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# KINNEYIA-TYPE WRINKLE STRUCTURES—CRITICAL REVIEW AND MODEL OF FORMATION

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## ABSTRACT

**Kinneyia structures are among the most typical wrinkle structures observed on ancient siliciclastic sediment surfaces since the Archean. Recently, Kinneyia structures have been grouped together with other microbially induced, crinkly decorations on ancient bedding surfaces as wrinkle structures. They are mainly preserved on upper surfaces of ancient siliciclastic-event deposits and are characterized by millimeter-scale, winding, flat-topped crests separated by equally sized round-bottomed troughs and pits. The structure resembles small-scale interference ripples including crest-dominated linear and pit-dominated honeycomb-like patterns. The steep slopes of the crests, however, exclude their formation at the air or water-sediment interface. Thin sections across Kinneyia structures reveal their formation beneath microbial mats. They formed at an early stage and do not arise from loading and other processes related to burial. Based on the close relationship to event deposits, a genetic model considering the specific hydraulic conditions on siliciclastic tidal flats after storms or floods is proposed. Numerical calculations show that, after microbial mats have been reestablished on the new sediment surface and groundwater is still flowing downslope, the top portion of the sediment confined beneath mats may be liquefied, thus allowing grains to move with the groundwater. Oscillations of groundwater flow owing to periodic reversals of flow direction at rising tides, and a tidal signal of oscillating pore pressure may enhance formation of ripple-like structures along the boundary with the overlying mat. The model applies primarily to Kinneyia structures presumed to be formed beneath cohesive microbial mats in peritidal zones.**

## INTRODUCTION

Within a group of sedimentary structures thought to be related to microbial mats (microbially induced sedimentary structures; Noffke et al., 2001a), wrinkle structures (Hagadorn and Bottjer, 1997, 1999) are among the most prominent indicators of microbial mats formerly existing on sedimentary surfaces. Wrinkle structures are on a millimeter scale and, in most general terms, are characterized by ‘‘oddly contorted, wrinkled, irregularly pustulose, quasi-polygonal, commonly oversteepened surface morphologies that can occur on bed tops and bottoms’’ (Hagadorn and Bottjer, 1999, p. 73). Despite this highly conceptualized definition, wrinkle structures frequently reveal patterns of more or less regular troughs and crests with amplitudes in the range of 0.3–3 mm and intercrest distances of 1–5 mm, sometimes resembling miniature interference ripples. The most typical examples of such structures are known as Kinneyia structures and were characterized as *Runzelmarken* (wrinkle marks) by Häntzschel and Reineck (1968) when they observed them on the upper surfaces of Jurassic siltstone beds. Kinneyia structures have been described from the Archean (Noffke et al., 2003b) to the Jurassic (e.g., Häntzschel and Reineck, 1968; Bloos, 1976), with a maximum occurrence in the Neoproterozoic–Lower Ordovician (Hagadorn and Bottjer, 1997); they have not yet been observed in relationship to modern microbial mats.

Kinneyia structures (Figs. 1A–G) consist of comparatively short, curved, frequently bifurcating, flat-topped crests, 0.5–1 mm high and 1–2 mm wide, which are separated by parallel, round-bottomed depressions. The crests are usually steep sided and may run parallel or form honeycomb-like patterns. The depressions frequently exhibit constrictions and may be reduced to isolated, round, or elongate pits. A problematical feature of the structures is the steep-to-almost-vertical flanks of the crests, which are too steep to persist at the sand-water interface. Attempts to explain formation of the structures are numerous but still not satisfactory.

This paper is focused on clearly defined Kinneyia structures only and does not cover the whole range of wrinkle structures, as meant by Hagadorn and Bottjer (1997, 1999). We review the history of the term Kinneyia, document typical Kinneyia structures, and briefly discuss the suspect participation of microbial mats in the formation of the structure. This is succeeded by a discussion of various occurrences of Kinneyia structures, as reported in the literature and studied by the authors in Morocco and Namibia. We then assess previous models and conditions for their formation. Finally, a new model is proposed.

## HISTORICAL REVIEW

The term *Kinneyia* was introduced by Walcott (1914), who observed linear, rarely bifurcating, flat-topped crests, 2–3 mm wide and 1–2 mm high, separated by narrow depressions on etched bedding surfaces of Neoproterozoic (Algonkian) limestone. He described the crests as surface outcrops of thin, subparallel layers or lamellae that extended almost vertically through the layer and related the pattern to the growth of a new algal genus, *Kinneyia*. Holtedahl (1921) observed slightly coarser structures of the same type (*Newlandia frondosa* Walcott) in Permian limestone and considered them inorganic and caused by secondary changes in the rock. Fenton and Fenton (1936) also suggested that *Kinneyia* is inorganic, resulting from the segregation of dolomite and calcium carbonate. Häntzschel (1962) pointed out that the relief was similar to very small ripple marks but also compared the structure with *Furchensteine* (furrow stones) or corroded limestone flags and thus suggested that it was possibly inorganic. In both the original definition and subsequent discussion, *Kinneyia* is a dominantly linear structure developed in carbonate rocks and likely of inorganic origin.

Additional irregular, small-scale wrinkle structures characterized by curved and frequently bifurcating crests have been described from upper bedding surfaces of sandstone and siltstone layers. These structures differ considerably from Walcott's genus *Kinneyia* with respect to lithology and curved crests. Nevertheless, Martinsson (1965, p. 192), who observed such irregular wrinkle structures on upper surfaces of Cambrian siltstone beds, decided ‘‘for historical reasons and for the lack of a genetically neutral term’’ to name them ‘‘Kinneyian ripples’’ (after the genus *Kinneyia* Walcott). Häntzschel and Reineck (1968) observed similar structures on upper surfaces of Jurassic siltstone beds and introduced for them the term *Runzelmarken* (wrinkle marks). Unfortunately, this term was applied later by several authors (Reineck, 1969; Singh and Wunderlich, 1978; Reineck and Singh, 1980) to structures that differ from the original Runzelmarken of Häntzschel and Reineck (1968) and the Kinneyian

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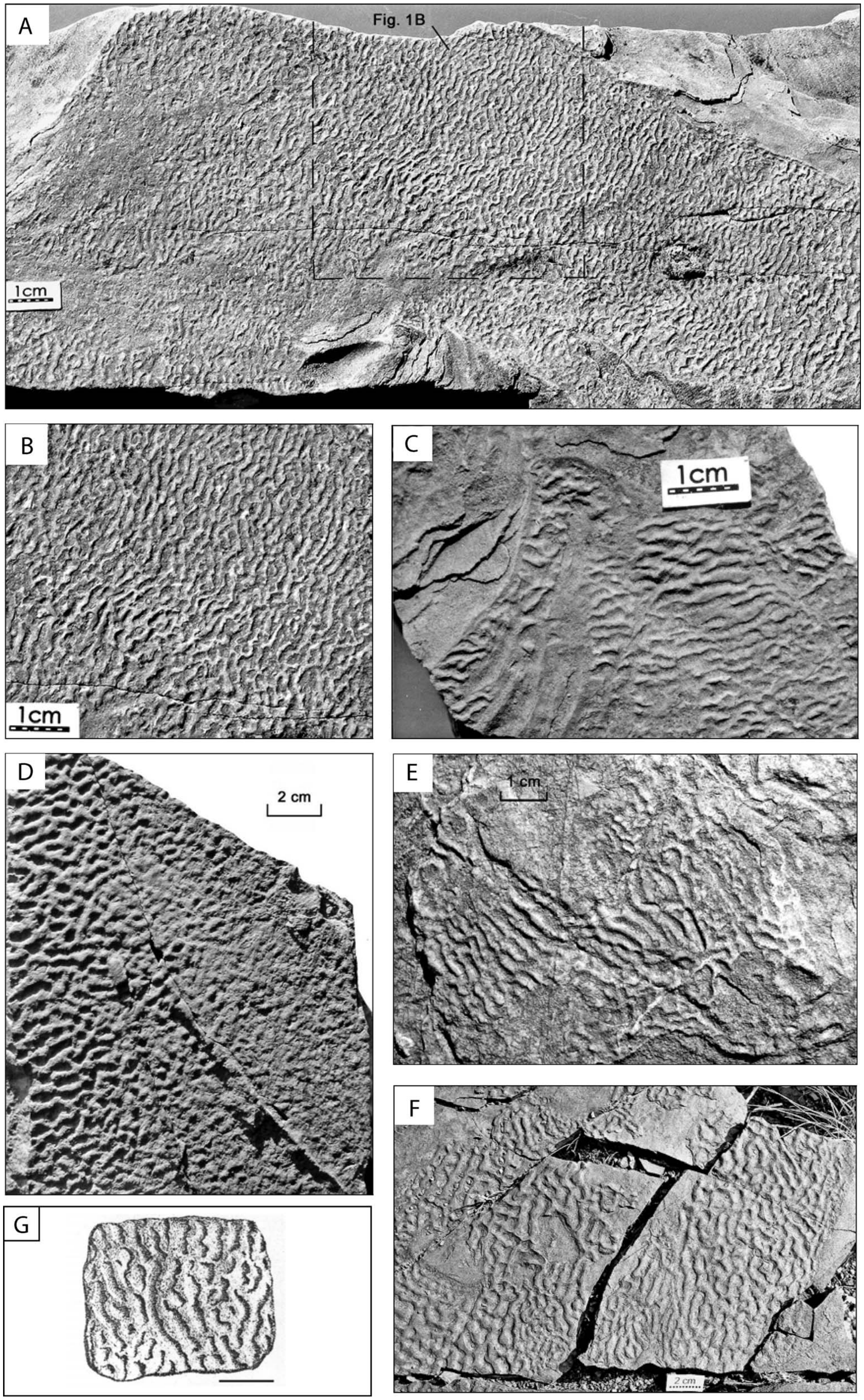

