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Polygonal sandcracks: Unique sedimentary desiccation structures in Bahamian ooid grainstone

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ABSTRACT

Sandcracks, which are ubiquitous in Holocene eolian and beach backshore carbonate grainstone on Alligator Point, Cat Island, Bahamas, resemble polygonal mudcracks, but formed in ooid sand without muddy matrix. In experiments on Cat Island beach sand, sediment surfaces cracked polygonally in the absence of mud or biofilms while drying at room temperature due to contraction generated by capillary effects related to surface tension attraction of interstitial water. Gravitational collapse of irregular open pores and repacking of sand grains due to loss of cohesion between particles caused by evaporation of water enhance the cracking process and appearance of polygons by providing space for cracks to expand. The polygons are held together by any remaining capillary moisture and associated meniscus cement, which precipitates as the sand dries. Polygonal sandcracks can be preserved by rapid lithification of carbonate sand, but have been documented only rarely from other localities because their formation requires well-sorted, well-rounded spherical grains rather than those making up the more common, heterogeneous skeletal and peloidal sediment in carbonate settings. Interpretation of this primary sedimentary desiccation structure provides new insights into sedimentation and diagenesis of ooid-rich deposits and can aid in recognizing ancient subaerial exposure horizons.

INTRODUCTION

Polygonal patterns are common in nature and vary greatly in mode of origin, host material, and scale (e.g., Williams and Robinson, 1989; Chan et al., 2008). In this study we focus on submeter-scale polygonal sandcracks from Holocene eolian and beach backshore carbonate grainstone on Alligator Point, Cat Island, Bahamas. The formation of such structures in mud-free sand is not well understood. It is commonly presumed that siliciclastic sand and gravel cannot crack polygonally during desiccation because such sediment lacks the contractive and cohesive properties of mud. Polygonal cracks in terrestrial coarse siliciclastic sediment instead have been explained by thermal contraction and expansion of interstitial evaporites (Kocurek and Hunter, 1986), and by seasonal or diurnal temperature variations producing ice-wedge, sand-wedge, or frost-crack polygons in frozen ground (e.g., Sweet and Soreghan, 2008). In the absence of clay or biofilms, these processes require salt or frozen interstitial water to maintain cohesion within polygons.

Discovery of polygonal patterns on Mars (e.g., McLennan et al., 2005) has drawn attention to the formation of cracks in sand. Although attributed to thermal contraction (Levy et al., 2010) and sandstone weathering (Thomas et al., 2005; Chan et al., 2008), other studies of possible terrestrial analogs considered contraction cracks formed by desiccation of gypsum dune sand (Chavdarian and Sumner, 2006).

Little is known about polygonal cracking of carbonate sand. Longman et al. (1983) explained sandcracks in Mexican Holocene carbonate eolianite by compaction of weakly lithified crusts under overlying deposits. Mylroie et al. (2006) made note of abundant polygons in Holocene oolite on Cat Island and attributed them to the homogeneous nature of the eolianite. Elsewhere in the Bahamas, polygonal cracks are present in Holocene eolianite on San Salvador, and Kindler and Hearty (1995) reported structures resembling prism or desiccation cracks in Pleistocene eolianite on Eleuthera. We examined polygons on Cat Island, performed petrographic analyses, and conducted laboratory experiments with oolitic sand to better understand sandcrack formation. Our results suggest that polygonal cracks can be easily produced by desiccation of well-sorted, well-rounded spherical carbonate sand lacking mud or microbial coatings. These findings have implications for interpreting the geological record of this unique sedimentary structure as an important indicator for desiccation during subaerial exposure of sand, and may prompt more discoveries in ancient ooid-rich strata.

FIELD STUDY

Study Area

Alligator Point, on the leeward coast of Cat Island, was interpreted by Lind (1969) as a cuspate barrier spit consisting of a broad, terraced northern ridge, and a narrow, steep southern ridge separated by a branching tidal channel opening into Exuma Sound (Fig. 1).

