MICROBIALLY INDUCED SEDIMENTARY STRUCTURES—A NEW CATEGORY WITHIN THE CLASSIFICATION OF PRIMARY SEDIMENTARY STRUCTURES—DISCUSSION

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INTRODUCTION

Noffke et al. (2001) introduced a new category of primary sedimentary structures that they named ''microbially induced sedimentary structures.'' Their attempt is laudable and timely, inasmuch as the importance of microbial influences on sedimentary substrates is becoming increasingly recognized.

The authors are perfectly correct in pointing out the requirement for, and validity of, nomenclature for sedimentary structures that result from microorganic interaction with sediment. Among the sedimentary structures shown in their paper, one group is especially interesting because it is similar to sedimentary structures that carry weighty and beleaguered interpretations. Noffke et al. (2001) refer to this sedimentary structure as organically dimpled surfaces (erosional remnants and pockets; multidirectional/palimpsest ripples), which look very much like runzelmarken, or wrinkle marks. Noffke et al. (2001) differentiate between structures that are induced by microbial leveling (wrinkle structures) and structures that are interpreted to be post-biostabilization, erosional remnants and pockets. ''Wrinkle structures'' are particularly similar to runzlemarken, in that they have a micro-rippled appearance, millimeter-scale amplitudes, millimeter-scale wavelengths, and rather chaotic orientations. However, Noffke et al.'s (2001) wrinkle marks have a pronounced dimpled appearance and lack sinuous, parallel crests that are common with runzlemarken. Also, Noffke et al.'s suggestion that wrinkled surfaces result from microbial leveling is not consistent with mechanisms previously suggested for the emplacement of runzelmarken. Indeed, the primary physical requirement to develop runzelmarken, which is an elevated cohesiveness of the sediment, has more in common with erosional remnants and pockets that result from biostabilization.

In the recent literature, some authors have linked ''wrinkle structures'' to microbial stabilization of sediment (Hagadorn and Bottjer 1997; Pflueger 1999). In the case of runzelmarken, the recognition that penecontemporaneous deformation is a fundamental process is well documented (Reineck 1969; Teichert 1970; Allen 1984). So, given their similarity to Noffke et al.'s (2001) biogenically leveled ''wrinkle structures,'' and their apparent dependence on biostabilized sediment (like ''erosional remnants and pockets'') why are runzlemarken not included in the classification of microbially influenced sedimentary structures?

WRINKLE MARKS (RUNZELMARKEN)

Runzelmarken were initially described by Häntzschel and Reineck (1968). Similar ripples, Kinneyia, were described by Martinsson (1965). The initial description, irregular ripple-like features that have low relief, pronounced symmetry, and a chaotic distribution, has led to their unfortunate linkage with adhesion ripples. However, adhesion ripples are sinuous to straight crested antiripplets of sand that have an extremely steep stoss side. Given the accepted descriptions of these sedimentary structures, it is clear that runzelmarken are not synonymous with adhesion ripples.

In Reineck (1969) it was reported that runzelmarken are produced in sand that is semicohesive. Because it was thought that wind shear was primarily responsible for sediment wrinkling, Reineck suggested that runzelmarken indicated intermittent emergence of a substrate. That suggestion has, unfortunately, become dogma. In fact, the acceptance of Reineck's original interpretation has led to its being overused as an interpretive tool. Reineck and Singh (1980) recognized that there had to be other ways to produce such wrinkle marks; ''. . .likely there is some other mode of origin as well active in flysch sediments.'' Unfortunately, this revelation has been mostly lost in the literature.

Conceptually, it is better to think of runzelmarken as the product of sediment cohesiveness and shear stress exerted on the sediment. Reineck (1969) suggests that water is the main agent for sediment cohesion. However, it is well known that microorganisms effectively bind sediment and that they can rapidly transform loose sediment into cohesive sediment. The process of microbially induced binding is summarized by Noffke et al. (2001). With microbial influence, sediment cohesion is increased dramatically in both intertidal and subtidal settings (Noffke 1998).

