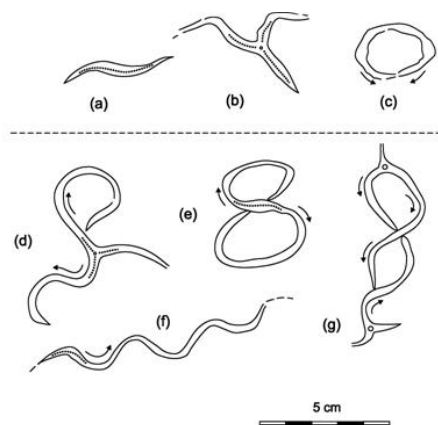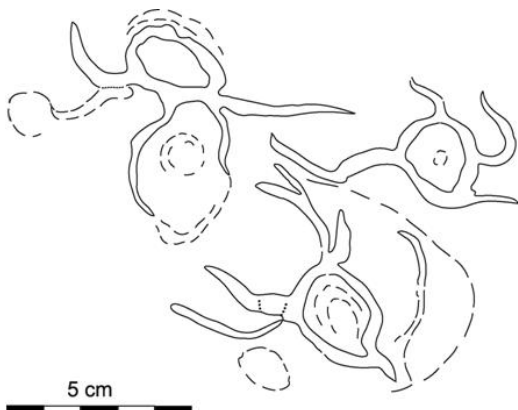

Figure 5: (a) Development of curved crack systems from (a) initial sigmoidal cracks, (b) triple junctions, (c) possible circular cracks. Crack propagation from initial structures may lead to loops (d), 8-shaped marks or double-loops (e), long sinusoidal cracks (f) and chains of elliptic cracks (g). The latter develop when cracks propagating from different triple junctions interfere (d, e and f drawn from Seilacher (1995), his Fig. 2).
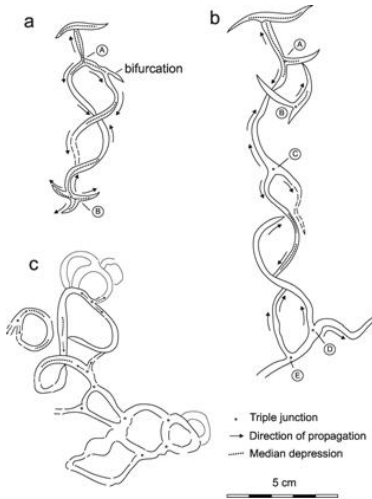
Figure 6: Examples of sub-elliptical (a, b) and sub-circular (c) networks of cracks developed in ripple troughs (a, b) and shallow depressions (c) on smoothed rippled upper bedding surface (a from Fig. 3c, c from Fig. 3b). Development of networks starts at triple junctions from which cracks propagate and interfere, partly at different rates. Encircled letters indicate possible sequences of triple junction formation and subsequent crack propagation; 90° junctions occur where a propagating cracks meets a completed crack. (c) shows crack propagation along preferentially curved traces, producing loops and closed circular structures.

ements. Consequently, the patterns may be described as consisting of chains of sub-circular rings more or less connected by straight elements (Fig. 8).

In some of the ring structures, a faint pattern of more or less regular concentric rings is preserved (Fig. 7). Very vague circular to ovoid rings, 1-3 cm in diameter, forming faint shallow impressions in upper bedding surfaces are also observed close to or independant of ring stuctures. They are only recognizeable at low-angle illumination and resemble impressions of microbial mats described from the Neoproterozoic Belt Supergroup by Horodyski (1993). This feature, although recognize-
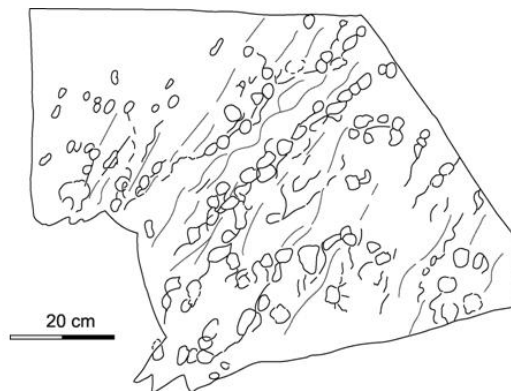
able on some of the published examples (Plummer and Gostin, 1981; Frarey and McLaren, 1963), has not been described yet.

