SILICICLASTIC STROMATOLITES AND OTHER MICROBIALLY INDUCED SEDIMENTARY STRUCTURES IN AN EARLY DEVONIAN BARRIER-ISLAND ENVIRONMENT (MUTH FORMATION, NW HIMALAYAS)

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ABSTRACT: **Microbially induced sedimentary structures, including spectacular siliciclastic domal stromatolites, up to 80 cm wide and 30 cm high, have been found in coastal quartzites of the Lower Devonian Muth Formation (Pin Valley, NW Himalayas). The microbial structures occur in intervals of the formation associated with physical sedimentary structures that indicate, at least temporally, emergent conditions. These observations support the interpretation of a peritidal setting for the microbial structures within the wave-dominated, barrier-island depositional environment of the Muth Formation. The siliciclastic domal stromatolites probably formed in a shallow subtidal to intertidal environment with high hydraulic energy, where periods of high sedimentation rates are interrupted by periods of low or zero sedimentation. Microbial gas pits and microbial gas domes were produced by ascending gas from degrading buried organic material in a lower supratidal zone, influenced by tidal flushing. Multidirected ripple marks document a series of erosion events interfering with microbial stabilization in lower supratidal settings. Polygonal shrinkage cracks from supratidal environments indicate a semiarid paleoclimate. The replacement textures of the microquartz matrix in the stromatolites indicates the former existence of syngenetic carbonate cements, which may explain the preservation of the domal stromatolites in the high-energy, siliciclastic environments of the Muth Formation. The Muth stromatolites, commonly containing more than 60 vol. % siliciclastic grains, prove the existence of microbial activity in environments of higher sedimentary stress than generally thought and extend our knowledge of the capability of benthic microbial organisms to settle in siliciclastic shallow marine environments.**

INTRODUCTION

Most studies on microbially induced sedimentary structures focus on carbonate environments, where rapid mineral precipitation and cementation enhances the formation of microbial buildups like stromatolites, with a relatively high preservation potential in the fossil record (for review see Riding 2000). Depositional environments with a considerable siliciclastic influence have generally been regarded as less suitable for the formation of microbial sediments than pure carbonate environments. However, modern analogues indicate that microbial communities can become established even in strongly siliciclastic influenced areas, if periods of high sedimentation rates are interrupted by periods of low or zero deposition, thus facilitating the repeated resettlement of microbial communities on the sediment surface (Reineck and Gerdes 1997; Lee et al. 2000).

The scarcity of siliciclastic stromatolites in the geologic record possibly results from the observation that early carbonate lithification, which is essential for the preservation of microbial buildups (Logan 1961), is usually reduced in siliciclastic dominated settings (Braga and Martín 2000). Additionally, the identification, description, and especially definition of stromatolites is challenging, because they ''are simultaneously fossils and sediments'' (Riding 1999), which is especially true for siliciclastic stromatolites (Schieber 1998). Consequently, sedimentary structures indicating microbial activity in siliciclastic-dominated environments have been increasingly recognized only in the past few years (Martín et al. 1993; Hagadorn and Bottjer 1997; Schieber 1999; Gerdes et al. 2000).

Riding (1991) introduced the term agglutinated stromatolites for microbial buildups with significant amounts of detrital grains. Martín et al. (1993) defined siliciclastic stromatolites as those microbial sediments with $> 10\%$ detrital, siliciclastic particles. The group of microbially induced sedimentary structures (MISS) in siliciclastic coastal environments have recently been defined as new category of primary sedimentary structures (Noffke et al. 2001b; Noffke et al. 2003). Though small amounts of siliciclastic grains are common in many recent and fossil carbonate stromatolites, reports on microbial sediments containing higher amounts of siliciclastic particles are rare.