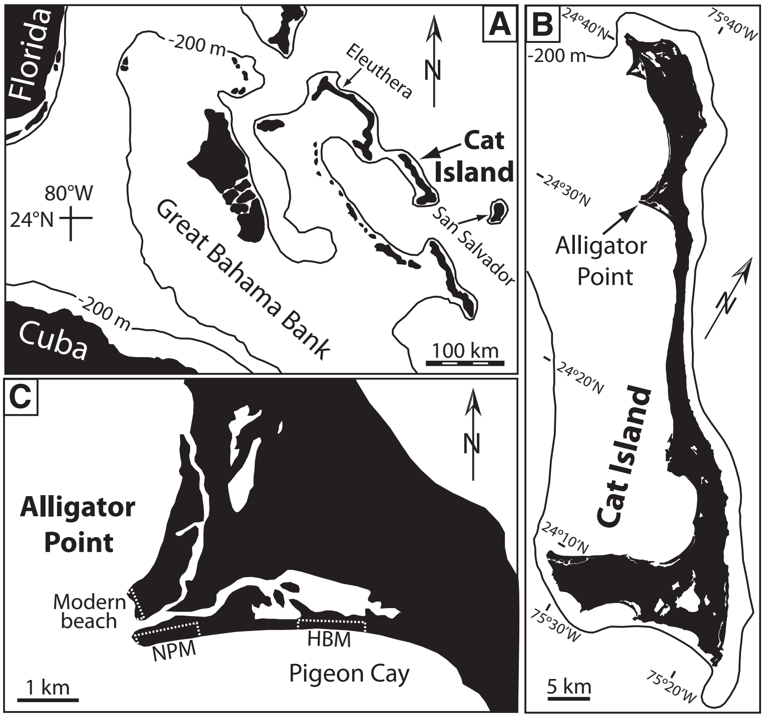

Figure 1. Study area on Alligator Point, Cat Island, Bahamas. Polygonal cracks were observed in North Point Member (NPM) and overlying Hanna Bay Member (HBM) of Holocene Rice Bay Formation (stratigraphy after Carew and Mylroie, 1995), and in modern beach backshore sediments.

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Well-exposed rocks of the southern ridge represent the windward flank of the Holocene dune-ridge complex composed of ooid grainstone (Mylroie et al., 2006) and assigned to the Rice Bay Formation, which consists of the older North Point Member (NPM, 6–3 ka), and younger Hanna Bay Member (HBM, younger than 3 ka; after Carew and Mylroie, 1995). We examined NPM eolianite along the western part of the southern ridge of Alligator Point, and HBM eolianite and backshore deposits to the east in the Pigeon Cay area (Fig. 1C). We also investigated a modern beach along the western coast of northern Alligator Point ridge (Fig. 1C).

Field and Petrographic Observations

Hanna Bay Member Eolianite and Beach Backshore Deposits

HBM deposits have the most abundant and best-developed sandcracks. Eolian beds of HBM have various dip orientations and angles (to 30°). Toward the beach, these beds level to near horizontal and transition to backshore deposits (Mylroie et al., 2006). Wind ripples are exposed on some bedding planes, and almost all beds are extensively polygonally cracked (Fig. 2A). Sandcracks also exist in modern dune and backshore deposits present on and around HBM exposures.

Polygons are 4–6 sided, with diameters of 2–68 cm, and some have smaller polygons nested within larger ones (Fig. 2B). Polygon edges are jagged, tightly fitting, and never curled or open more than 1–2 cm, except if displaced by weathering. Both weathered and freshly exposed beds are cracked equally, but polygons are more visible on weathered surfaces. In cross section, cracks are vertical to subvertical to bedding, and in finely laminated eolianite they do not seem to disturb laminae. We traced individual cracks vertically for 85 cm through multiple beds with variable porosity (Fig. 2C). The beds ranged in thickness from <1 to 25 cm, and there is no consistent relationship between polygon diameter and bed thickness.