**FIGURE 1**—Kinneyia structures of different ages from various localities. All show upper surfaces of event deposits; intercrest distances are in parentheses. A–C) Middle Cambrian *Paradoxissimus* siltstone, Äleklinta, Öland, Sweden. D–E) Neoproterozoic Carbonate and Quartzite Group, Anti-Atlas, Morocco. A, B) Structures with long, flat-topped, winding crests in thin siltstone layer (topset veneer) above flattened upper surface of event deposit (~2 mm). C) Truncated ripples partly overlain by Kinneyia. Note exposed and truncated foresets (left) and flat tops of Kinneyia crests (below scale). D) Structure in fine-grained quartzite with short, steep-sided, flat-topped crests and numerous round-elongate pits (6–8 mm). E) Structure with more linear crests (3–5 mm). Note local constrictions of intercrest depressions and isolated pits (right). F) Structure with short, flat-topped crests interfering at two diverging directions. Note numerous round-elongate pits resulting from crest interference (8–10 mm). Terminal Proterozoic, Vingerbreek Member, Schwarzrand Subgroup, Nama Group, Farm Haruchas locality, Namibia. G) Reproduction of Quenstedt's (1858) drop plate (Tropfenplatte), possibly the first documentation of Kinneyia structures in the literature. Scale bar = 1 cm. Jurassic, Göppingen, southern Germany.

ripples of Martinsson (1965) and that subsequently have been interpreted as small-scale load structures of nonbiogenic origin by Allen (1985a, 1985b).

There have been numerous descriptions and interpretations of the Kinneyia type of wrinkle structure on sandstone and siltstone surfaces for nearly 150 years. Arguably, Quenstedt (1858) was the first to document them (Fig. 1G) on upper surfaces of Jurassic sandstone beds. He considered them to be formed by strong rain on even ground. A few years later, Geinitz (1863) interpreted similar structures on Permian sandstone beds as dinosaur skin. Shrock (1948, fig. 79) explained the structures as ''eroded symmetrical ripple marks,'' and McKee (1954, fig. 17) interpreted them as small-scale interference ripple marks that formed a pattern of small, deep pits among rounded-to-elliptical ridges. Kummel and Teichert (1970) considered the structure as truncated interference ripples of minute size, whereas Bloos (1976) advocated their formation by oscillatory water movement over fine silty sediment. Kinneyian ripples were compared with eolian microridges on beaches by Hunter (1969) and interpreted as wind-induced antiripples by Goldring (1971), whereas Allen (1966) suspected that they might have formed on tidal flats as marks produced by wind-driven foam. Based on earlier experiments (Reineck, 1969), Singh and Wunderlich (1978) and Reineck and Singh (1980) suggested that Kinneyian ripples formed when strong wind blew over cohesive sediment covered by a thin film of water. Seilacher (1982) and Seilacher and Aigner (1991) observed Kinneyia structures on upper surfaces of storm deposits and suggested an intrasedimentary origin caused by instability release related to sediment loading and dewatering.

In 1997, Hagadorn and Bottjer proposed that Kinneyian and other wrinkle structures may be formed by microbial activities and in 1999 speculated that they reflect surface structures that were microbially bound. Simultaneously, Pflüger (1999) proposed that Kinneyia structures result from gas trapped beneath a sealing microbial mat layer topping the sediment. Subsequently, Noffke (2000) interpreted Kinneyia-type wrinkles as fossilized microbial mat structures, whereas Noffke et al. (2001a) considered them to reflect depositional surfaces overgrown and leveled by microbial mats. Later, Noffke et al. (2002, 2003a) suggested that Kinneyia-type wrinkles originated from loading and dewatering of microbial mats.

This brief historical review shows that, although physical processes were initially used to explain the structures, explanations now involve microbial activities. Noffke et al. (2003b) observed in Archean sandstone beds that wrinkled upper surfaces were overlain by dark laminae including filamentous microstructures resembling trichomes of modern bacteria or cyanobacteria; this work seems to indicate that microbial mats may have played an important role, though still in an unknown way.

Concerning nomenclature, we suggest describing this specific type of wrinkle structure as a Kinneyia structure, Kinneyia-type wrinkle structure, or, briefly, Kinneyia. Since its inorganic nature has become evident, particularly when developed on siliciclastic sediment surfaces, the nonitalicized spelling appears adequate. Italicizing is, however, required when *Kinneyia* refers to Walcott's (1914) original work.

## BASIC OBSERVATIONS

### Previous Observations

All described examples of Kinneyia structures occur on upper bedding surfaces of sandstone or siltstone layers. These layers usually form distinct beds in successions of finer-grained sediments, frequently shales (e.g., McKee, 1954; Martinsson, 1965; Häntzschel and Reineck, 1968; Bloos, 1976; Pflüger, 1999; Noffke, 2000; Gingras, 2002; Noffke et al., 2002, 2003b) and are in many cases interpreted as event deposits, resulting from either storms or floods. As is common in such successions, only a few layers show Kinneyia structures on their surfaces. For example, a Kinneyia-carrying layer of *Paradoxissimus* siltstone from the type locality on Öland, Sweden (Fig. 1A) exhibits scour and traction marks on the lower bedding surface and is itself distinctly current rippled (Martinsson, 1965). Usually ripple crests are truncated (Fig. 1C), and the flattened surface is covered with a topset veneer of one-to-several laminae. According to Martinsson (1965), the layer most likely represents a flood deposit, whereas the topset veneer may be interpreted as upper flow-regime flat beds formed at shallow-water depth and high-flow velocities that also caused truncation of the ripple crests. Martinsson (1965) measured the orientation of both paleocurrent vectors and Kinneyia-type structures preserved in individual siltstone layers at various localities on Öland and documented that the strike of Kinneyian ripples is uniformly perpendicular to the direction of the paleocurrents from which the silty event layers were deposited. He concluded that, if the flood-related paleocurrents were mainly directed downslope, Kinneyian ripples were thus oriented along strike of the slope.

Kinneyia structures typically occur on flat or slightly undulating upper bedding surfaces (Fig. 1), as documented by Martinsson (1965), Häntzschel and Reineck (1968), Bloos (1976), Hagadorn and Bottjer (1997, 1999), Pflüger (1999), Noffke (2000), Noffke et al. (2001a, 2002, 2003a), and others. Bloos (1976) showed that the Kinneyia-carrying surface usually is at an angle to the lamination in the underlying sediment. Pflüger (1999) noticed that Kinneyia commonly develops on the tops of truncated ripples, as is the case at the type locality in Sweden (Figs. 1A, C).

Within Kinneyia structures, the flat tops of the crests all lie in a common plane. This feature was addressed for the first time by Bloos (1976) who also noted that, where Kinneyia occurs in patchy distribution, the enveloping plane passes into the surrounding sediment surface. A bed of pelitic siltstone or silty shale is usually overlying, which has been suggested to represent layers of former microbial mats (e.g., Noffke et al., 2003b).

