



Initiation and growth of cracks during desiccation of stratified muddy sediments

Ram Weinberger

Geological Survey of Israel, 30 Malkhe Israel Street, Jerusalem 95501, Israel

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Abstract

Persistent desiccation and contraction of muddy sediments gives rise to mud cracks. These cracks form networks of interconnected tension fractures arranged in remarkable polygonal patterns. Because tensile stress due to drying declines downwards through the sediment, mud cracks have generally been theorized to nucleate near the surface, propagate downwards, and terminate at depth. Here I trace the nucleation and growth path of natural mud cracks by analyzing in detail crack-surface morphology. The present observations show that systematic nucleation at the bottom of the polygons and upward propagation of mud cracks are much more prevalent than previously postulated. The cracks predominantly rupture the desiccated layers before they significantly extend laterally and sequentially form the polygonal patterns. The consistent location of crack origins at depth, along the bottom of the polygons, strongly suggests that stress concentration at flaw discontinuities and layer boundaries play a fundamental role during mud fracturing. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Cracking of muddy sediments during loss of moisture is an ubiquitous phenomenon that is commonly observed on drying puddles, river-flood plains, and lake margins during droughts. The arising cracks, known as ‘mud cracks’ or ‘desiccation cracks’, form arrays of tension fractures that divide the sediment into thin prismatic columns. In plan view, mud cracks form spectacular polygonal patterns (Fig. 1), which have been extensively described in the geological literature (e.g. Pettijohn, 1957; Neal et al., 1968; Baldwin, 1974; Leeder, 1982; Selley, 1982; Allen, 1985; Astin and Rogers, 1991). Mud cracks have generally been envisioned as downward propagating cracks that nucleate at the surface and terminate at depth (Neal et al., 1968; Selley, 1982; Allen, 1985), because the rate of moisture loss and capillary forces declines downwards through the layers as do the tensile stresses. In this scenario, a newly formed crack presumably nucleates on a defect at the surface of the sediment where the

tensile stress is maximal; subsequently, it propagates downwards to the level in which the horizontal stress acting within the sediments becomes compressive, as a result of the weight of the overlying sediments (Allen, 1985). The downward-tapering shape of the mud cracks apparently further supports this view (Selley, 1982). Indeed, surface defects such as bird’s footprints (Allen, 1985), gastropod trails (Baldwin, 1974), worm tracks (Soleilhavoup and Bertouille, 1976), and air bubbles (Corte and Higashi, 1960) are all associated with near-surface initiation and downward growth of mud cracks. However, cracking of muddy sediments occurs even in the absence of such peculiar defects, suggesting that the mud fracturing mechanism may be more complex.

The rupture through the thickness of the muddy sediment represents the vertical components of crack propagation. The dominant lateral components of crack propagation give rise to the polygonal crack pattern. With progressive desiccation, successive generations of mud cracks appear. In plan view, these cracks typically intersect at right angles forming T-junctions (Fig. 1). This pattern forms because the first crack mostly releases the normal stress in its vicinity; a

E-mail address: rami@earth.es.huji.ac.il (R. Weinberger)



Fig. 1. Mud cracks forming in a muddy sediment at the foot of Massada, Dead Sea region, Israel. Square shows a T-junction. Geological hammer indicated by an arrow provides a scale.

second crack tends to approach the first crack orthogonally, because it propagates perpendicular to the local maximum tensile stress (Lachenbruch, 1962). Similar crack patterns appear during drying in other substances such as plaster, coffee–water mixture (Groisman and Kaplan, 1994) and starch–water mixture (Müller, 1998) as well as during thermal contraction in substances such as basalt flows (Aydin and DeGraff, 1988) and permafrost (Lachenbruch, 1962). Polygonal patterns are found on a wide variety of scales ranging from a fraction of a millimetre in some polymerized substances to several hundreds of metres in fault systems in mudrocks (Lonergan et al., 1998), playas (Neal et al., 1968) and permafrost (Lachenbruch, 1962). While mechanical properties and chemistry of these substances are quite different from those of mud, it is tempting to generalize the mechanism that accounts for the evolution of the crack patterns in all of these substances (Groisman and Kaplan, 1994; Müller, 1998).