This paper describes siliciclastic microbially induced sedimentary structures from shallow marine quartzites of the Lower Devonian Muth Formation in the NW Himalayas (Fig. 1). The microbial structures include spectacular siliciclastic domal stromatolites, as well as microbial gas pits, microbial gas domes, characteristic multidirected ripple marks, and typical polygonal shrinkage cracks. In a general approach, all of these structures can be explained by the formation of microbial mats (Krumbein 1983) and their subsequent modification by a variety of processes. The structures have close analogues in modern peritidal environments, where they reflect complex interactions between biological, physical, and sediment-dynamic processes. Therefore, they represent sensitive tools for the paleoenvironmental reconstruction of siliciclastic peritidal areas (Logan 1961; Gerdes et al. 1993; Gerdes and Krumbein 1994; Gerdes et al. 2000; Noffke et al. 2001a; 2001b; Noffke et al. 2003).

The microbially induced sediments in the Muth Formation, commonly containing more than 60 vol. % siliciclastic grains, find hardly any comparison in the literature. The aim of our study is thus to investigate the formation and the paleoenvironment of the various types of microbial structures in the Muth Formation. A comparison with modern and fossil analogues contributes to our understanding of microbial activity in settings with a strong siliciclastic influence.

GEOLOGIC SETTING

Tectonic Framework

The Muth Formation is part of the Tethyan Zone of the Higher Himalaya tectonic unit. The Tethyan Zone comprises more than 7 km of Neoproterozoic to Eocene sediments of the former northern Indian passive margin and has been traced along the entire Himalayan orogen (Gansser 1964; Bhargava and Bassi 1998). To the north, the Tethyan Zone is bordered by the ophiolithic mélange of the Indus–Yarlung Suture Zone, which represents the boundary between Indian and Asian continental crust (Gansser 1964). The southern limit is formed by the normal faults of the Southern Tibetan Detachment System and its equivalents (Burg et al. 1984).

The studied sections of the Muth Formation in the Pin Valley are situated in the Himalayan fold-and thrust belt, which resulted from Eocene Eo-Himalayan deformation. The sediments are folded into NW–SE trending folds with maximum wavelengths of approximately 5 km (Fuchs 1982; Wiesmayr and Grasemann 2002). The Muth Formation represents a competent layer within the Tethyan sediments and does not carry second-order folding as do less competent formations. As a result, sedimentary structures are well preserved. The illite crystallinity values of the investigated sections range within diagenetic conditions (Wiesmayr and Grasemann 2002).

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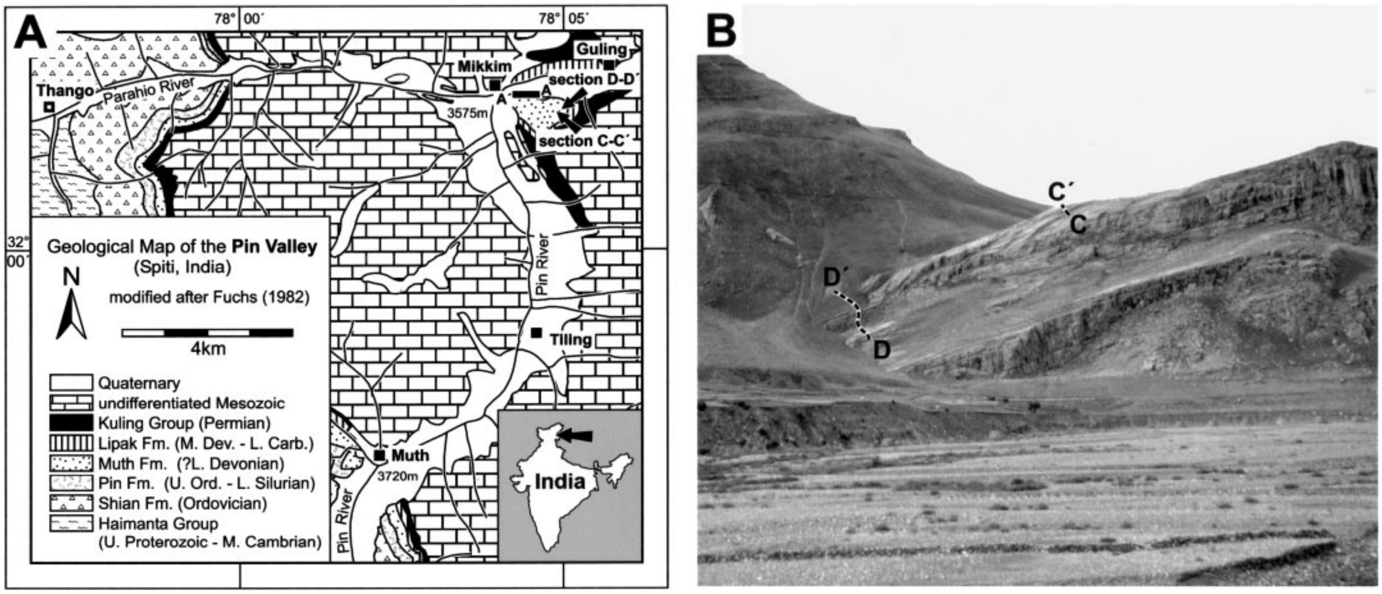