Just as there are subaqueous means of binding sediment, there are many subaqueous mechanisms that might strain the upper portion of the sediment–water interface. These include: (1) wave orbitals interacting with the bottom sediment; (2) sediment creep down dune, ripple, and foreset surfaces; and (3) shear stress resulting from gentle hydraulic currents. These examples suggest that runzelmarken should be abundant in the rock record and are certainly not strong evidence of intertidal processes.

Indeed, examples of ancient subtidal runzelmarken are common (Fig. 1A, B). Proximal offshore, storm-influenced rocks, such as those reported by Tanoli and Pickerill (1988), Brenchley et al. (1993), and Hagadorn and Bottjer (1997), have runzelmarken in abundance. The runzlemarken generally occur in fine-grained sandstone and are associated with oscillation ripples. Unfortunately, these structures are commonly taken to be intertidal indicators, leading to misinterpretation of the sedimentary succession.

Although Noffke et al. (2001) do not suggest that wrinkle marks should be limited to intertidal occurrences, the realization that runzlemarken could easily occur in subtidal settings evokes three questions. (1) How can one tell intertidal from subtidal runzelmarken? (2) Are all runzelmarken indicative of microbial stabilization of the substrate? (3) What interpretations might be drawn from the observation of runzelmarken in the rock record? Although it is outside the scope of this discussion to thoroughly answer these questions, intuitive answers would include: (1) Using the other sedimentological evidence, such as the presence of rills (Reineck and Singh 1980), nature of the bioturbation (Gingras et al. 1999; Zonneveld et al. 2000), and the overall sedimentary context (Clifton 1982); (2) although Reineck (1969) showed that dampening of muddy sand was enough to make it cohesive if the sediment is sporadically emergent, microbial stabilization may be the cause of all subtidal wrinkle marks; and (3) microbial colonization evidences colonization windows during which bedforms were moribund and thereby is related to sporadic sediment mobilization.

Because runzelmarken appear to represent the effects of sediment creep (shortening) following sediment stabilization, they are not perfectly synonymous with Noffke et al.'s (2001) ''structures induced by biostabilization.'' Rather, runzlemarken appear to represent both ''bedding deformed by penecontemporaneous processes'' (after Pettijohn and Potter 1964) and the former. Therefore, runzlemarken cannot be classified within the framework of Noffke et al.'s (2001) proposed scheme. Moreover, Noffke et al.'s (2001) biogenically leveled ''wrinkle marks'' and microorganically stabilized ''erosional pockets and remnants'' are probably not just the result of bio-mat leveling, but may be influenced by penecontemporaneous defor-

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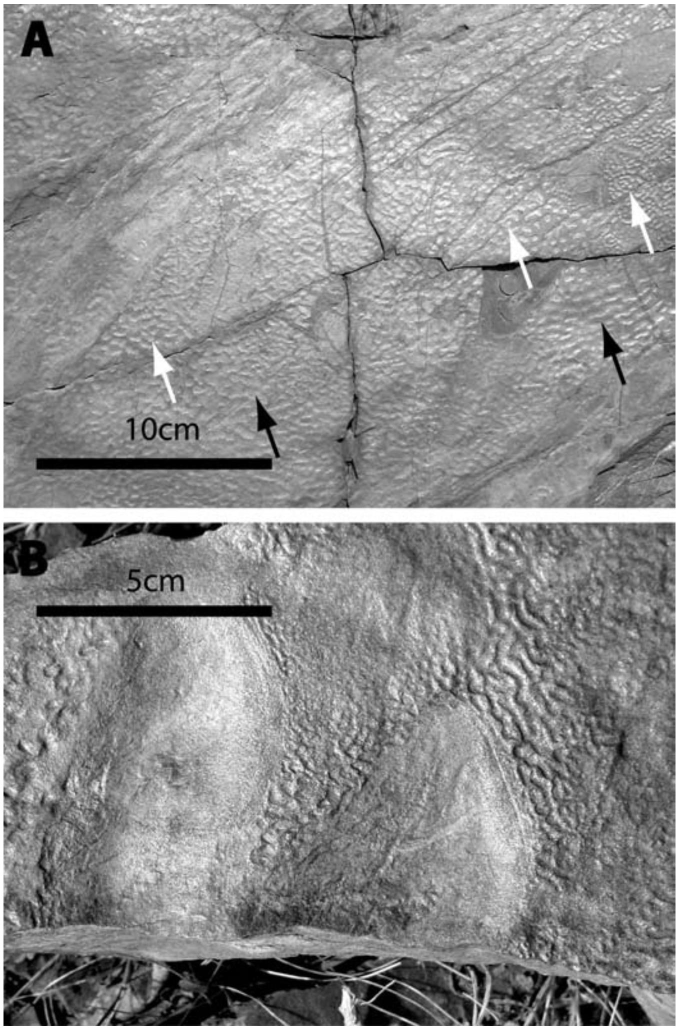