Laboratory experiments on cracking in drying mud (Corte and Higashi, 1960) and coffee–water mixtures (Groisman and Kaplan, 1994) successfully show the relation between the scale of crack patterns and the thickness of the desiccated substance. Corte and Higashi (1960) further show that crack pattern strongly depends on the thickness of the mud and on the bottom material. These experiments were carried out with single desiccated layers of uniform grain-size distribution and generally did not account for layering and stratification of the desiccating substance. In

nature, however, muddy sediments are typically stratified, forming sets of mud layers in which the grain size usually increases with depth. The objective of this study is to elucidate the nucleation and three-dimensional growth of mud cracks in naturally desiccating mud. The study focuses on the kinematics of cracks at depth and their relation to observed patterns in plan view. It shows that nucleation at depth and upward propagation of mud cracks can be a common mechanism of mud fracturing, and discusses the significance of these observations to our understanding of the mechanics of crack growth during desiccation.

2. Method of study

In this study I take advantage of the well developed surface morphology of natural mud cracks, which record uniquely the kinematic history of fracture nucleation and growth. This morphology, known as a plumose structure, consists of a crack origin and faint ridges or ‘hackles’ that radiate from the origin and fan away from the plume axis toward the peripheries of the crack planes (Bankwitz, 1965, 1966; Bahat, 1991) (Fig. 2). Plumose structures have been used as a powerful field tool for studying fracture characteristics of rocks (Bankwitz, 1965, 1966; Kulander et al., 1979; DeGraff and Aydin, 1988), and were utilized in this study to examine the following features of the mud cracks: (a) the crack origin location and propagation direction; (b) the shape of the crack front at frequent

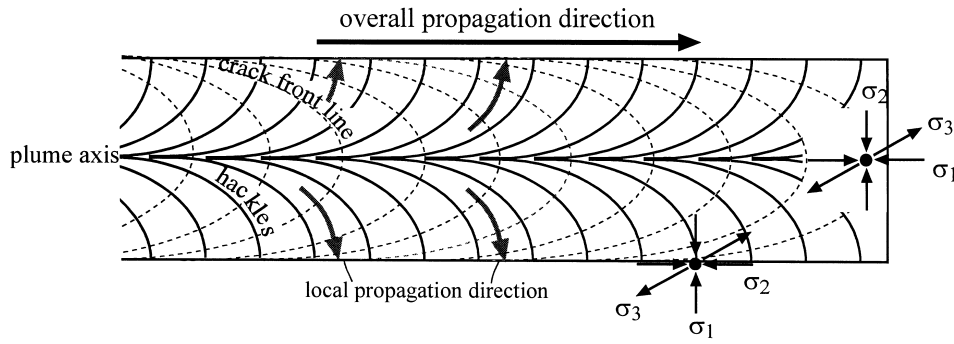


Fig. 2. Symmetric plumose structure illustrating the use of hackles to interpret local propagation directions (grey solid arrows), overall propagation direction (solid black arrow), past crack fronts (broken lines), and fracture stress distributions. The plane containing the plumose structure is perpendicular to the least compressive principal stress (σ_3) and contains the greatest and intermediate compressive principal stress (σ_1 and σ_2 , respectively). σ_3 is tensile, σ_1 can be compressive and is parallel to the plume axis, and σ_2 can be also compressive and is perpendicular to the plume axis. Crack origin is located to the left of the illustration.

times during the crack growth; and (c) the relative fracture stress distributions throughout the fractured layers at the time of failure. The crack origin may be an inhomogeneity, such as a void or grain, and is usually marked by a fine hole or dimple on the crack surface. Hackles fan away from the plume axis in the overall direction of crack propagation. The local propagation direction of the crack is represented by the orientation of the hackles. For a symmetric plumose structure on a crack surface and an axis parallel to the crack periphery, the local propagation direction changes from being parallel to the periphery at the

centre, to being oblique or nearly perpendicular to the periphery away from the centre (Fig. 2). The shape of the crack front is inferred by drawing curves normal to the hackles, which define past positions of the crack front (Kulander et al., 1979; DeGraff and Aydin, 1988). The plume axis and hackles also allow us to infer the directions of the principal effective stresses (Fig. 2).