On the base of the layer that overlies the structures, a system of parallel, thin and nearly straight linears is recognized at low-angle illumination. The linears cut across the ripple morphology at a high angle and are quite distinct from the faint cleavage crenulation of tectono-metamorphic origin which has a different orientation. A section perpendicular to the bedding surface (Fig. 4b) reveals that the linears are intersections of small-scale faults with the bedding surface. The faults are invariably restricted to the layer above the structures and terminate at the base of the layer. They may be classified as early diagenetic microfaults accommodating differential compaction of the upper layer.

Discussion

The frequent occurrence of triple junctions and branches with blind tapering ends, crescent-shaped to sigmoidal bodies as well as evidence of propagation and interference of propagating branches strongly indicate that the curved structures observed at Hatsamas are cracks that have been filled by the same siliciclastic material making up the beds below and above. Development from initial crack structure is schematically summarized in Figure 5. Yet, there are some aspects that do not fully agree with a desiccation crack origin (see also Frarey and McLaren, 1963): (1) the complete absence of an argillaceous layer on the bedding plane; (2) the easy separability of the bodies from both overlying and underlying beds, leaving impressions in each bedding surface; (3) the constancy of maximum width of most of the bodies, irrespective of their position relative to ripple morphology; (4) the overall strong tendency to curving and development of circular to sub-circular structures of approximately constant diameters, and (5) the possibly initial development of ring structures.

Frarey and McLaren (1963, p. 462) dismissed a des-

Figure 7: Isolated circular cracks with radial branch-offs propagating along curved courses and forming incomplete networks. Faint concentric rings inside circular cracks may originate from compacted domal (stromatolitic) buildups (from Fig. 3a).

Figure 8: Photo interpretation, focussed on circular structures, of the upper bedding surface shown in Fig. 3a. Dotted lines are ripple crests. The interpretation reveals that sub-circular structures are the dominating features of the networks of cracks developed at Koedoeberg mountain, farm Hatsamas 92.

iccation crack origin of the bodies. They furthermore excluded the possibilities of the bodies being "feeding burrows" or "worm casts" because of their separation from the beds below and above and the occurrence of branch-offs. Instead, due to the fact that the bodies are easily separated from both upper and lower bedding surfaces, they concluded that they are "fossil relics of tapering branching tubes deposited in ripple troughs". Although it is true that the bodies are separated from both upper and lower bedding surface and thus related to some process acting in the interval between deposition of the beds below and above, we dispute that they have undergone transport and subsequent deposition. The perfect preservation of subtle details such as acute ends and 90o junctions of the bodies as well as the lack of disturbance (except compaction) of the networks indicate rather that the structures are still in place.

Curved segments and occasional sub-circular structures are not uncommon in desiccation or shrinkage crack systems (e.g. Picard, 1966) and are often associated with the outer limits ("pond edges") of dessicating mudrocks. It is, however, unusual that such structure dominate as is the case at Hatsamas. Nevertheless, dominantly curved cracks may form a geometric end member of a series of possible configurations (Glaessner, 1969).

The strongest argument against a desiccation crack origin of the structures, is the absence of an argillaceous layer in which the cracks were opened. Glaessner (1969, p. 371) argued that "clay which was present on bedding planes may be reduced to insignificant thickness by compaction and totally lost by weathering". However, careful examination of fresh samples has shown that this is not applicable to the Hatsamas locality. Nevertheless assuming that clay was indeed present in the ripple troughs, where most of the structures occur, the layer should have had a double-wedged form, being thickest in the trough's centre and attenuating towards the margins. Taking into account, however, that the maximum width of the bodies is constant, irrespective of their position in a ripple trough, the layer should have been of nearly constant thickness.

Despite the strong argument of a missing argillaceous layer, evidence in favour of an origin of the structures by cracking is overwhelming. This apparent contradiction demands an explanation of what has cracked and subsequently disappeared. The microfaults developed in the layer above the structures, but absent from the layer below (Fig. 4b), seem to indicate some kind of unusual compaction restricted to the layer above. They are considered as evidence for the early diagenetic break-down of some material, originally existent below the faulted bed.