Polygons exist in fairly well sorted (eolianite) to moderately well sorted (backshore) deposits dominated by well-rounded, spherical to elliptical, fine to medium sand-size ooids (100–400 μm). Backshore deposits also have some coarse sand (as large as 600 μm) composed of skeletal fragments, compound or composite ooids, grapestone aggregate grains, and peloids. Ooids are made of aragonite and have well-developed cortical microfabric of thin laminae around mainly peloidal nuclei. Microborings are common and result in partial to complete micritization. No micrite was observed as matrix of these deposits, which are very porous and poorly lithified with finely crystalline bladed to equant meniscus and rim clear calcite cement.

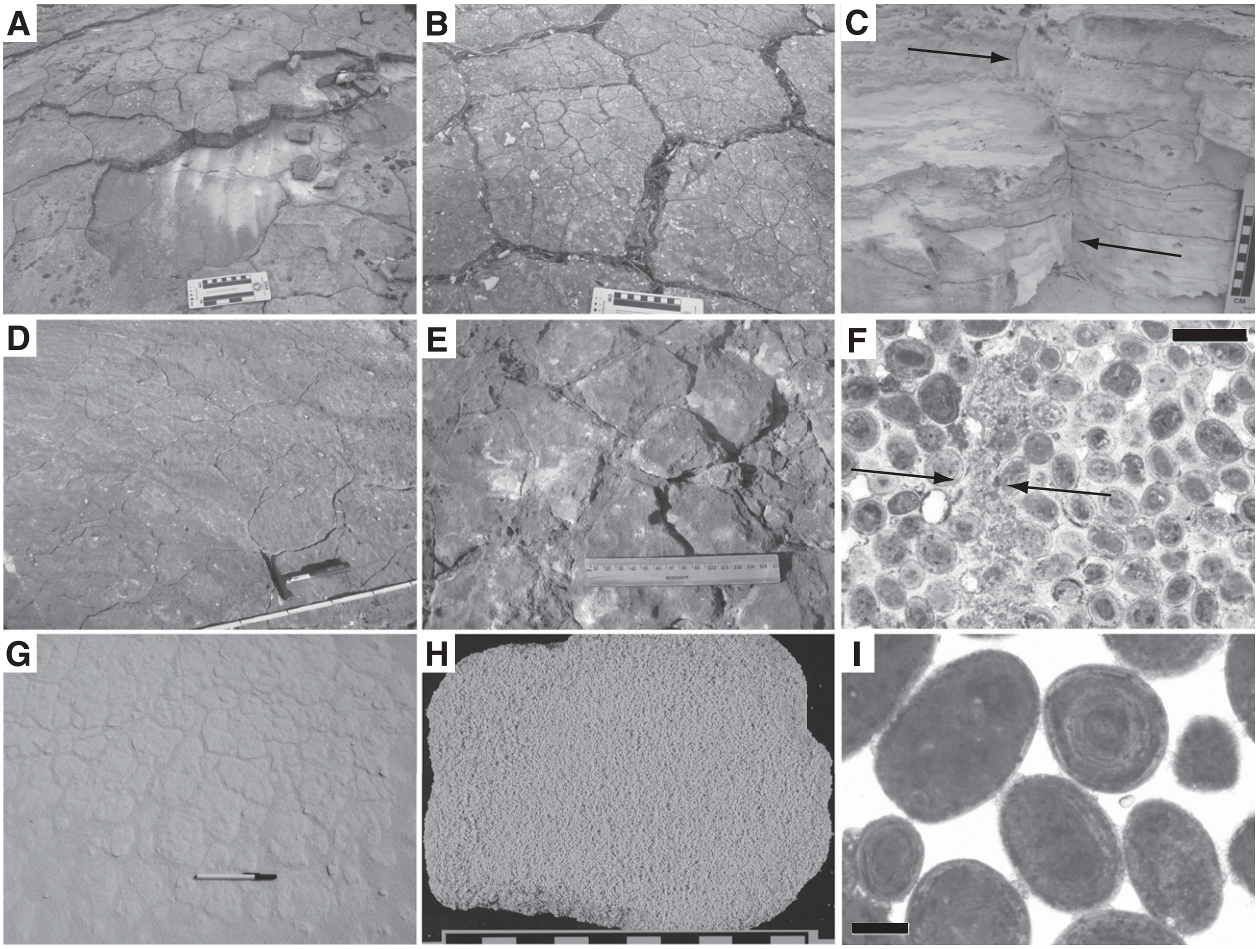

Figure 2. Field and petrographic observations of polygonally cracked deposits. A: Eolian ooid grainstone of Holocene Hanna Bay Member (HBM) with polygons and wind ripples. B: Nested polygons in HBM eolianite. C: Individual crack (arrows) extends vertically through several layers. D: Eolian ooid grainstone bed of North Point Member (NPM) with tightly fitting and jagged polygonal cracks. Hammer for scale is 28 cm. E: Cracks and space between displaced polygons of NPM eolianite filled with sediment. F: Photomicrograph of vertical crack (edges marked by arrows) in well-lithified NPM eolianite. Scale bar = 500 μm. G: Polygons in poorly lithified ooid-rich modern beach backshore sand. Note effects of polygon edge erosion. Pen for scale is 15 cm. H: Characteristic size, shape, and texture of friable backshore polygon. Scale is in cm. I: Photomicrograph of backshore polygon with meniscus carbonate cement between ooids. Scale bar = 250 μm.

North Point Member Eolianite

NPM beds dip southward at 10°–15° and in places have well-preserved wind ripples. Although abundant, sandcracks are less obvious in this older, less friable ooid grainstone (Figs. 2D and 2E) compared to HBM deposits. NPM polygons are morphologically like those in the HBM, but are slightly larger (10–72 cm diameter) and do not display nested patterns. NPM deposits are compositionally similar to HBM eolianite, but are more firmly lithified with bladed and equant clear calcite cements (Fig. 2F). A narrow crack revealed thin and discontinuous micritic coating along polygon edges and microsparitic infill with pelleted texture (Fig. 2F). Some abrasion of ooids along the crack may indicate a preferred pathway for diagenetic fluids that resulted in influx of rainwater and surficial (soil) material, and in dissolution and reprecipitation of carbonate.

Recent Beach Backshore Deposits

Modern backshore deposits laterally transition into eolian dunelets and are characterized by irregular pores, ghost crab burrows, and wind ripples. Surfaces of these deposits cracked into polygons (Fig. 2G) with diameters of 1–20 cm and thicknesses to 3 cm (Fig. 2H). Wind erosion of sediment along polygon edges produces a knobby relief (Fig. 2G). The modern sediment is similar to older Holocene deposits, but is somewhat coarser, only moderately well sorted (Fig. 2H), and composed mainly of medium to coarse sand-size (300–600 μm) spherical ooids, as well as some larger elliptical superficial ooids, aggregates, and skeletal grains as large as very coarse sand size (to 1.6 mm). Ooids and skeletal fragments are commonly micritized by microboring, although no micritic matrix is present. Polygons are friable and poorly cemented with finely crystalline, equant meniscus carbonate cement (Fig. 2I).

EXPERIMENTAL STUDY

Methods

We experimented with well-sorted, mud-free beach sand (from Pigeon Cay; Fig. 1C) composed mainly of well-rounded, fine to medium sand-size (100–400 μm) ooids. All experiments involved placing sand in clear containers to dry at room temperature (22 °C). Our six different experimental runs involved sand that was (1) naturally moist from time of sampling and ~5 cm thick; (2) moistened with deionized (DI) water and placed in layers 1, 3, and 5 cm thick; (3) repeatedly soaked and rinsed with DI water over a 74 μm (3.75ϕ) sieve to remove salt and any loose mud size particles (none detected); (4) moistened with DI water and sterilized (autoclaved) to remove any biofilms from sediment surfaces (none observed); (5) placed as layers of dry sand and then completely saturated with DI water; and (6) deposited as a layer of dry sand using a blow drier and moistened with a spray bottle to simulate rain.