FIG. 1.—Subtidal runzelmarken from Atlantic Canada. **A)** Wrinkle marks from outcrops of the Cambrian–Lower Ordovician Saint John Group, near Saint John, southern New Brunswick. These strata are interpreted to represent shelfal, storm-reworked deposits (Tanoli and Pickerill 1988). Notice the composition of wrinkles (black arrow) and dimples (white arrow), suggesting that small erosional remnants (due to microbial fixing) are superimposed or adjacent to runzelmarken (due to sediment strain). **B)** A similar surface from the Bell Island Group, Bell Island, Newfoundland, Canada. This has been interpreted to be intertidal, and is virtually indistinguishable from Part A.

mation and thereby hybridized with runzelmarken; the interpretation of such structures should be clarified.

The persistent omission of runzlemarken from sedimentary-structure classification schemes has: (1) diminished their importance as interpretive tools; (2) led to misinterpretation of sedimentary deposits; and (3) failed to recognize the diverse and mostly undocumented effects of microbial stabilization on sedimentary structure. It is apparent that Noffke et al. (2001) fill a void by erecting their classification scheme. However, that scheme should be modified so that sedimentary structures such as runzelmarken are also included.

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MICROBIALLY INDUCED SEDIMENTARY STRUCTURES—A NEW CATEGORY WITHIN THE CLASSIFICATION OF PRIMARY SEDIMENTARY STRUCTURES—REPLY

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The comments of Murray Gingras on our article on the classification of Microbially Induced Sedimentary Structures (Noffke et al. 2001b) are highly appreciated. In our reply, we first clarify some terms. Then we respond to the different points of Gingras' discussion, and finally make concluding statements.

CLARIFICATION OF TERMS

1. In his discussion, Gingras states that erosional remnants and pockets as well as multidirected ripple marks would be Runzelmarken (English translation: wrinkle marks). However, neither the dimensions nor the shapes of both these surface structures resemble Runzelmarken, which are small-scale, irregular crinkles on bedding planes (Häntzschel and Reineck 1968). Erosional remnants and pockets consist of two structural elements both up to several square meters in size: elevated planar and mat-covered surface parts; and deeper-lying, rippled and noncolonized surface parts (compare Gerdes et al. 2000, Noffke 1999, or Noffke and Krumbein 1999). Multi-directed ripple marks are chaotic-like patterns of current ripples of normal dimensions (Noffke 1998).

2. In his discussion, Gingras argues that erosional remnants and pockets are products of post-biostabilization processes. This is not true. Erosional remnants and pockets, as outlined, e.g., in Noffke (1999) and Gerdes et al. (2000), are products of overlapping of both biostabilization and erosion. Biostabilization, as we define in our article, is especially important in erosional dynamic regimes.

POINTS OF DISCUSSION

According to the points presented in the discussion by Gingras, we regard his Runzelmarken as identical with our wrinkle structures. This we would like to explore in the following:

1. In his discussion, Gingras states that wrinkle structures are particularly similar to Runzelmarken. We refer to Noffke (2000), where ''transparent'' and ''non-transparent'' wrinkle structures are shown from siliciclastic shelf and tidal-flat environments. Similarities with Runzelmarken are apparent, and a first conclusion would be that both phenomena are the same.