The independance of the structures from both overlying and underlying bed exclude intrastratal cracking and infilling from below or above. Additionally, the non-cohesive nature of the fine-grained siliciclastic sediment will not have permitted cracking of the sur-

face upon aerial exposure and infilling of the cracks during subsequent flooding. Eolian infilling may also be excluded because there is neither a trace of eolian erosion nor deposition recognizeable on the bedding plane (e.g. a "sand-drift surface" with medium-grained sand layer and crack infillings of the same grain size). On the contrary, the bedding surface is smooth and gently undulating as if it were covered by a sheltering sheet. We suggest that the bedding surface was covered by a microbial mat that underwent shrinkage and cracking during dewatering and support our suggestion on the following lines:

(1) The smooth relief of the bedding surface indicates that wave action, which presumably was slight to modest in the shallow marine or marginal lacustrine environment at Hatsamas, did not affect and modify the sediment surface to form the usual crested ripple marks. Sediment stabilization and surface levelling are well known effects of microbial colonization on sediment surfaces in siliciclastic environments (e.g. Noffke *et al.*, 1997; Noffke, 1999). "Biostabilization" (Krumbein *et al.*, 1994) as a result of colonization of the pore spaces by microbes (particularly cyanobacteria) increases the critical current velocity at which a sand grain of *ca.* 0.2 mm size is removed from the sediment surface by at least nine times (Führböter and Manzenrieder, 1987). As a complementary process, trapping and incorporation of sand grains in the upwardly growing mat will lead to progressive levelling and smoothing of the inherited and stabilized morphology (Noffke, 1999; Noffke and Krumbein, 1999).

(2) At Hatsamas, deposition in a non-reducing environment is indicated by the exposed succession of light coloured, fine-grained subarkoses and siltstones with intercalations of coarser grained reddish quartzite. The horizon at which the cracks occur is made up of 0.5 - 1 cm thick, light grey siltsone beds separated by thin and partly "patchy" Fe-oxide layers. Pseudomorphs after pyrite occur on the adjoining bedding surfaces, thus suggesting locally or temporarily prevailing reducing conditions in the sediment. The potential for iron sulfide and pyrite formation through hydrogen sulfide, produced during decay of organic matter in an anaerobic microenvironment below a redox-discontinuity layer has been described from modern microbial mats colonizing siliciclastic substrata, e.g. from the tidal flats of the southern North Sea (Gerdes *et al.*, 1982; Gerdes and Krumbein, 1987; Noffke *et al.*, 1997) and salterns in Yugoslavia (Schneider and Herrmann, 1980). Formation of pyrite related to Neoproterozoic microbial mats has been described by Pflüger and Gresse (1996). We interpret the occurrence of pyrite in an oth-

erwise non-reducing depositional environment as related to microbial activity and organic decay. In addition, it has been shown that carbonate, in small quantities, is precipitated in the oxidic upper layer of a mat through extraction of CO_2 from the overlying water, whereas it is produced in much larger quantities below the redox discontinuity by bacteriological processes (Gerdes *et al.*, 1982). This is in accordance with the observed co-occurrence of pyrite and probably ferroan carbonate at Hatsamas.

(3) The origin of the Fe-oxide horizon separating the beds and surrounding and infiltrating the crack fillings is not certain. It may be deposited from fluids that circulated during metamorphism or it may be related to weathering. Certainly, it is secondary in its present distribution since it fills cracks and forms irregular patches on the bedding surfaces and in the beds. Yet it cannot be excluded that it is partly derived from former pyrite or from primary Fe_3O_2aq, enriched above the redox discontinuity in a microbial mat.

(4) The tendency of the cracks to propagate along curved paths and the predominant development of sub-circular structures in the networks contrasts with "normal" polygonal crack patterns developed in desiccated argillaceous layers, but may be appropriate for shrinking microbial mats. Descriptive nomenclatures of microbial mat forms include terms like pustular, knoll and cuspate, blistered and crinkled, while growth forms are described as nodular, domal, biohermal and stromatolitic (Till, 1978). These terms indicate that there is a high potential for sub-spherical and, in plan view, sub-circular structures to form in microbial mats during growth and possibly as well in destructive situations. The occasionally recognizeable faint sub-circular and partly concentric patterns preserved in some ring structures at Hatsamas (Fig. 7) may trace compacted small domal build-ups, 1 - 2 cm in diameter, initially developed in the presumed microbial mat. A comparable example of stromatolites of this type has been described from quartzites of the Belt Supergroup by Garlick (1988). Faint sub-circular patterns have also been described and interpreted as impressions of microbial mats by Horodyski (1993). These are comparable to similar structures observed between the ripple troughs and adjoining the networks.