The fracture characteristics of mud cracks were studied in dehydrating mud puddles in the Dead Sea region, Israel. The mud consists mainly of carbonate and clay particles typically displaying fining upward

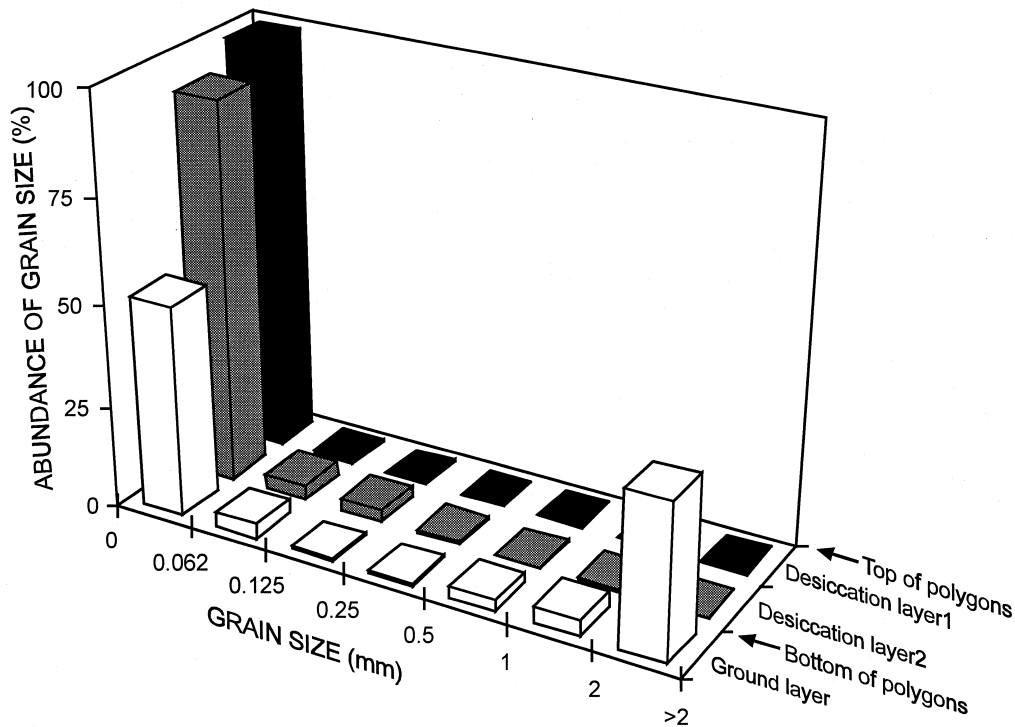


Fig. 3. Grain-size distribution in the studied sediment displaying fining upward (sorting effect) and stratification. This distribution was obtained by gently disintegrating the grain aggregates of each layer and sieving the grains through screens of decreasing mesh size.