Bloos (1976) observed a continuous layer of relatively enriched heavy minerals (mainly rutile, zircon, and tourmaline) in x-radiograph sections across Kinneyia; this layer underlies the crests and troughs and discordantly rests upon the sedimentary bedding below (Bloos, 1976, pl. 10, fig. 2C; see also Fig. 4A). The Kinneyia-carrying top layer is identical with the sediment below the heavy mineral horizon, except for depletion in heavy minerals, and Bloos (1976) concluded that the previous sediment surface had undergone some kind of reworking before formation of Kinneyia.

### New Observations

A review of Kinneyia structures in the literature and observations made by the authors reveal that the basic geometry of Kinneyia is remarkably similar throughout the numerous examples, whereas there is considerable variation in crest distances—between 2 mm and 2 cm (Figs. 1A–F, 2). This variation may be partly correlated with the grain size of the sediment involved, the smallest structures being present in fine to very fine-grained sandstone. Furthermore, there is a wide variation in the relative proportions of pits and troughs versus ridges (Fig. 2).

Contrary to previous descriptions of a more or less linear, though wavy, arrangement of the crests, we observe that most Kinneyia structures exhibit two preferred crest orientations, but commonly one direction is dominant (Fig. 3). The two directions frequently are at an angle of 45° ± 5° and are here considered responsible for the wavy trends of the troughs and crests. Many of the pits appear to result from interference of crests developed along two directions (Fig. 3, no. 1). On some crests relic shallow pits are preserved, whereas in some troughs incipient crests are developed, and locally there is a superposition of earlier, lower crests by later, higher ones (Fig. 3, nos. 2–4).

Sections across Kinneyia structures from Sweden (Figs. 4B, D, F) show Kinneyian troughs and crests in the uppermost millimeters of the topset veneer above the event deposit. This top light-colored portion is separated from a lower, darker portion by a distinct boundary at a level that nearly coincides with the trough bottoms. A heavy mineral layer is not developed at the boundary, but thin sections (Figs. 4C, H) reveal conspicuous textural differences between the layers above and below. The lower is

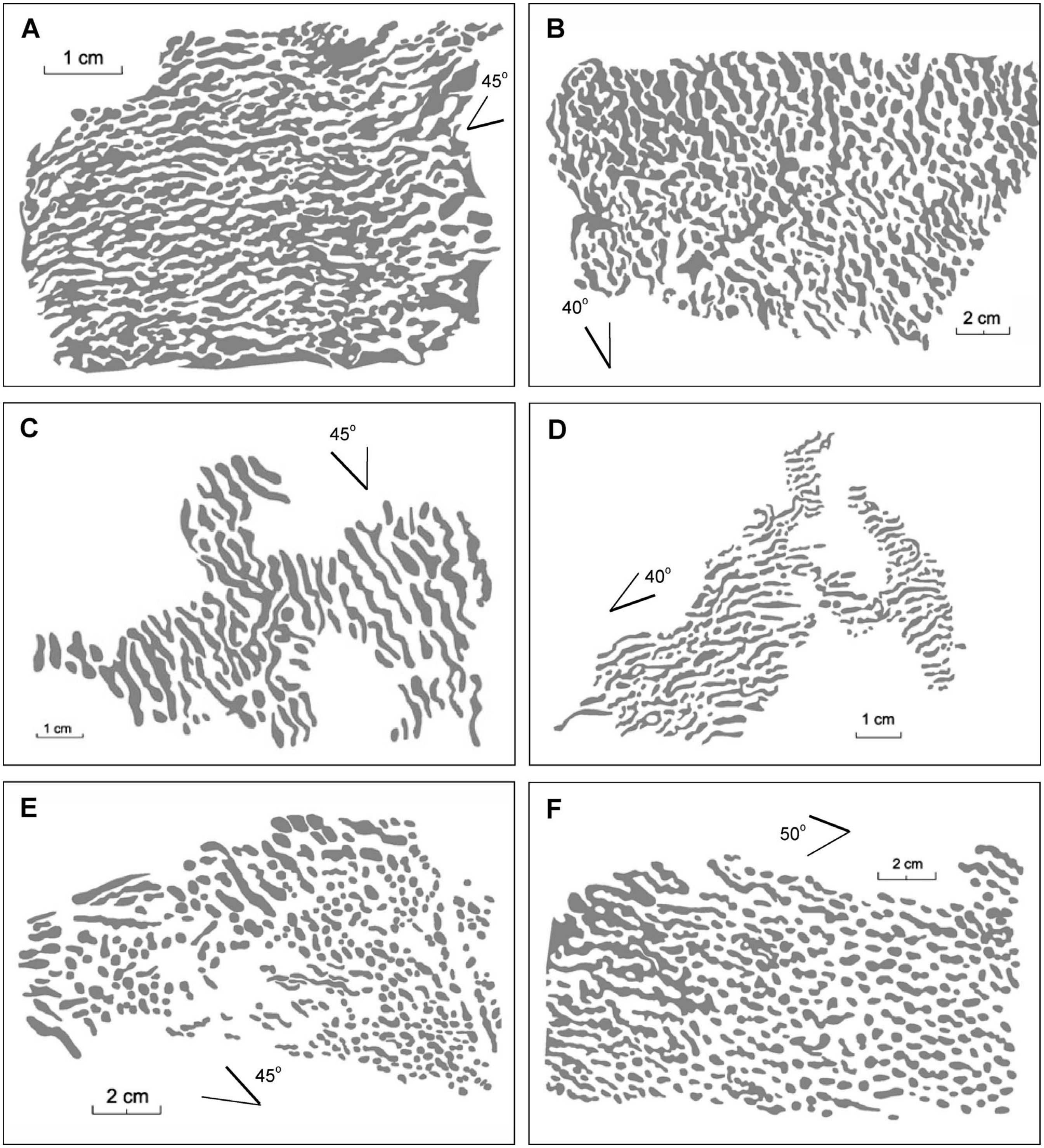

**FIGURE 2**—Graphic rendition of Kinneyia structures (pits and troughs in gray) from various localities and ages showing differences in intercrest distances and in relative proportions of pits and troughs vs. ridges. Angle = main (thick line) and secondary (thin line) direction of crests. A) *Paradoxissimus* siltstone, Sweden. B) Carbonate and Quartzite Group, Morocco. C) Lower Jurassic (Hettangian), Helmstedt, Germany; type locality of *Runzelmarken* (drawn after Häntzschel and Reineck, 1968, pl. 6, fig. 2). D) Lower Jurassic (Hettangian), southern Germany, first rendition (redrawn from Bloos, 1976). E) Silurian, Murzuk Basin, southwest Libya (drawn after Pflüger, 1999). F) Lower Jurassic (Hettangian), southern Germany, second rendition (redrawn from Bloos, 1976).

characterized by dense packing, concavoconvex grain contacts, and a faint, near-horizontal shape-preferred grain orientation reflecting bedding, whereas the upper, Kinneyia-bearing layer exhibits sediment grains coated by sericite (see discussion below) and a random-to-upward-directed grain-shape orientation.

In typical Öland samples (Figs. 4B–H) the Kinneyia structure is overlain, with a distinct boundary, by thin layers of silty argillite and siltstone (Figs. 4F, G). The basal argillitic layer is up to 0.2 mm thick and drapes the relief of crests and troughs, slightly attenuating toward the crests. It consists of a sericitic matrix that includes isolated silt-sized grains of quartz (floating grains) and some larger muscovite flakes (Figs. 4E, G). Thin, disrupted layers of carbon-rich material are occasionally preserved

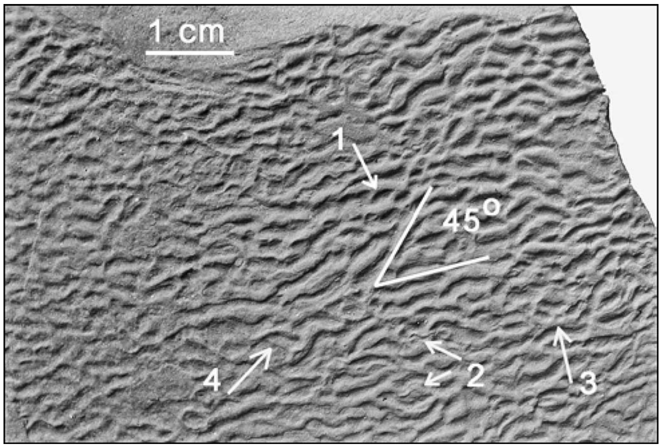

**FIGURE 3**—Kinneyia structure in siltstone, showing flat-topped crests oriented in two directions at an angle of 45°. 1 = pits resulting from interference of crests; 2 = incipient crest; 3 = relic pit; 4 = superposition of lower crest by higher one. *Paradoxissimus* siltstone.