Results and Implications

Polygons formed in experimental runs 1–4 during drying of layers made of moist cohesive sand (Fig. 3). Such layers had common irregular open pore space between grains (Fig. 3C). When dried, porosity was reduced by gravitational collapse and repacking of grains and the sand surface cracked (Fig. 3). Gentle tapping of the container or table hastened this process. The absence of cracking in runs 5 and 6, which involved layers deposited as dry sand without common large open spaces, suggested that the presence of pores and their collapse during desiccation of sand played an important role in polygon formation. Irregular pores are common in beach sand and can also be produced in eolian deposits by rainfall (e.g., Bain and Kindler, 1994), storm flooding, trapping of sand by vegetation, and by transport and deposition of moist sand by strong winds.

Drying of naturally moist beach sand (run 1) resulted in polygons that were similar to field examples, including some nested patterns, but were smaller (2–80 mm in diameter; Figs. 3A, 3B). The polygons had jagged edges, which made them appear irregular, although most were four to six sided. The cracks ranged from tightly fitting to several millimeters wide.

Run 2 demonstrated that polygons were bigger in thicker layers, with a maximum diameter of 3 cm in 1-cm-thick sand versus 11 cm in 5-cm-thick sand. A similar relationship exists in desiccation mudcracks (e.g., Tanner, 2003), and suggests that polygon size and formation of a nested pattern (Fig. 2B) are related to thickness of dry surficial sand, which is not always equal to layer thickness.

Polygons in runs 1 and 2 formed by cracking of a loosely lithified surficial crust of variable thickness (to 14 mm; Fig. 3B). Sand below the crust was unlithified while the crust had meniscus cement similar to field examples (Fig. 2I), but composed mainly of halite (NaCl), which was naturally present in beach sand and precipitated as the sand dried. Run 3 with rinsed sand demonstrated that in the absence of salt, polygons still form but are much more friable. Drying of sterilized sand in run 4 also produced very friable polygons. This indicates that salt in interstitial fluids and biofilms on sand surfaces are not required for cracking to occur, but they can enhance cohesion of sediment and aid in polygon lithification and preservation. Our experiments also indicated that thermal contraction did not produce polygons, which formed in sand kept at constant temperature.

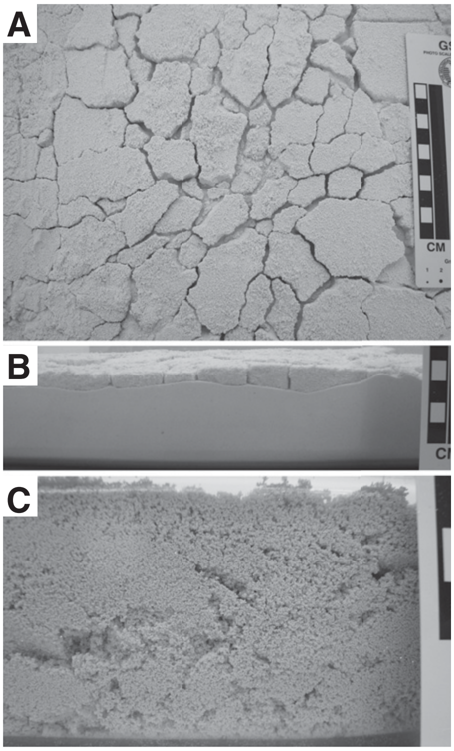

Figure 3. Experiments with beach sand from Cat Island. Polygonal cracks produced by drying of naturally moist ooid sand (run 1). A: Plan view. B: Cross section. C: Remoistened sand (run 2) displayed substantial amount of irregular open pore space in cross section. Drying resulted in porosity reduction and in polygonal cracking of sand surface.