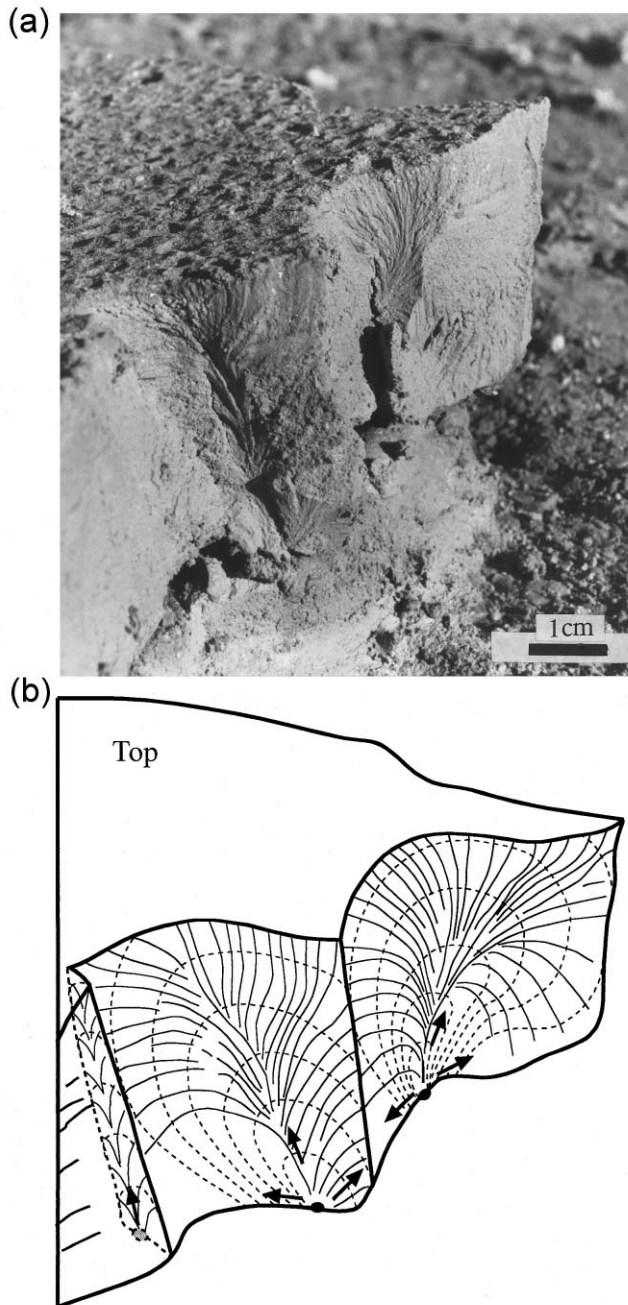


Fig. 4. Oblique view of two adjacent mud cracks (a) and their surface-morphology interpretation (b). Crack origins (solid dots) are located at the bottom of the polygon. Crack morphology shows no relation to layering (Type 1 plumose structure). En-échelon twist hackles at the vertical peripheries of the crack are associated with curved paths in plan view. Solid thick lines are hackles; broken thin lines are past position of crack fronts; solid thin lines are hackles of an out-of-sight orthogonal crack. Arrows show local propagation directions.

(Fig. 3). There is a distinct surface discontinuity between the upper desiccated layers (that tend to contract and crack) and the uncracked lower ones. This surface is hereafter referred to as the bottom of the

polygons. Mud cracks with delicate plumose structures formed several days after a rainstorm and ceased to propagate a few days to weeks after initiation. Several polygons of convenient size and weight (mostly containing a pair of desiccated layers) were then systematically lifted out of the dried puddles and their walls examined under optimal oblique illumination. In this way, the surface morphology of hundreds of mud cracks were studied in precise detail.

3. Surface morphology of mud cracks

3.1. Crack origins

In the absence of surface defects such as animal footprints, roots, and large raindrops, crack origins are consistently located at or near the bottom of the polygons (Figs. 4–6). The origins are commonly marked by a very small dimple or a fine hole on the crack surface, and occasionally are associated with relatively coarse grains. Cracks rarely originate elsewhere along the desiccated layers or along other crack surfaces, and are seldom located along the boundary between these layers. To get a general view of the distribution of crack-origin points, I studied all single cracks that were nucleated in an area of about 8 m². This area contains 68 polygons that were formed by 156 single cracks, 144 of which originated along the bottom of the polygons. The consistent location of origins at depth indicates that cracks predominantly propagate upward.

3.2. Crack propagation directions

During desiccation, cracks initiated at the bottom and propagated vertically upward toward the free surface and laterally outward toward adjacent cracks (Figs. 4b and 5b). The crack walls show two main types of surface morphology. The first type (Type 1, Fig. 4) comprises a quasi-symmetric plumose structure about a vertical to subvertical plume axis. This structure cuts through both desiccated layers and is not affected by layering. The second type (Type 2, Fig. 5) is an asymmetric plumose structure about a curved plume axis. The axis is vertically oriented perpendicular to bedding near the bottom, then gradually curves close to the boundary between the desiccated layers, and may align itself with the boundary between these layers. In some cases, a single vertical plume axis branches into two or more separate subhorizontal axes along which cracks propagate in opposite directions (see details in Fig. 5). Both Type 1 and Type 2 plumose structures may develop coarse en-échelon steps or twist hackles at the crack peripheries that accommodate the curvature of crack paths (observed in plan