FIG. 1.—**A)** Geological map of the Pin Valley (note the inset for location in NW India) modified from Fuchs (1982), with the position of the investigated Muth Formation sections at the anticline southeast of Mikkim. The thick line indicates the course of section A–A′; arrows point to the location of sections C–C′ and D–D′. **B)** View to the south to the steep cliffs formed by the Muth Formation at the eastern limb of the anticline near Mikkim; location and course of sections C–C′ and D–D′ are indicated by dashed lines.

Stratigraphic Context and Age of the Muth Formation

The Cambrian to Lower Carboniferous portion of the Tethyan Zone is dominated by siliciclastic rocks deposited in a vast, shallow, and relatively planar basin, deepening towards the north-northeast (Bhargava and Bassi 1998). Generally, microbial sediments are not uncommon in the shallow marine record of the former northern Indian passive margin (Bhargava and Bassi 1998). In addition to the microbially induced sedimentary structures in the Muth Formation, dolomitic domal stromatolites have been found in the Middle Cambrian Karsha Formation in Upper Lahaul (Vannay 1993), siliciclastic columnar stromatolites occur in the Ordovician Shian Formation, and thick intervals of carbonate stromatolites occur in the Middle Devonian–Lower Carboniferous Lipak Formation (Draganits et al. 2002).

The stratigraphic context of the Muth Formation has been discussed recently by Draganits et al. (2001) and Draganits et al. (2002). In the Pin Valley, near the village of Mikkim, the Muth Formation reaches c. 300 m thickness. The contact with the underlying Pin Formation (a peritidal, dolomitic-calcareous, argillo-arenaceous succession with sporadic small reefal complexes) is a pronounced unconformity showing subaerial exposure and erosion (Fuchs 1982; Bhargava and Bassi 1998; Draganits et al. 2001). The gradational contact with the overlying Lipak Formation inhibits a precise lithostratigraphic boundary definition. Draganits et al. (2001) and Draganits et al. (2002) placed the boundary at the first appearance of dark carbonaceous, argillaceous siltstone and shale (with plant fragments) interbedded with sandstones. These lithologies contrast strongly with the mature, unfossiliferous quartzites of the underlying Muth Formation and indicate a gradual but fundamental change in sedimentation.

The Muth Formation is almost devoid of fossils. Rare fossils with little age information include poorly preserved brachiopods and corals from Garhwal (Goel et al. 1987), a single brachiopod from Kumaon (Bassi 1988), and badly preserved radiolarians (Draganits 2000). Thus, its age is constrained mainly by the fauna of the strata above and below. The spurious paleontological reports by V.J. Gupta in the 1970s and 1980s (Talent et al. 1988) have been ignored.