(Figs. 5A–B). The muscovite flakes and some elongate quartz grains are shape-oriented parallel to bedding. Overlying is a 0.3–0.5 mm thick layer of sericitic siltstone (Fig. 4G) that fills the troughs and thins out toward the crests so that its upper surface is almost flat. In the sericitic siltstone, the quartz grains are usually coated by sericite and thus not in direct contact (coated grains). Overlying the crests is a continuous layer of silty argillite, as below (Fig. 4F). It is capped by homogranular siltstone exhibiting subrounded grain shapes, dense packing, and concavoconvex to sutured grain contacts.

### Deformed Kinneyia Structures

Although Kinneyian ripples are commonly symmetrical, distinctly asymmetric shapes have been observed in a few cases (e.g., Bloos, 1976). In such cases the sawtoothlike ripples (Fig. 4A, sec. 3) are oriented in one direction with steep-to-overturned, concave slopes on one side and flat, convex slopes on the other. This geometry suggests deformation of previously symmetrical ripples by shear stress acting upon the overlying microbial mat. The lack of any brittle deformation indicates that deformation was prelithification. It is envisaged that deformation occurred during burial of the mat by sediment deposition from currents. Such a process would allow preservation of the momentary deformational state, avoiding recovery to normal symmetric ripples.

An ancient example of deformed Kinneyia ripples has been described, though not recognized as such, by Bouougri and Porada (2002). In plan view, the structure is characterized by 2–3 mm wide and 5–10 mm long bifurcating, interconnected crests and intervening troughs (Fig. 5C). The crests are 1–2 mm high, smoothly flat topped and distinctly asymmetric with the steep-to-overturned sides always facing in one direction and partly thrust onto neighboring troughs. The crests consist of fine-grained quartzite identical with and arising from the underlying sediment, whereas relics of sericitic siltstone are preserved in the troughs. Bouougri and Porada (2002) interpreted the structure as resulting from an interaction of shear stress acting upon a cohesive microbial mat and dewatering after liquefaction of the sediment below.

## SUSPECT INVOLVEMENT OF MICROBIAL MATS

It has been suggested that the layers of silty argillite and sericitic siltstone immediately overlying Kinneyia ripples are related to microbial activities. In particular, the silty argillite that typically contains isolated sediment grains (floating grains) and relics of carbon-rich layers is considered to represent the remains of former microbial mat layers. Other ancient examples exhibiting both types of layers have been interpreted by Noffke et al. (2002, 2003b) and Bouougri and Porada (2002), based mainly on the peculiar textural features of the sediments. In one example (Noffke et al., 2003b), organic structures resembling bacterial trichomes have been observed in silty argillite directly overlying Kinneyia.

Peculiar floating-grain and coated-grain fabrics have also been observed in modern, strongly cohesive, layered cyanobacterial mats in upper intertidal to lower supratidal zones of siliciclastic depositional systems. If compared with these mats (e.g., Gerdes and Krumbein, 1987, 1994; Noffke et al., 1997a, 1997b, 2003a; Gerdes et al., 2000), the layers of silty argillite comprising floating grains may originate from former microbial mats that consisted of dense networks of filaments with a low clastic mineral content (Gerdes et al., 2000). In such layers, isolated sediment grains floating in the sericitic groundmass would once have been incorporated into the mat by microbial trapping and binding processes (Black, 1933), as described in detail by Noffke et al. (1997b, 2001a, 2003a).

For the layers of sericitic siltstone comprising coated grains, modern examples suggest three possible origins:

1. They may represent previously cohesive sediment with a high content of sedimentary grains and a more concealed distribution of the biomass (Gerdes et al., 2000). The peculiar fabric of these layers, in which sediment grains are coated by sericite, would then have been derived from grain separation, a process in which particles are moved aside by their organic envelopes as a microbial mat continues to grow (Noffke et al., 2003a). In this interpretation, the sericitic siltstone layers would reflect initial stages in the development of microbial mats.
2. A similar fabric of coated grains may result when, after establishment of a mat, new groups of bacteria, mainly heterotrophic types adhering to grains, spread out in the underlying sediment and destroy or consume the organic matter produced by cyanobacteria in the overlying mat (e.g., Van Gemerden, 1993; Stolz, 2000; Noffke et al., 2003a).
3. The alternating layers of silty argillite and sericitic siltstone that fill Kinneyian troughs and overgrow crests (Fig. 4F) may represent small sections of biovarvites, as described from recent mats by Gerdes and Krumbein (1987). Such laminations may form in response to seasonal changes, when mats are dominated by different cyanobacterial assemblages, for example, by coccoid cyanobacteria producing high amounts of extracellular polymeric substances during summer and by filamentous species forming strong networks during winter (for details, see Gerdes et al., 1991, 2000; Noffke et al., 2003a). This scenario suggests that the layers of sericitic siltstone would reflect seasons in which coccoid species preferentially grew.

In two examples studied by the authors in detail (see below), Kinneyia structures occur together with a variety of mat-related sedimentary structures and sections of siliciclastic planar and domal biolaminites, contained in heterolithic successions of laminated sandstone, siltstone, and shale. This also supports a likely microbial participation in the formation of Kinneyia.

## OCCURRENCE AND DEPOSITIONAL SETTING OF KINNEYIA STRUCTURES

Kinneyia structures have been reported from the Jurassic to the Archean. They occur on silty-to-sandy event beds from storms or floods, intercalated in shallow marine, heterolithic, silty and shaly sedimentary successions, deposited largely on low-gradient margins of epicontinental basins or embayments thereof (e.g., Martinsson, 1965; Häntzschel and Reineck, 1968; Bloos, 1976; Beukes, 1996; Pflüger, 1999; Noffke, 2000; Noffke et al., 2003b; Pruss et al., 2004). Within basically similar environments and comparable lithostratigraphic successions, they occur equally in subtidal and intertidal depositional settings (Table 1), based in both cases on sedimentary structures, facies distribution, and regional depositional trends. Subtidal deposition has been deduced from (1) a lack of features indicating emergence, (2) development of hummocky cross-stratification in the event beds, or (3) occurrence of trace fossils such as