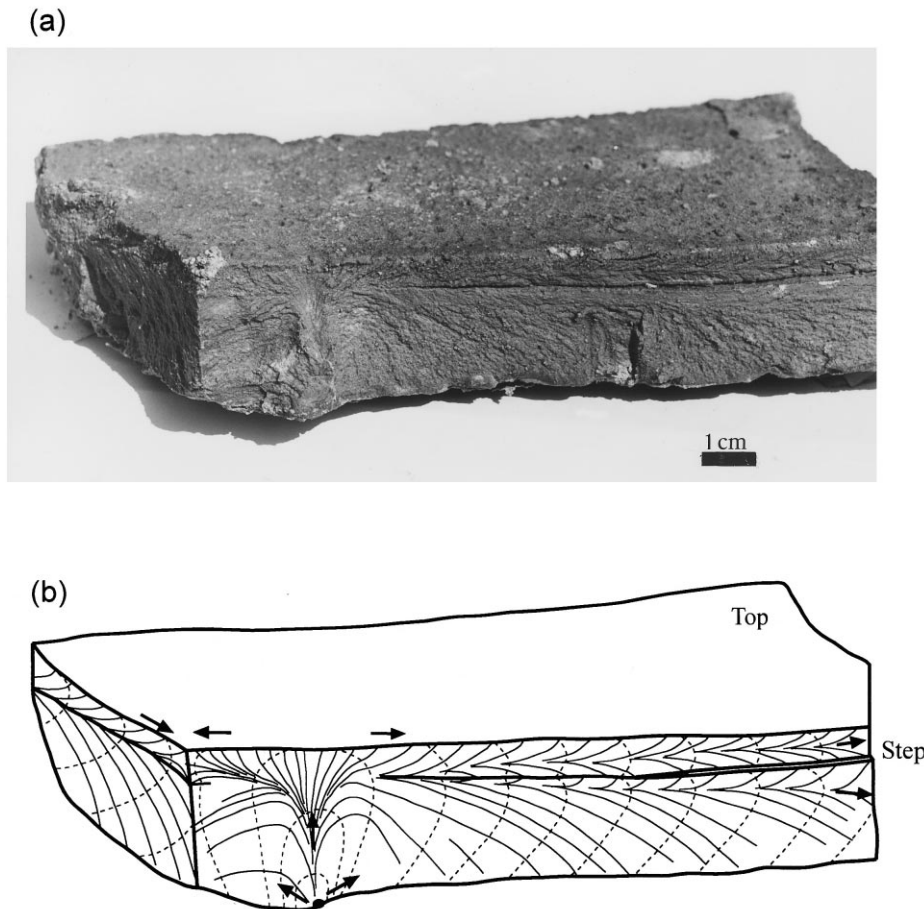


Fig. 5. Oblique view of a recovered polygon (a), and surface-morphology interpretation of an associated bounded crack (b). A single vertical plume axis branches into separate subhorizontal axes (along which cracks are propagated at opposite directions) that are obliquely oriented with respect to bedding. The crack propagated laterally along distinct coplanar fracture surfaces; one fracture with asymmetric plumose structure cuts through the lower layer and the other fracture with quasi-symmetric plumose structure cuts through the upper layer. Fracture surfaces are slightly noncoplanar, forming an offset of a few millimeters and leaving a delicate step along the through-going crack. Solid thick lines are hackles; broken thin lines are past position of crack fronts. Arrows at the top of the polygon and throughout the polygon show overall propagation directions and local propagation directions, respectively.

view). Curved paths are associated with both types of plumose structures and form either during a predominantly vertical propagation (Fig. 4) or during lateral propagation (Fig. 6).