FORMATION OF POLYGONS ON CAT ISLAND

We interpret polygonal sandcracks as primary sedimentary structures related to desiccation because (1) we observed them on Cat Island in modern, poorly lithified beach sediment and on freshly exposed Holocene grainstone beds; and (2) we produced them experimentally by drying carbonate sand. Our experiments suggested that gravitational repacking of grains and collapse of open pores in beach sand due to evaporation of water and associated reduction in surface tension enhances polygon formation by providing space for crack propagation and widening (Fig. 3), but we also observed polygons in laminated eolian deposits without large pores. Although the eolianite may have been more porous when deposited, the undisrupted lamination may reflect the crack formation processes related to the model of Chavdarian and Sumner (2011) for sulfate dune sands. In this model, rain and dew moisture enters a dune, dissolution of unstable particles occurs, and meniscus cements precipitate. Capillary action transports water upward and its surface tension provides additional cohesion. During drying this cohesion is lost, sand contracts, and cracks form at weakly cemented grain boundaries (Chavdarian and Sumner, 2011). Our experiments with deposition of dry sand and simulated rain did not produce cracks, possibly because the experimental apparatus did not allow for moisture replenishment from below, nor did it involve repetitive surface wetting and drying over an extended time period.

Polygonal cracks appear to be easily produced by drying of porous sand, and yet are rarely reported features. It is possible that some are mistaken for mudcracks and/or that most sandcracks are not preserved in the absence of significant early cementation. Slow lithification can explain their paucity in mud-free siliciclastic rocks, but carbonate sand typically lithifies rapidly. This suggests that polygons do not form ubiquitously in carbonate sand, but rather they require sediment of unique composition and/or texture under specific environmental conditions. Beach and eolian sand from Alligator Point on Cat Island is dominated by relatively well sorted spherical ooids, unlike the texturally and compositionally more heterogeneous skeletal and peloidal sediment common elsewhere in the Bahamas. Therefore, the texture of the sand is deemed to be the most important control of polygon formation.

Tension fractures can only form in materials with sufficient cohesive strength (van Mechelen, 2004). Cohesion of moist sand is caused by capillary effects, which are mainly related to surface tension force of liquid in interstitial bridges between grains. The overall cohesion depends on the number density of bridges and on the distribution of liquid within them, which in turn depend on the geometry of grain contacts as a function of grain size and shape (e.g., van Mechelen, 2004; Richefeu et al., 2008). The uniform size and regular shape of Cat Island ooids appear to provide the grain contact geometry with homogeneous distribution of liquid required for optimal cohesion. Polygons form in such cohesive sand by contracting and cracking at grain boundaries due to stresses generated by surface tension when continuous films of water formed by liquid bridges in well-sorted, round, spherical to elliptical grains break into isolated capillary films during desiccation (Chavdarian and Sumner, 2011). Irregularly shaped skeletal and peloidal sediment has heterogeneous distribution of grain contacts, and angular grain edges can pierce liquid bridges, decreasing their binding efficiency (van Mechelen, 2004). Capillary cohesion force is diminished and not uniformly distributed in such sand, and it may not readily crack polygonally when subjected to desiccation.

CONCLUSIONS

Field observations of sandcracks on Alligator Point (Cat Island, Bahamas), coupled with experiments on sand from an adjacent beach, suggest that polygonal cracks can easily form by drying of homogeneous ooid sand without muddy matrix or microbial biofilms. Polygons form by the contracting and cracking of subaerially exposed sand at grain boundaries due to stresses generated by surface tension when continuous films of interstitial water break into isolated capillary films during desiccation. Any remaining moisture and cements precipitated during drying provide cohesion within polygons. Repacking of sand grains and collapse of open pores due to loss of cohesion related to evaporative loss of water enhance polygon formation by providing space for crack propagation. Sandcracks are abundant in Holocene eolian and beach backshore deposits on Alligator Point, but they have been rarely documented from other localities because their formation requires homogeneous sediment that consists of well-sorted, well-rounded spherical sand grains unlike the more common skeletal and peloidal carbonate sediments. Our findings may initiate more discoveries of these primary sedimentary desiccation structures in ooid-rich deposits elsewhere.

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