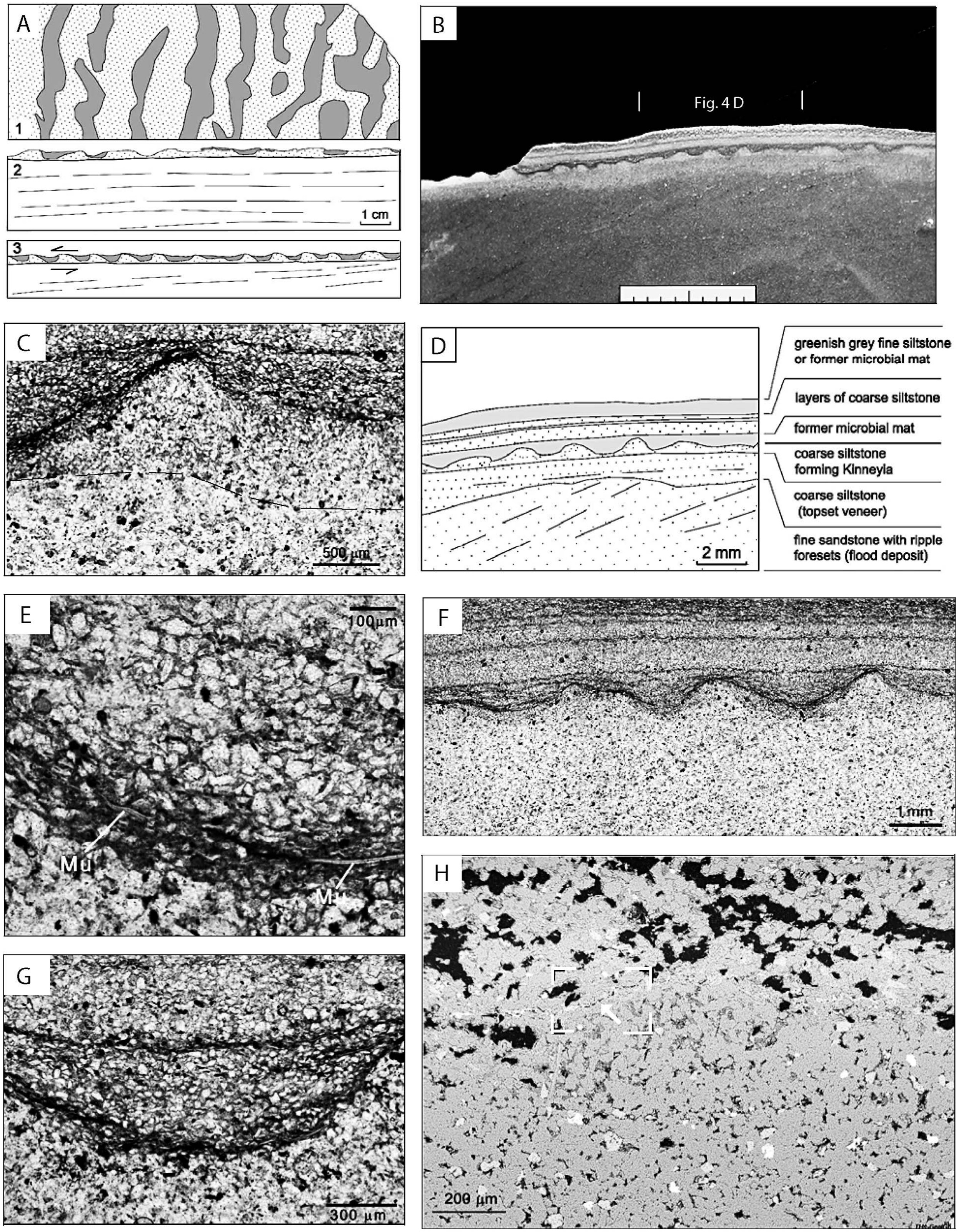

**FIGURE 4**—Kinneyia sections and microstructures. A) Lower Jurassic sandstone, Germany (after Bloos, 1976); gray = troughs (silty argillite); stipple = crests. 1 = upper bedding surface; 2 = section through sandstone layer; line below Kinneyia crests = heavy mineral enrichment; dashed lines = bedding; 3 = asymmetric Kinneyia crests, possibly due to deformation by shear stress (indicated by arrows). B–H) *Paradoxissimus* siltstone. B) Section through Kinneyia structure developed on top of an event deposit and overlain by silty argillite (dark) and siltstone (light). Note flat lower bedding surface of siltstone layer overlying silty argillite. Scale in millimeters. C) Thin section across Kinneyia crest showing textural differences in layers below. Dashed line separates loose packing of coated grains above from dense grain packing below. D) Graphic rendition of part of Figure 4B showing details of lithology. E) Details of thin layer of silty argillite immediately overlying crest. Layers contain flakes of detrital muscovite (Mu) and sedimentary grains floating in argillite and carbonaceous material (black). F) Thin section showing gradual filling of Kinneyia troughs by interbedded layers of silty argillite and sericitic siltstone eventually leading to a flat surface. G) Thin section through trough showing details of gradual filling with onlapping relationships toward adjoining crests. H) Scanning electron micrograph of section through crest showing coated-grain fabric and upward-directed grain shape orientation in the crest and dense grain packing below. Black areas in upper part of image are holes in thin section. Inset = Figure 5A. Faint diagonal line across inset marks upper contact of Kinneyia crest (arrow).

*Rhizocorallium, Gyrochorte,* or *Planolites* in the succession. Intertidal deposition, in contrast, has been inferred mainly from widespread development of flaser and lenticular bedding in the heterolithic succession and the occurrence of desiccation cracks.

The question of whether Kinneyia structures develop in subtidal or intertidal settings, or in both, is of interest with respect to their possible use as paleoenvironmental indicators. A differentiation between subtidal and intertidal heterolithic deposits, however, is problematical in ancient sediments (e.g., Reineck and Singh, 1980), mainly for the following reasons: (1) similar sedimentary structures may develop in both zones; (2) hummocky cross-stratification, usually considered a strong argument for subtidal deposition, may also form in storm-induced deposits on intertidal flats (e.g., Yang et al., 2006); (3) most of the trace fossils quoted in favor of subtidal settings (e.g., *Planolites, Teichichnus, Halopoa, Rhizocorallium, Gyrochorte, Corophioides*) are also common in the intertidal zone (e.g., Zonneveld et al., 2001); and (4) the absence of features indicating emergence does not argue *a priori* for deposition in the subtidal zone. If cohesive microbial mats were widespread in the intertidal zone, the usual indicators (e.g., swash marks, rill marks, desiccation cracks) might be suppressed, and, in contrast, specific mat-related sedimentary structures might be developed.

A variety of such structures co-occurring with Kinneyia in the same succession have been observed in Neoproterozoic intertidal successions studied by the authors in Morocco (Bouougri and Porada, 2002) and Namibia (Bouougri and Porada, 2007) and by Noffke (2000) in the Ordovician of France. Recent studies (Parizot et al., 2005; Sarkar et al., 2005) have shown that such features, complementing data derived from normal sedimentary structures, may help to better identify intertidal environments. Some of the structures, particularly shrinkage cracks with upturned-to-involute margins, require subaerial exposure of strongly cohesive mats for their formation, by comparison with modern examples. Such mats are characterized by a leathery surface layer of high mechanical resistance and very low water permeability, which is a few millimeters thick (Zavarzin, 2003) and today occur exclusively in intertidal to supratidal zones. The leathery surface layer resists erosion and prevents the underlying bacterial community from water loss. Permanently subaqueous mats—for example, in the subtidal zone—usually do not develop such continuous and strongly cohesive surface layers but are, rather, soft or gelatinous, although some types may be quite erosion resistant (e.g., Neumann et al., 1970).

The association of Kinneyia structures with microbial shrinkage cracks and other mat-related structures requiring strongly cohesive mats for their formation, as well as the close relationship to floating-grain and coated-grain fabrics, all well known from modern intertidal mats (e.g., Noffke et al. 1997b, 2001b, 2003a; Gerdes et al., 2000), suggest that Kinneyia structures formed below similar cohesive mats. Considering the distribution of modern cohesive mats, it may thus be argued that Kinneyia-carrying event layers likely were deposited in the intertidal zone of low-gradient tidal flats, where they soon became overgrown by microbial mats. This does not exclude, however, that in the Precambrian and in exceptional cases later in the Phanerozoic, similar conditions may have prevailed in the subtidal zone.

## FORMATION OF KINNEYIA STRUCTURES

### Discussion of Previous Models

Since Hagadorn and Bottjer's (1997, 1999) suggestion of a genetic linkage between wrinkle structures (including Kinneyia) and microbial activities, four models invoking the presence of microbial mats have been proposed.

1. Kinneyia structures reflect mat surface structures (Hagadorn and Bottjer, 1999). These authors studied freshly formed mats in shallow pools on modern supratidal flats (Redfish Bay, Texas) after flooding by a storm-induced high tide. They observed small-scale linear growth patterns produced by vertically oriented cyanobacterial filaments on the mat surface and suggested that these structures were the modern equivalents of ancient wrinkle structures. In similar situations it is usually observed that mat growth produces polygonal and reticulate patterns of various size (see overview in Gerdes et al., 2000); such structures are known as elephant skin in ancient examples (Runnegar and Fedonkin, 1992; Gehling, 1999) and are characterized by a reticulate pattern of sharp-crested ridges. As observed on some tidal flats along the Mediterranean coast of southern Tunisia, more linear growth patterns may occasionally develop, for example, induced by persistent wind-driven water oscillation or controlled by the retreating water limit in evaporating pools. Following Hagadorn and Bottjer's (1999) suggestion that wrinkle structures reflect mat growth patterns, ancient examples should exhibit similarities to elephant-skin textures, but none of the examples documented by Hagadorn and Bottjer (1999) show this feature, although some strongly resemble Kinneyia. Clearly, Hagadorn and Bottjer's (1999) suggestion relates only to growth structures on mat surfaces and does not apply to Kinneyia.

2. Kinneyia structures result from gas trapping beneath a sealing microbial mat (Pflüger, 1999). This model implies that the first structures to form are round-to-elliptic pits, resulting from localized trapping of gas in the sedimentary substratum at the contact with the overlying mat. As discussed above (see Fig. 3), it appears more likely that pits result from interference of crests that develop in divergent directions.