Past positions of the crack front show that initially cracks propagate mainly in a vertical direction toward the free surface, whereas during later stages they propagate laterally. Upon reaching the free surface, propagation proceeds laterally in both directions. Type 1 plumose structure indicates that the crack front radiates away from the origin forming a semielliptical or semicircular crack front, and shortly afterward terminates against other cracks (Fig. 4b). Type 2 plumose structure indicates that, near the crack origin, the vertical periphery of a crack propagates a much greater distance than that of the horizontal periphery, forming a pronounced semielliptical crack front (Fig. 5b). Subsequent lateral propagation is associated with crack segmentation along layer boundaries and the

formation of several semielliptical or semicircular segment fronts.

3.3. Crack termination

The lower and upper vertical terminations of a mud crack are, respectively, an intersection between the crack and the ground, and an intersection between the crack and the free surface. The lateral terminations of a crack occur generally at another crack, forming an intersection between the two cracks. If the lateral propagation occurs along coplanar fracture segments, both segments terminate at the same position against the through-going crack. If the lateral propagation occurs along noncoplanar fracture segments, the intersected segments terminate at a slightly offset position against the through-going crack. Lateral blind terminations are commonly observed where pairs of closely

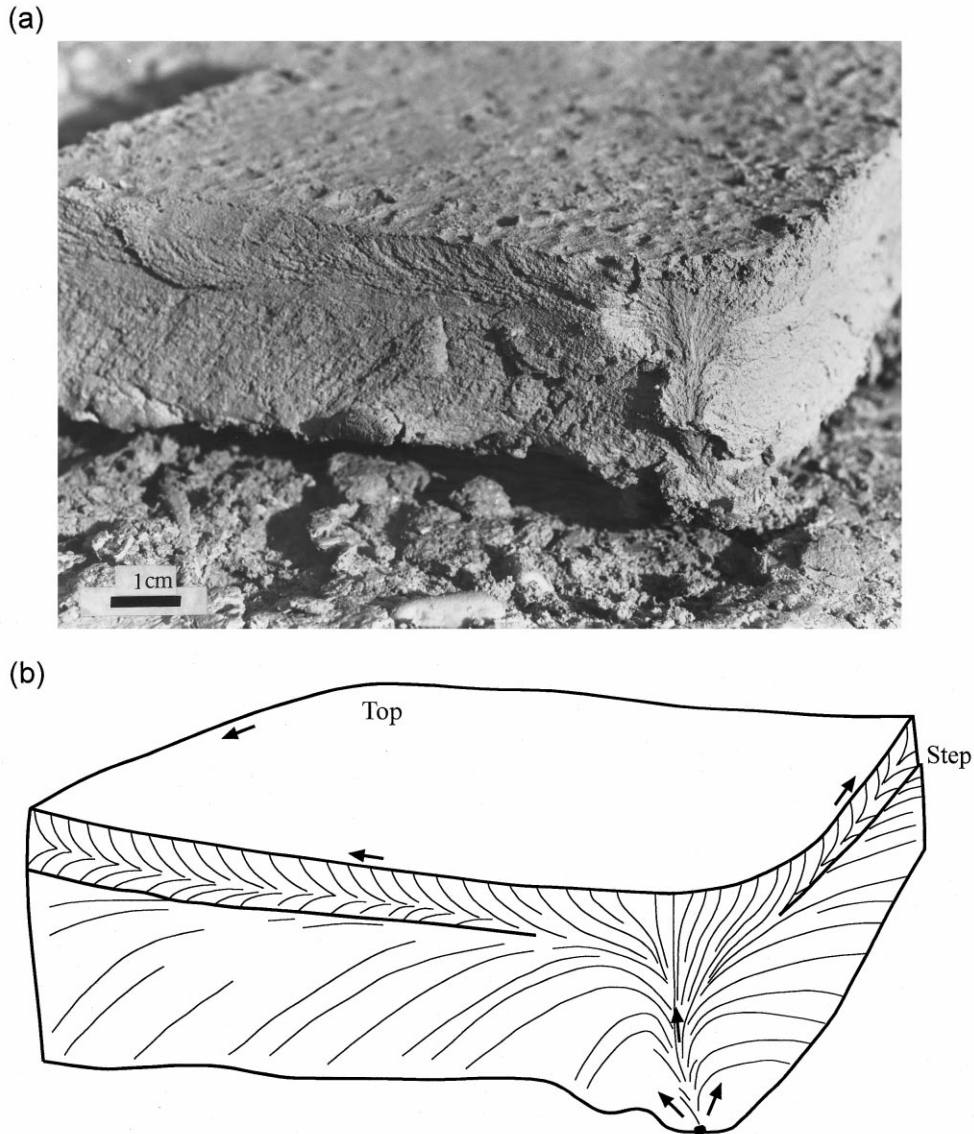


Fig. 6. Oblique view of a polygon (a) and interpretation of surface morphology of an associated mud crack (b). The crack nucleates at depth, ruptures the desiccated layers, and subsequently propagate bi-laterally away from the origin along curved paths (Type 2 plumose structure). Minor damage caused to the polygon wall during recovery (left corner in photograph) is not presented in the surface-morphology interpretation (b). For legend see Fig. 5.

spaced cracks overlap along curved paths (see also Pollard and Aydin, 1988).