Conodonts, recently found in the uppermost levels of the Pin Formation near Mikkim, unequivocally indicate a Llandoverian age (Ruth Mawson and John Talent, personal communication 2001). Conodonts from the base of the overlying Lipak Formation indicate a Middle Devonian age (Givetian, mid to late Early *varcus* Subzone) (Draganits et al. 2002). Considering the pronounced erosional unconformity between the Pin and Muth formations and the transitional contact between the Muth and Lipak formations, the Muth Formation of Spiti is probably Lower Devonian, although a late Silurian age for basal parts cannot be completely excluded (Goel et al. 1987).

Depositional Environment of the Muth Formation

The general depositional environment of the Muth Formation is interpreted as a wave-dominated barrier-island system (Draganits 2000 and references cited therein). On the basis of differences in sedimentary structures, paleocurrent directions, and lithologies, Draganits (2000) divided the formation into four facies associations (FA 1 to FA 4, Fig. 2).

Facies Association 1.—FA 1 comprises pure quartzite. The lowermost beds show root casts, followed by relatively well-bedded, horizontally laminated sediments, with increasing abundance of tabular cross-bedding at higher levels. FA 1 is regarded as an overall transgressive coastal succession with beach sediments above the unconformable contact to the Pin Formation and upper-shoreface to upper-foreshore deposits in higher levels. Only two beds with siliciclastic domal stromatolites (Fig. 2) are found within FA 1.

Facies Association 2.—FA 2 consists of pure quartzites. Most of the described siliciclastic microbial structures have been found within FA 2 (Figs. 2, 3); they are associated with physical sedimentary structures that indicate shallow intertidal to lower supratidal marine settings. In section A–A′, these sedimentary structures are dominated by high-angle large-scale tabular and tangential, concave-upward cross-bedding alternating with planar laminated beds, sometimes with symmetrical ripples. They represent coastal dunes alternating with upper-foreshore and possibly beach sediments. Sedimentary structures such as flat-topped ripples, adhesion ripples (Kocurek and Fielder 1982), tear-shaped ridges (McKee 1957), multidirected ripple marks (Noffke 1998), and polygonal shrinkage cracks (Gerdes et al. 1993) indicate at least temporally emergent conditions. Additionally, arthropod trackways found in this interval show deeply impressed tracks, especially on foreset surfaces. The formation of these tracks under water