3. Kinneyia structures are load structures formed "in response to loading pressure originated by freshly deposited sediment" (Noffke et al., 2002, p. 540; 2003a). In detail, this model suggests that liquefaction occurred in the mat because of a sudden increase in loading pressure and that this moving mass protruded upward from the mat surface, displacing overlying sediment. As a consequence, the interface between the now fluid-rich microbial mats and freshly deposited overlying sediment formed a series of casts and molds. In contrast, Figures 4B–D show that upward protrusions rising from the mats do not exist and the lower boundaries of overlying sediment layers are flat. Thus, considering the physical processes at loading (see Allen, 1985b), Kinneyia should not be interpreted as load structures.

At some localities (e.g., Öland, Helmstedt), Kinneyia and small-scale load structures both occur in the same sedimentary succession, though on different layers. In plan view, the two structures differ by the more irregular geometry of load structures, the sharp-crested ridges between individual loads (Fig. 5D), and, in some cases, by the restriction of load structures to mud-draped ripple troughs (Fig. 5E). Load structures may occasionally be mistaken for Kinneyia or wrinkle structures in general. In such cases, thin sections revealing the internal structure and lithological sequence (Fig. 5F) are required for distinction.

4. Kinneyia structures result from dewatering after liquefaction of the sediment below mats (Bouougri and Porada, 2002). In a general way, dewatering processes have already been invoked by Seilacher and Aigner (1991). Bouougri and Porada (2002) showed subvertical dewatering structures entering Kinneyian crests from the underlying sediment and speculated that a wave-related, cyclic decrease in pressure might instantaneously cause uprising of water and sediment from below the cohesive mat. The dewatering model does not conflict with observations presented in this paper. It leaves unresolved, however, the development of the typical geometry of small-scale crests, troughs, and pits, frequently resembling interference ripples, that are generally observed along with Kinneyia structures.

### Discussion of Possible Factors Controlling Formation of Kinneyia

*Biologic*.—As described above, Kinneyia structures may develop where microbes settle on a new sediment surface and eventually form a cohesive mat. The structures form beneath or in the under part of the mat. These zones consist of water-saturated sediment and organic material, originating mainly from heterotrophs and their mucilage. The bacteria, some motile or adhering to sediment grains (e.g., Fenchel and Kühl, 2000; Overmann and van Gemerden, 2000), tend to form colonies rather

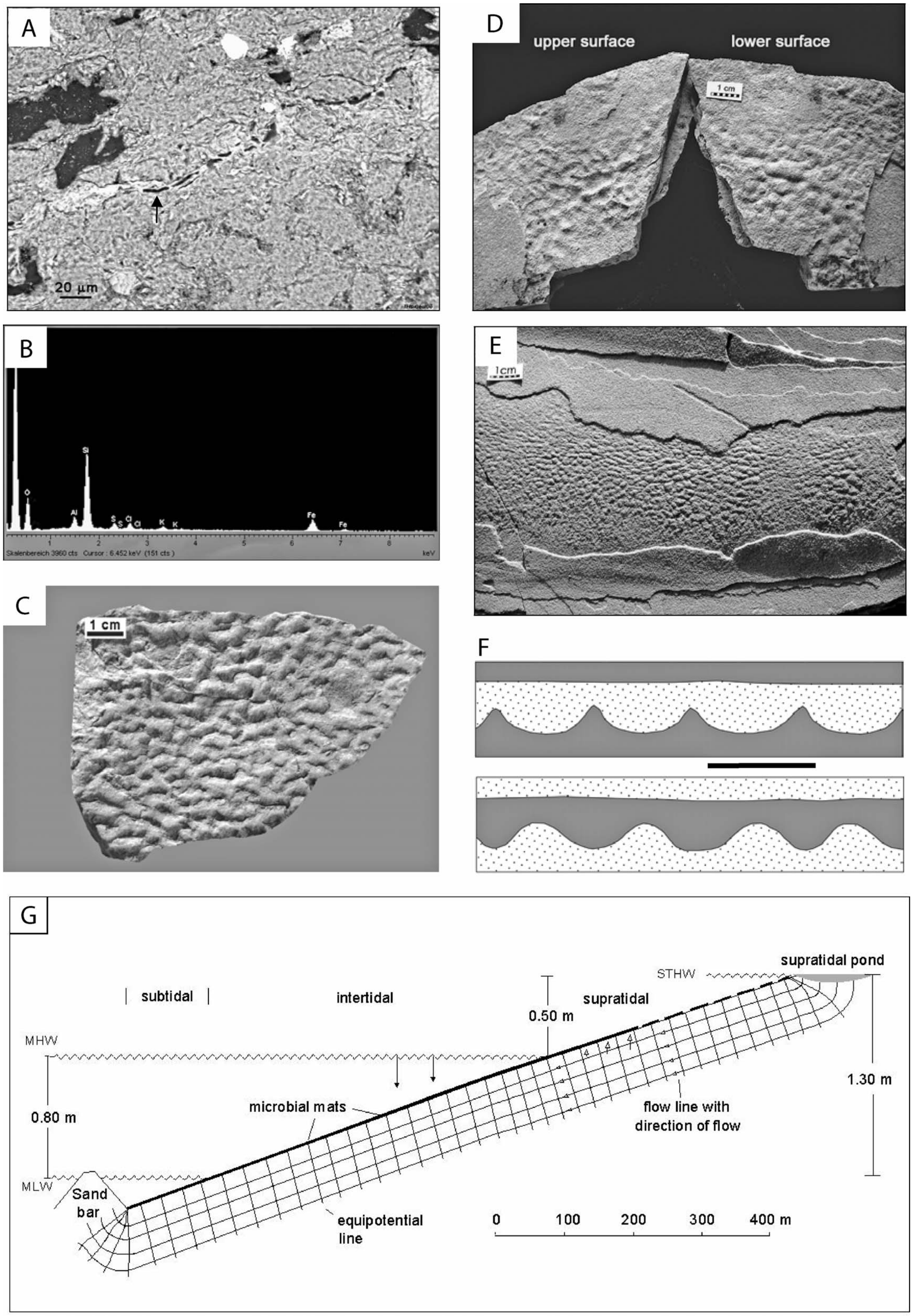

**FIGURE 5**—Kinneyia structures, load structures, and scenario for hydraulic modeling. A) Äleklinta, Öland, Sweden. Scanning electron micrograph showing interrupted preserved layer of carbonaceous material at upper contact of Kinneyia crest (arrow,); inset from Figure 4H. B) Äleklinta, Öland, Sweden. Representative energy-dispersive X-ray spectrum of carbonaceous layer showing high carbon content (large peak at left side) accompanied by alumosilicate, such as montmorillonite or illite, and possible compounds of iron sulfide. C) Wrinkle structure of Bouougri and Porada (2002), here interpreted as deformed Kinneyia structure (same sample as in Bouougri and Porada, 2002). D) Äleklinta, Öland, Sweden. Small-scale load structures on sandstone layer (right) and imprints of structures on upper surface of underlying sandstone bed (left). Note irregular trends of sharp-crested ridges, in contrast to Kinneyia structures. E) Small-scale load structures formed on lower bedding surface of a sand-silt layer in a mud-draped ripple trough. Lower Jurassic, Helmstedt. F) Graphic comparison of small-scale load structures and Kinneyia structures in sectional view. Scale bar = between 2–5 mm, depending on sediment parameters (e.g., grain size, bed thickness). Top: Load structures forming downward protrusions from sandstone or siltstone (dots) into underlying argillite-mudstone (gray). Individual loads are separated by sharp-crested ridges. Bottom: Kinneyia structures forming upward protrusions from sandstone or

than strong cohesive networks. The bacterial colonies likely are nonhomogeneously distributed in the sedimentary-organic mixture and may locally induce loosening of the sedimentary grain fabric. As an indication of these processes, coated grains are recognized in ancient samples (Noffke et al., 2002, 2003b; Bouougri and Porada, 2002) and are also present in Kinneyian crests (Figs. 4C, 4H). It may thus be argued that, in addition to the covering mat, loosening of the grain fabric in bacterial colonies interspersed in the water-saturated contact zone between mat and substratum may play an additional role in the formation of Kinneyia structures.