4. Discussion

The present field observations systematically show that the examined mud cracks nucleated at or near the bottom of the polygons and propagated vertically upward and laterally outward. We can gain some insight into this mode of fracturing by adopting basic concepts of fracture mechanics of brittle solids (Lawn, 1993), keeping in mind that there are differences between fracturing of mud and fracturing of an ordin-

ary solid. Mud cracks generally initiate at flaws such as grain boundaries, small dimples or holes, and inclusions that perturb the stress field in such a way that the magnitude of local tensile stresses at the flaw exceeds the tensile strength of the sediment. These flaws are likely to be located at depth because favourable stress concentrating flaws (in terms of size and perhaps shape) are more abundant toward the bottom due to the natural sorting of grains (Fig. 3). Moreover, since maximum stresses seem to be concentrated along layer boundaries (Kranz, 1983; Bahat, 1991) these flaws tend to lie along the bottom of the polygons, at the boundary between the cracked layers and the uncracked lower ones. Thus, the consistent location of

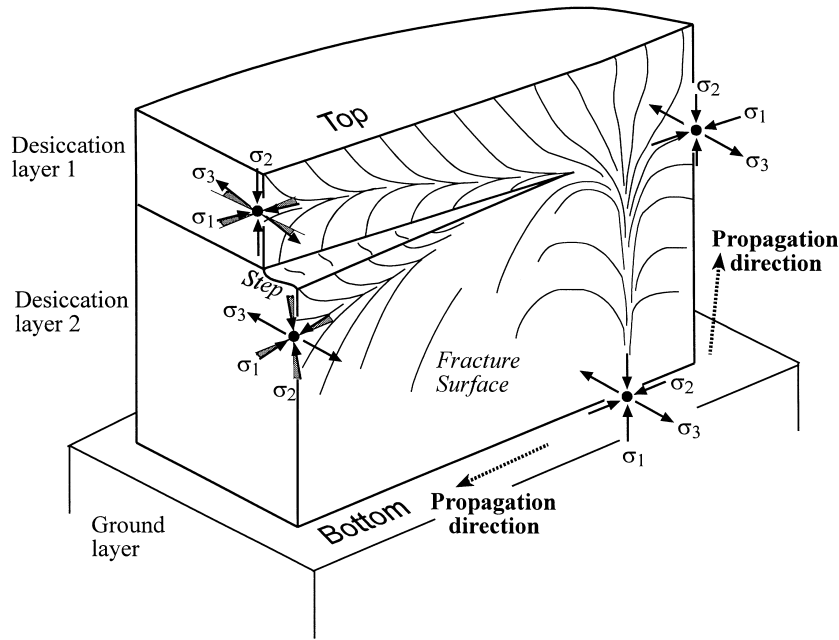


Fig. 7. Schematic illustration of stress distribution throughout a polygon wall. The least compressive principal stress σ_3 is everywhere perpendicular to the crack plane, but the greatest compressive principal stress σ_1 and the intermediate compressive principal stress σ_2 vary in orientation from place to place on that plane. Next to the crack origin, where the crack extends predominantly vertically, σ_1 is vertical and perpendicular to bedding, on account of the weight of the overlying sediment. Away from the crack origin, at the region where the crack extends predominantly laterally, the in-plane horizontal stress due to contraction seems to be more significant than the in-plane vertical stress due to the weight of the sediment, and σ_1 and σ_2 switch directions. Branching and segmentation along layer boundaries are associated with the indicated rotations of the local principal stresses.