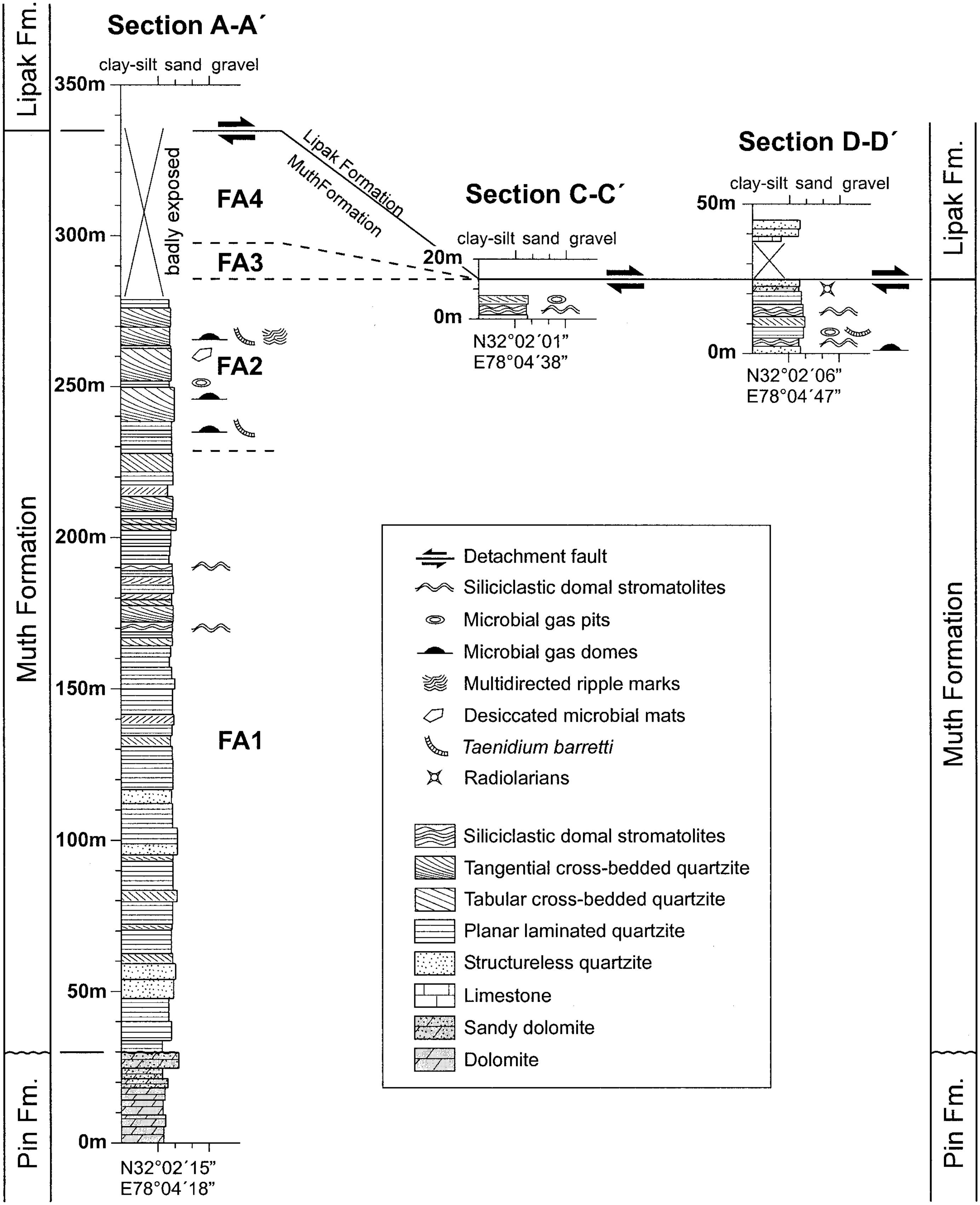

FIG. 2.—Lithostratigraphic sections of the Muth Formation southeast of village Mikkim; their correlation to each other is indicated. FA = facies association. Microbially induced sedimentary structures are found at two levels in FA 1 in section A–A′ and are common in FA 2 in all sections. Note that the occurrence of the trace fossil *Taenidium barretti* commonly coincides with the occurrence of microbial gas domes in section A–A′ and with the occurrence of microbial gas pits in section D–D′ (Fig. 3).