*Gas Trapping*.—Gases, mainly CO$_2$, H$_2$S, and methane, uprising from buried and decaying organic matter, tend to accumulate beneath cohesive mats covering the actual sediment surface (see e.g., Reineck et al., 1990; Noffke et al., 1996; Pflüger, 1999; Gerdes et al., 2000). This may particularly be the case if mature microbial mats are covered abruptly by an event deposit of some thickness. The accumulating gases are believed to induce local doming of the mat (gas domes; Gerdes et al., 2000) or to deform the mat into buckles and folds (some $\alpha$-petees, after Reineck et al., 1990). Beneath the strongly cohesive surface layer of the mat, which inhibits gas escape into the air or water, the gas will accumulate in the pore spaces of the sediment and between the bacterial colonies. With increasing gas pressure, grains and clusters of bacteria may be pushed aside, resulting in the formation of fenestrae-like cavities several millimeters in diameter (Gerdes et al., 2000) and, in extreme cases, of a sponge pore texture of the sediment (Noffke et al., 1996). It appears unlikely that gas trapping alone will lead to the typical and recurring pattern of Kinneyia, but the gas-filled pore spaces and cavities represent local inhomogeneities in the water-saturated sediment, which may modify groundwater flow on a micro scale.

*Hydraulic Conditions and Liquefaction*.—From a mechanical perspective, the specific geometry of Kinneyia structures, which resemble small-scale interference ripples (Fig. 3), appears to necessitate some kind of cyclic stressing, allowing rearrangement of the fabric by grain movement and eventual formation of ripplelike structures at a small wavelength. As an analogous example, rolling grain ripples of similar size and wavelength (Bagnold, 1946) result from oscillatory water flow, when grains are lifted from the bed and dragged along with the flow, near the sand-water interface (e.g., Stegner and Wesfreid, 1999; Bundgaard, 2003). Kinneyia ripples, however, likely form in the mat substratum where sediment grains are confined in a fabric and are not exposed to surface water flow, yet grain movement and reorganization of the fabric may take place if the sediment becomes liquefied.

From a hydraulic perspective, Kinneyia structures form beneath a sealing layer—for example, a cohesive mat—in a water-saturated sediment layer that may be regarded as a confined aquifer. This approach would allow application of modeling techniques, as used in hydrogeology of unconsolidated rocks, to simulate the distribution of hydraulic upward pressure acting against the sealing cover and to calculate the potential for liquefaction in the confined sediment layer beneath. Such modeling has been carried out for a hypothetical section across a low-gradient tidal flat, continuously covered by cohesive microbial mats in the intertidal to supratidal zones (Fig. 5G). In an additional run, the section was extended into the subtidal zone, again assuming continuous cover by cohesive, sealing mats over the whole section. The modeling is described and documented in Supplementary Data 1–5.[1]

The modelling provides several main results: (1) Considerable hydraulic pressure (seepage pressure) is built up in the mat substratum;[2] it increases downslope under steady and waning groundwater flow conditions and undergoes strong variations down to negative values in the lower intertidal zone caused by superimposed tidal hydrodynamics. (2) Over much of the intertidal to supratidal zones, hydraulic pressure attains sufficiently high values to create a potential for liquefaction down to a few centimeters in the sedimentary mat substratum. (3) Extension into the subtidal zone enhances the potential for liquefaction in general, attaining a maximum value near the subtidal-intertidal transition. (4) Because of superposition of regional groundwater flow and tidal hydrodynamics, cyclic downslope-upslope changes of groundwater flow direction occur in the potentially liquefied sediment close to shore in the intertidal zone. (5) In the subtidal and lowermost intertidal zone, a tidal signal, manifested in oscillations of seepage pressure, is superimposed on the regional hydraulic system.

*Additional Energy Input and Cyclic Stressing*.—As has been shown, liquefaction down to a few centimeters may easily occur beneath microbial mats settling on tidal flats, provided there is a regional or tidal groundwater flow and respective hydraulic pressure in the confined sediment. Sufficient potential for liquefaction alone, however, does not explain formation of the typical millimeter-scale Kinneyian ripples in the mat substratum. Unless some additional energy is introduced into the system, the liquefied sediment will remain in metastability without much fabric change. The calculations suggest four possible sources of additional energy input: (1) tidal hydrodynamics inducing strong cyclic variations in seepage pressure; (2) a recurrent tidal signal of oscillating pore pressure propagating in the mat and confined layer; (3) a short-term seismic signal of oscillating pore pressure; or (4) reversals of groundwater flow direction.

Wind-induced wave action, effective mainly in the subtidal and intertidal zones, would cause short-term, small variations in pore pressure propagating through the confined sediment at varying wavelengths and frequencies, whereas related orbital motion of water would apply nonstationary tractional forces on the mat surface. Both effects do not appear adequate to produce a regular pattern of small-scale crests and troughs in the mat substratum, mainly owing to their variability and nonstationary effect.

Tidal hydrodynamics are superimposed on the hydraulic system in the confined sand layer in the intertidal zone, leading to recurrent cyclic alternations between compression and liquefaction in the confined layer and to repeated changes of downslope-upslope groundwater flow with the tides (see Supplementary Data 2–3[1]). Compression induced by loading increases the effective stress at the grain-to-grain contacts, decreases porosity, and creates excess pore fluid pressure, whereas unloading allows loosening of the packing, liquefaction, and dissipation of excess pressure. The rate at which excess pore pressure can be dissipated at unloading will depend on the rate and amount of pressure variations and on the permeability of the sediment, but the calculations show that grains may momentarily float under effective stress conditions tending to zero (liquefaction), thus loosening the packing in the uppermost millimeters to

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[1] www.paleo.ku.edu/palaios.

[2] If evaporation occurs, hydraulic pressure resulting from elevation differences of heads may be complemented by a vertical hydraulic gradient resulting from replacement of the evaporative water loss near the surface. This evaporative pumping (Hsü and Siegenthaler, 1969) creates an additional uplift force depending on the rate of loss of pore fluids. It will be most effective where microbial mats are not developed and the sediment surface is subaerially exposed, but it may also take place beneath mats during low tides to replace water that is lost by evaporation or taken up by the mat organisms.

←

siltstone into overlying silty argillite representing former microbial mats. Note flat bottom of sandstone or siltstone bed overlying argillite. G) Scenario of hydraulic conditions on a low-gradient siliciclastic tidal flat covered by microbial mats in the intertidal to supratidal zones. A supratidal pond acts as hydraulic head for groundwater flow. Solid arrows = hydrostatic pressure (load); open arrows = hydraulic (upward) pressure. MLW = mean low water; MHW = mean high water; STHW = spring tide high water.

**TABLE 1**—Occurences of Kinneyia structures from the Jurassic to the Archean, as reported in the literature in some detail.

| Author(s) | Age | Depositional setting | Features quoted to indicate depositional setting |
|---|---|---|---|
| Häntzschel and Reineck (1968) | Jurassic | Subtidal | No features indicating emergence, but channels below event beds may indicate episodic emergence of the sea bottom. |
| Bloos (1976) | Jurassic | Subtidal | No features indicating emergence, but event beds laterally grading into tidal flats |
| Pruss et al. (2004) | Triassic | Subtidal | Hummocky cross-stratification in event layers. Trace fossils: *Rhizocorallium, Planolites, Gyrochorte* |
| Wunderlich (1970) | Devonian | Intertidal | Planar lamination, flaser bedding, oscillation ripples, mud cracks; tidal channels. |
| Pflüger (1999) | Silurian | Far offshore | Planar and cross lamination; spill-over oscillation ripples; isolated gutter casts. Trace fossils: *Skolithos, Gyrochorte, Corophioides* |
| Noffke (2000) | Ordovician | Intertidal, lagoonal | Sedimentary association of fine-grained sandstone and shale (intertidal); shale (lagoonal) |
| Martinsson (1965) | Cambrian | Subtidal | No oscillation ripples on event beds. Mud burrowers in shale-mud: *Teichichnus, Halopoa* |
| Noffke et al. (2002) | Terminal Proterozoic | Subtidal | Interbedded fine-grained sandstone and shale; sandstone beds exhibit planar lamination, ripple marks and abundant large mud clasts |
| Fedo and Cooper (1989) | Lower Cambrian | Intertidal | Laminated mudstone-siltstone. Flaser and lenticular bedding. Trace fossils; *Planolites, Rusophycus* |
| Bouougri and Porada (2002) | Neoproterozoic | Intertidal | Interbedded fine-grained quartzite, siltstone and argillite; planar lamination, wave ripples, current and interference ripples; desiccation cracks; mud chips |
| Sarkar et al. (2005) | Neoproterozoic | Intertidal to supratidal | Marine sandstone beds separating drying-upward aeolian successions |
| Beukes (1996) with reference to Eriksson et al. (1981) | Mid-Archean | Nearshore to tidal flats | Interbedded siltstone and shale with intercalated storm beds; siltstone beds with horizontal lamination, small-scale ripples. Some event beds possibly exposed at low tide |
| Noffke et al. (2003b) | Mid-Archean | Shallow marine | Interbedded siltstone and shale with intercalated fine-grained quartzites (event beds) |
| Hagadorn and Bottjer (1997) | Precambrian | Shallow subtidal to intertidal | Sedimentary structures and vertical facies relationships within specific measured sections |

centimeters of the confined layer. Because of the upwardly directed force of the hydraulic pressure, an upward movement of grains and water may then be anticipated. The effect of this process has been described by Bloos (1976), who observed a continuous layer enriched in detrital heavy mineral grains at the base of Kinneyia crests and troughs (Fig. 4A), suggesting that hydraulic pressures were sufficient to compensate the weight of low-density minerals like quartz and feldspar but were insufficient for higher-density mineral grains. It also shows that the process was restricted to the uppermost few millimeters of the confined layer. Cyclic compression and liquefaction, however, would basically lead only to a fractionation of grains according to their densities, not necessarily to a pattern of Kinneyian ripples and troughs at small distances.