crack origins at the bottom of the polygons strongly suggests that stress concentration due to flaw discontinuities and layer boundaries play a fundamental role during mud-crack nucleation (note that layer boundaries also play a fundamental role during joint nucleation in sedimentary rocks; e.g. Bahat and Engelder, 1984; Helgeson and Aydin, 1991). Consequently, I argue that the stress gradient due to drying (possibly related to capillary forces) may be less important for mud-crack nucleation than has been previously postulated.

The strength (or loosely, the adhesive force) along the layer boundary between the desiccated mud and the underlying material may govern the location of the initiation point of mud cracks. If adhesive force is higher than the strength through the mud mass (loosely, the cohesive force), cracking would start anywhere along the mud column but at the bottom. However, if the adhesive force along the layer boundary between the desiccated mud and the underlying material is lower than the strength through the mud mass, then cracking might start at a favourable flaw located along or near the bottom. Laboratory experiments using a uniform mud layer on glass substance indicate that cracking starts at the top or at the centre of the desiccated layer (Corte and Higashi, 1960). This result is in a marked contrast with the present field observations indicating that cracking begins at the bot-

tom of the polygons. Indeed, the adhesive force between the mud and glass is much larger than that between the mud and sand (Corte and Higashi, 1960). In that sense, laboratory experiments utilizing glass as a bottom material may not simulate well the incipient mechanics of mud cracks in nature.

Mud-crack propagation consumes energy in the form of surface energy for the creation of a new crack surface. This energy comes from the release of elastic strain energy within the drying mud. In this mechanism the only mechanical energy available to drive a crack is the elastic strain energy, which must decrease while the surface energy increases during crack growth (Engelder and Fischer, 1996). Adhesive forces along the bottom of the polygons resist the horizontal contraction of the mud. This resistance gives rise to stresses along the bottom and causes the elastic strain energy to be stored. Since crack growth strongly depends on the stored energy, the boundary effect probably plays a key role not only for crack nucleation but also for crack propagation.

Surface morphology of mud cracks unambiguously shows that mud cracks predominantly rupture the desiccated layers before they significantly grow laterally (Fig. 5b). From a mechanical point of view, a mud crack begins to propagate from the origin when the elastic strain energy exceeds a critical value required for propagation. During propagation, the

actual crack path is determined by the principal stress field the crack encounters. As with other joints (Ingraffea, 1987), a mud crack propagates in a direction normal to the direction of maximum principal tensile stress, and by itself modifies the state of stress. Since the high stress concentration next to the origin is relieved upon initiation, it is likely that the free-surface effect and stress gradient due to drying become more significant at this stage of growth. Consequently, the crack propagates vertically upward toward the free surface into the region of greatest tensile stress due to drying. Upon reaching the free surface the stress along the vertical front of the crack is relieved. This facilitates significant growth of the lateral fronts along straight or curved propagation paths. This stage of growth is commonly associated with horizontal segmentation along layer boundaries and branching into several crack fronts (Fig. 5). These fronts generally terminate against through-going cracks as the stresses cannot be further transferred through preceding cracks. Segmentation and branching is probably due to upward changes in the direction of the local principal stresses, facilitated by layer discontinuities. This complex pattern of crack growth is the result of non-uniform stress distribution throughout the desiccated layers as illustrated in Fig. 7.

The results of the present study highlight the importance of flaw discontinuities and layer boundaries in the mechanics of crack growth during desiccation. At this stage, the role of other factors such as the thickness and composition of muddy sediment, and the rate of contraction is not well known. Further field-based detailed studies combined with experimental observations should shed more light on the role played by the mechanism inferred from the present observations.

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