Concluding thus that a microbial mat had once colonized the sediment surface at Hatsamas, how did the cracks form and why are they preferentially located in ripple troughs?

Modern microbial mats develop at very shallow depth, sometimes not more than 2 - 5 mm below the water surface (Gerdes and Krumbein, 1987). On the sil-

iciclastic tidal flats of the southern North Sea, microbial mats grow in the intertidal to lower supratidal zones at depths from 0.5 - 40 cm below the water surface (Noffke *et al.*, 1997). The mats of the lower supratidal zone are reported to be "inundated by seawater 0.5 - 5 cm deep during high spring tides" (Noffke, 1998). The shallow depth at which mats grow involves repeated subaerial exposure, sometimes over longer periods. The mats usually survive shorter periods of subaerial exposure, but with more advanced or complete desiccation, a polygonal network of wide shrinkage cracks, sometimes with small-scale sub-fracturing of the polygons (Gerdes *et al.*, 1993; 2000) and uparched crack margins develops and the microbial mat may be destroyed. Environment-dependant frequency and duration of alternating exposure and flooding/wetting are reported to be the major controlling factors for mat morphology (Kinsman and Park, 1976).

On aerial exposure, moisture stored in the extracellular polymeric substances (EPS) below the uppermost living mat layer drains away or evaporates and is partly replaced by water drawn up from the sediments below by capillary action (Gerdes and Krumbein, 1987). It is envisaged that prolonged exposure would lead to unreplaced loss of moisture in the EPS and concomitant shrinkage of the organic slime. At a critical stage, EPS shrinkage would force the overlying mat layer to crack, beginning with few single fissures and, at certain points, triple junctions from which cracks start propagating with progressive shrinkage. The process, if not fully completed, would partly be reversible with renewed wetting or flooding and recovery of the EPS and would then not be traceable, the more so if the mat continues growing. There are, however, two exceptions allowing preservation of traces of the process: (1) the cracks are immediately filled by sediment transported at flooding; and (2) the microbial mat grows around the crack margins thus preventing healing of the cracks (Gerdes *et al.*, 1993) which are subsequently filled by sediment. In both cases the crack fillings will be preserved, while the microbial mat is destroyed at burial.

We envisage that the structures at Hatsamas are filled cracks that developed in a microbial mat, undergoing shrinkage of the EPS and progressive cracking of the surface layer during subaerial exposure. The cracks would have been filled with subsequent flooding of the mat. The easy separability of the crack fillings from the overlying bed indicates that the filled cracks were overgrown by the recovered mat before deposition of that layer. The structures are thought to preserve a critical stage of advanced desiccation at which cracks were starting to form. Since microbial activity and shrinkage are involved in the development of the cracks, we suggest naming these structures "microbial shrinkage cracks".

At Hatsamas, confinement of the cracks to ripple troughs is by no means ubiquitous since the rippled bedding surface has been extensively levelled. However,

examples illustrated in the literature show that cracks may almost entirely be restricted to troughs if a well developed ripple morphology is preserved (e.g. Stauber, 1942; Frarey and McLaren, 1963; Plummer and Gostin, 1981). Noffke *et al.* (1997) observed that ripple troughs and lee faces of ripples on tidal flats of the southern North Sea, are the first sites to be colonized by biofilms and mats. Noffke and Krumbein (1999) concluded: "Differences in the sedimentary surface relief induce distinct ecological responses by bacteria: deeper parts of the surface morphology, e.g. ripple mark valleys, are localities of higher biomass production, as ecological conditions (e.g. humidity) at these protected sites are more favourable compared with more exposed sites".

Conditions favouring such selective colonization occur in the lower supratidal and upper intertidal zones in a lower hydrodynamical regime (Noffke and Krumbein, 1999). In general, the growing mat will either encroach on the ripples and extend laterally or be buried by sediment. However, the selectively colonized and biostabilized surface may also undergo subaerial exposure, followed by partial dewatering, shrinkage, cracking, renewed flooding/wetting and continued microbial mat growth. This sequence of events may then lead to infilled cracks, preferentially developed and preserved in ripple troughs. Biostabilization affords preservation of the more exposed ripple crests.