2. Gingras proposes that we should think of Runzelmarken as the product of sediment cohesiveness and shear stress exerted on the sediment. This assumes microbial binding of sediment as complementary to the thixotropic material that Reineck used in his experiments (Reineck 1969). In response, we note that Friedman et al. (1992, p. 227) stated that ''geologists are confronted, not only with products of processes that operated in isolation, but with products of associated processes that operated collectively in what we know as depositional environments.'' With respect to our discussion, we thus should consider Reineck's model that Runzelmarken (wrinkle marks) rise from thixotropy or other abiogenic conditions. In case the of wrinkle structures, sediment-binding biofilms induce the ''thixotrophic'' mechanical reaction of the sediments on erosion and deformation. If physical processes (shear stress etc.) that in each case (physical from thixotropy, biologically induced by presence of biofilms) are similar, the resulting wrinkled surface patterns also may be similar. We refer to Noffke (2000), where different types of wrinkle structures are described. Transparent wrinkle structures (= the original physically shaped surface morphology is visible underneath the wrinkles) are originated by burial of thin-layered microbial mats. Nontransparent wrinkle structures (= no original physically shaped surface morphology is visible underneath the wrinkles) record burial of thick microbial mats. Sinoidal-shaped torn structures record onloading pressure. Generally, all Microbially Induced Sedimentary Structures, like physical sedimentary structures or bioturbation structures, experience burial before any consolidation and preservation takes place. Therefore, all fossil examples have a slightly deformed and compressed appearance in rocks.

3. Gingras argues that Runzelmarken have been mis-used as indicators for intertidal environments because other authors described them also from shelf environments. We do not dispute this and never implied a purely intertidal origin. As shown by Noffke (2000), different types of wrinkle structures are related to different facies zones. Wrinkle structures occur in tidal flats, lagoons, and shelf areas. They may be related mainly to the depth of light penetration, at least in cases where the mat constructors were photoautotroph cyanobacteria.

4. Gingras also states that Runzelmarken occur in fine-grained sandstones. We agree. In Noffke (2000) and Noffke et al. (in press) the relationship of substrate and occurrence of cyanobacteria is explained. Wrinkle structures occur exclusively in quartz-rich sandstones of fine sand grain sizes. The lithology of the rocks records moderate reworking by hydrodynamics. Also today we mostly (though not exclusively) observe that cyanobacteria preferentially colonize clear, translucent sands of fine grain sizes where they are able to construct their dense mat fabrics (e.g., Noffke and Krumbein 1999).

CONCLUSION

We thus would like to modify two of the conclusions drawn in Gingras' discussion:

1. Gingras states that Runzelmarken have been consistently omitted from sedimentary-structure classifications, including the one proposed by Noffke et al. (2001b). They have been and will continue to be underestimated as facies indicators. However, as shown above, we regard Gingras' Runzelmarken as identical with our ''wrinkle structures.'' Therefore, the phenomena are included in our scheme. Numerous recent studies have shown the relevance of wrinkle structures (and Microbially Induced Sedimentary Structures in general) as facies indicators (e.g., Gerdes et al. 1994; Noffke 1998, 1999, 2000; Noffke et al. 2001a).

2. Gingras states that Reineck's hypothesis on the origin of Runzelmarken became dogma: Runzelmarken indicate intermittent emergence of a substrate. However, the term ''Runzelmarken'' itself implies the abiogenic origin, because ''Marken'' per definition are related to physical processes (Reineck and Singh 1980, compare also discussion of the term in Hagadorn and Bottjer 1999, and Pfluger 1999). Hagadorn and Bottjer (1997) have placed physically generated Runzelmarken (wrinkle marks) into the overall group of wrinkle structures, which includes both physically induced and bio-induced crinkled bedding planes. This we have to keep although *wrin-*

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kle is the literal translation of the German word *Runzel.* ''Mit Stirnrunzeln'' idiomatically means that a person gets a wrinkled forehead or eye-brows because she or he is slightly concerned or in doubt about some statement or behavior. It looks as though H.E. Reineck, the great sedimentologist, would very friendly and ironically wrinkle or runzel his forehead, if he could hear us.

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