In the subtidal and lowest intertidal zone, a signal of oscillating pore pressure originating from the tidal up and down of the sea level propagates through the potentially liquefied layer and overlying mat. The velocity of propagation will be $\leq 1$ m per tidal cycle in a liquefied sand layer several centimeters thick and a few millimeters per tidal cycle in an overlying mat assumed to be 3 cm thick, including the underlying interspersed bacterial colonies. The resulting wavelength will then be $\leq 1$ m in the liquefied layer and a few millimeters in the overlying mat, respectively. Thus, a quasi-stationary pattern of alternating zones of slightly elevated and decreased seepage pressure, developed at distances of a few mm, may occur in the mat. Since the squared wavelength is theoretically directly proportional to the hydraulic diffusivity of the layer, which in turn is proportional to its thickness, similar small wavelengths may be achieved in the liquefied layer if its thickness becomes very small; this is periodically the case near the seaward boundary of the mat during each tidal cycle (see Supplementary Data 2–3,[1] left-hand plots). Indeed, Kinneyia structures seem to form in a very thin, 1–3-mm-thick layer below a cohesive mat (Fig. 4; see Bloos, 1976).

Within the tidally induced, quasi-stationary pattern of increased and decreased pore pressure that is similar in size to Kinneyia structures, effects of grain lifting will slightly be increased in zones of elevated seepage pressure (upward pressure), thus leading to alternating zones of more and less large numbers of uplifted grains, corresponding to Kinneyian crests and troughs. The amplitude of the tidally induced pore pressure variation, however, undergoes strong (exponential) damping with shore distance and is virtually unrecognizable beyond a few meters above shore. Its wavelength and amplitude may vary widely with the hydraulic diffusivity and proportional thickness of the potentially liquefied layer and the overlying mat, respectively. Thus millimeter-sized structures resulting from the tidal signal may only develop in restricted areas or patches where conditions are favorable, mainly in the subtidal-to lowermost-intertidal zones. Remarkably, a patchy occurrence of Kinneyia structures is frequently observed.

Small wavelengths in the liquefied layer would also result if the cycle period is reduced and a higher frequency wave source is applied, which momentarily may occur during seismic events. Short-term seismic signals may superimpose on the recurrent tidal signal and cause strong variations or oscillations of pore pressure, depending on their amplitudes. Apart from suitable wavelengths, however, formation of Kinneyia-like structures would also require a great number of cycles, that is, rather long-term seismic vibrations. Furthermore, the seismic events would have to occur always at the right time, that is, following major storm or flood events. Thus seismic events are considered unlikely to form Kinneyia structures, though theoretically possible.

Cyclic downslope-upslope changes in groundwater flow direction in the liquefied sediment close to shore may also play a role. To illustrate possible effects of such reversals in flow direction, processes involved in the formation of rolling grain ripples, which are produced at the water-sediment interface by oscillatory viscous flow of water, are taken as an example, although these ripples are unlike Kinneyia. Mechanisms to produce such ripples (initial wavelength = 5–7 mm) include lifting of grains from the bed, differential movement velocities between grains and fluid, creation of shadow zones behind grains, in which particles are trapped, and progressive congregation of grains in shadow zones growing with repeated reversals of water flow (e.g., Stegner and Wesfreid, 1999; Rousseaux et al., 2004). It may be speculated that in confined liquefied sediment in which grains also move at a lower velocity than the surrounding fluid, repeated reversals of groundwater flow direction could lead to similar results. Envisaging the process starts with a single grain at a local instability—for example, induced by a microbial colony or gas bubble—repeated change of flow direction could progressively involve neighboring grains and eventually result in a structure of alternating zones consisting of more or less great numbers of displaced grains forming crest and troughs, respectively.

That groundwater flow may play a major role in the formation of Kinneyia structures is supported by Martinsson's (1965) observation that the dominant strike of Kinneyian ripples is perpendicular to the slope and the inferred prevailing groundwater flow direction. Whether reversals of groundwater flow are required to form Kinneyia structures remains speculative, but this would explain the frequently observed interference patterns of Kinneyian ripples as resulting from deviating flow directions of regional groundwater and tidal waters.

## CONCLUSIONS

Kinneyia is the most common wrinkle structure on bedding surfaces of ancient fine-grained siliciclastic sediments. It consists of millimeter-scale, irregularly curved, flat-topped crests and intermittent winding troughs and isolated round-to-elongate pits. Proportions of pits versus troughs may vary widely between different localities. Stretches of crests and winding troughs usually are oriented in two directions, one of which is by far dominant. This feature brings about a similarity to small-scale interference ripples with isolated pits resulting from interference of ripple crests.

Kinneyia structures are preferentially or exclusively observed on upper surfaces of ancient event deposits resulting from either storms or floods. The structures are overlain by fine-grained sediment, frequently silty argillite, which is considered to represent former microbial mats covering the new sediment surface. At the type locality of Kinneyian ripples, Martinsson (1965) observed the strike of the ripples to be perpendicular to the direction of the current that caused the influx of the clastic material in the area.

In the geological record, Kinneyia structures are reported from the Archean to the Jurassic. They occur in shallow marine, heterolithic, silty and shaly sedimentary successions, deposited largely on low-gradient margins of epicontinental basins or embayments thereof. Within such environments, subtidal and intertidal depositional settings have been suggested equally.

It appears that formation of Kinneyia structures requires specific hydraulic conditions, including a regional groundwater flow in a sediment confined beneath a sealing layer, for example, a microbial mat. Such conditions may prevail on tidal flats in the aftermath of storms or floods, when downslope groundwater flow is still strong, cohesive mats have already formed, and hydraulically induced excess pore pressures lead to liquefaction in the top portion of the confined sediment. In the lower part of the tidal flat, intrasedimentary hydraulics are superimposed by tidal hydrodynamics, resulting in alternating compression and liquefaction of the confined layer and cyclic changes of groundwater flow direction. Additionally, a pressure signal originating from tidal changes in sea level propagates through the mat and confined layer beneath and may produce a quasi-stationary pattern of alternating elevated and decreased seepage pressure, at distances of a few millimeters.

It is proposed that Kinneyia structures result from a superposition of regional groundwater flow and tidal hydrodynamics. Two tide-related processes may be involved: (1) a tidal signal inducing pressure variations at a wavelength of a few millimeters in the mat and in a very thin liquefied layer beneath; and (2) cyclic reversals of groundwater flow direction in the liquefied layer underlying a cohesive microbial mat. The tidal signal would mainly be effective in the subtidal zone and near shore in the intertidal zone and may explain the frequently observed patchy occurrence of Kinneyia structures on bedding surfaces. Groundwater flow reversals may occur from the subtidal to the intertidal zone and may explain the interference patterns of Kinneyian crests as resulting from deviating flow directions of regional and tidal groundwater. The two processes may act together under favorable conditions. Seismic events are considered unlikely, though theoretically possible, to produce Kinneyia structures, mainly because of their necessary coincidence with storm or flood events. Strictly speaking, Kinneyia structures are not microbially induced sedimentary structures (Noffke et al., 2001a); rather, they result from physical processes and are thus physically induced, though microbes appear to play an important role in providing an interface for these processes to act upon.

Based on the proposed model, Kinneyia structures may form in the subtidal zone and in the intertidal zone at positions with repeated tidal inundation. Prerequisites include a cohesive, sealing layer—for example, a microbial mat—and a regional downslope groundwater flow in the substratum.

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