Similar structures could develop, without prerequisite shrinkage and cracking, on mats of small-scale stromatolitic type and would represent accumulations of clastic grains deposited between individual domal to columnar buildups. It may even be envisaged that both mat morphology and dewatering shrinkage cooperate in the development of the networks.

The same type of structure has been described as "spiral cracks" or "Manchuriophycus" type cracks (Pflüger, 1999) and "Manchuriophycus and other forms of syneresis cracks and pull-apart cracks" (Gehling, 1999). Pflüger (1999) suggests that the cracks were produced when biostabilized, cohesive sand shrunk and cracked after burial, whereas Gehling (1999, p. 54) considers the cracks as "likely to be products of post-depositional shrinkage in buried cyano-bacterial gels and mat-bound sediment". Both authors thus relate the cracks to microbial activity but suggest their origin and filling to be post-burial and intrastratal from the layers below or above. We exclude a post-burial intrastratal origin for the Hatsamas cracks because the fills are clearly independant from both the beds below and above.

Environmental implications

A low hydrodynamic regime with sufficient light would support colonization of the sediment surface and microbial growth. Peritidal, lagoonal and lacustrine environments most effectively meet these conditions. If occasional aerial exposure and rewetting of the mats is additionally required, possible environments are reduced to lower supratidal/upper intertidal and marginal lacustrine positions.

Presuming that the structures have formed on microbial mats that underwent shrinkage and incipient cracking during prolonged subaerial exposure, they may well be used as indicators of a supra- to intertidal marine environment or a marginal lacustrine facies. The latter environment does not typically undergo regular and short-termed changes of the water table but is rather controlled by seasonal events of flooding, evaporation and gradual exposure of the marginal sediment surfaces. Short-term changes in flooding and exposure, as required for the model suggested here, are more likely in a marine tidal environment.

The small-scale sedimentary structures, in particular hummocky stratification, observed near the crack level at Hatsamas, make up a facies architecture typical of a fluctuating shore face to beach zone. This includes sub- to intertidal, temporarily supra-tidal, and low wave-energy conditions and indicates a marginal marine environment (e.g. McCubbin, 1982). It has thus to be considered that marginal marine conditions may episodically have prevailed in the southern Nosib rift as far northeast as Hatsamas.

Conclusions

A specific type of genetically and morphologically "exotic" crack, known from Proterozoic and Phanerozoic sedimentary rocks all over the world but not observed under actualistic conditions, is characterized by dominantly sinuous and sub-circular forms. These must have developed under specific facies and preservation parameters.

An excellent example of this crack type, exhibiting morphological details, is exposed in siliciclastic rocks of the Nosib Group of Central Namibia (Hatsamas area). The structures are preferentially developed in shallow depressions of cm scale, rippled bedding surfaces of fine-grained psammites. The original shallow-water, wave ripple morphology was smoothened before burial.

The cracks are preserved in different ontogenetic stages, beginning with triple junctions, single spindle-like and sigmoidal forms and, probably, circular cracks. More evolved patterns, developed from these initial forms by crack propagation, include sinuous structures, 8-shaped marks, sub-circular loops and chains of ellitical rings. The latter result from interference of sinuous cracks progating in ripple troughs. More or less complete networks of dominantly sub-circular elements represent the evolutionary end member.

A main characteristic of the Hatsamas crack type is the easy separability and independance of the siliciclastic infill material from lower and upper bedding planes. A further characteristic is the absence of any shrinkable material (e.g. mud drape) from the crack-carrying bedding surfaces, whereas relics of organically induced

iron sulfides and carbonates are characteristically concentrated on the bedding interface carrying the cracks.

It is suggested that the Hatsamas crack type is genetically related to microbial activities on siliciclastic sediment surfaces, beginning with microbial surface stabilization and successive development of a microbial mat. Dewatering and shrinkage of the mat during aerial exposure, progressive cracking of the mat surface, infilling of the cracks and reactivation of mat growth with renewed flooding, and final aquatic burial under the next sheet of sand are the main processes to produce and preserve the cracks and their siliciclastic fill. A mud drape may or may not have been present on the sediment surface. A favourable environment to produce this type of crack is a shallow marine tidal flat.

If the model is correct, the Hatsamas crack type is evidence for the presence of an organic substrate that must have been of some importance for depositional processes but could not be fossilized itself. It is proposed to name the Hatsamas crack type "microbial shrinkage cracks" due to their close genetic relation to microbial mats.

Acknowledgements

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