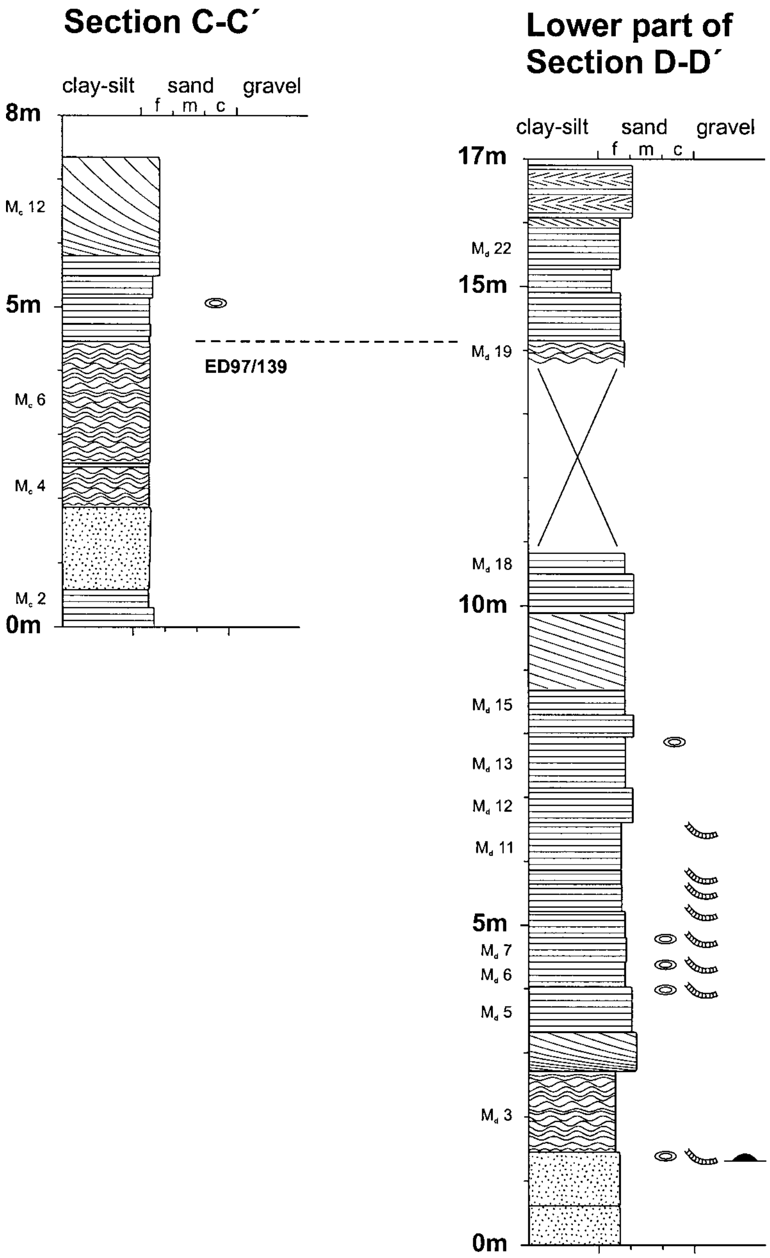

FIG. 3.—Detail of sections C–C′ and D–D′. Labeling to the left of the sections represents bed numbers referred in the text. For explanation of the symbols, see Figure 2. Both sections can be correlated by the prominent domal siliciclastic stromatolites of beds M_c6 and M_d19. Note the common combined occurrence of *Taenidium barretti* with microbial gas pits in section D–D′.

is unlikely, inasmuch as buoyancy would have reduced the weight of the producers considerably, resulting in much shallower tracks (Draganits et al. 2001).

In section D–D′, symmetrical, bifurcated ripples with short wavelengths on the upper bedding surface of M_d5 and M_d7 resemble wave ripples. Thin tabular cross-beds with opposite paleocurrent directions higher up in section D–D′ resemble herringbone cross-stratification, common in lower intertidal to subtidal environments. Bed M_d12 comprises exceptionally mature sand grains with low-angle lamination resembling beach lamination. The radiolarian fauna from a single dolomitic sandstone bed at 22 m in section D–D′, close to the domal stromatolites (Fig. 2), gives evidence for generally open marine conditions at least for this part of the Muth Formation (Draganits 2000). The complete lack of evaporitic minerals or pseudomorphs may exclude hypersaline conditions.

Facies Association 3.—FA 3 is a conspicuous interval, c. 10 m thick, comprising orange to brick red, very fine-grained dolomite, with some siltstone and sandstone beds. The sharp contact with FA 2 may represent a depositional break. Draganits (2000) and Draganits et al. (2001) interpreted the sediments of FA 3 as lagoonal deposits with coarser-grained back-barrier washover fans.

Facies Association 4.—FA 4 comprises quartzites, which gradually become slightly impure towards the top. In lower levels, a few large-scale cross-bedded beds, possibly representing coastal dunes, have been observed, followed by alternating planar bedding and tabular cross-bedding in upper levels. The latter comprises foreshore to shoreface sediments with an overall transgressive trend and a gradational contact to the peritidal deposits of the overlying Lipak Formation (Draganits et al. 2002).

MICROBIALLY INDUCED SEDIMENTARY STRUCTURES IN THE MUTH FORMATION

All the microbially induced sedimentary structures described were found in three lithostratigraphic sections (Figs. 2, 3) in the anticline southeast of

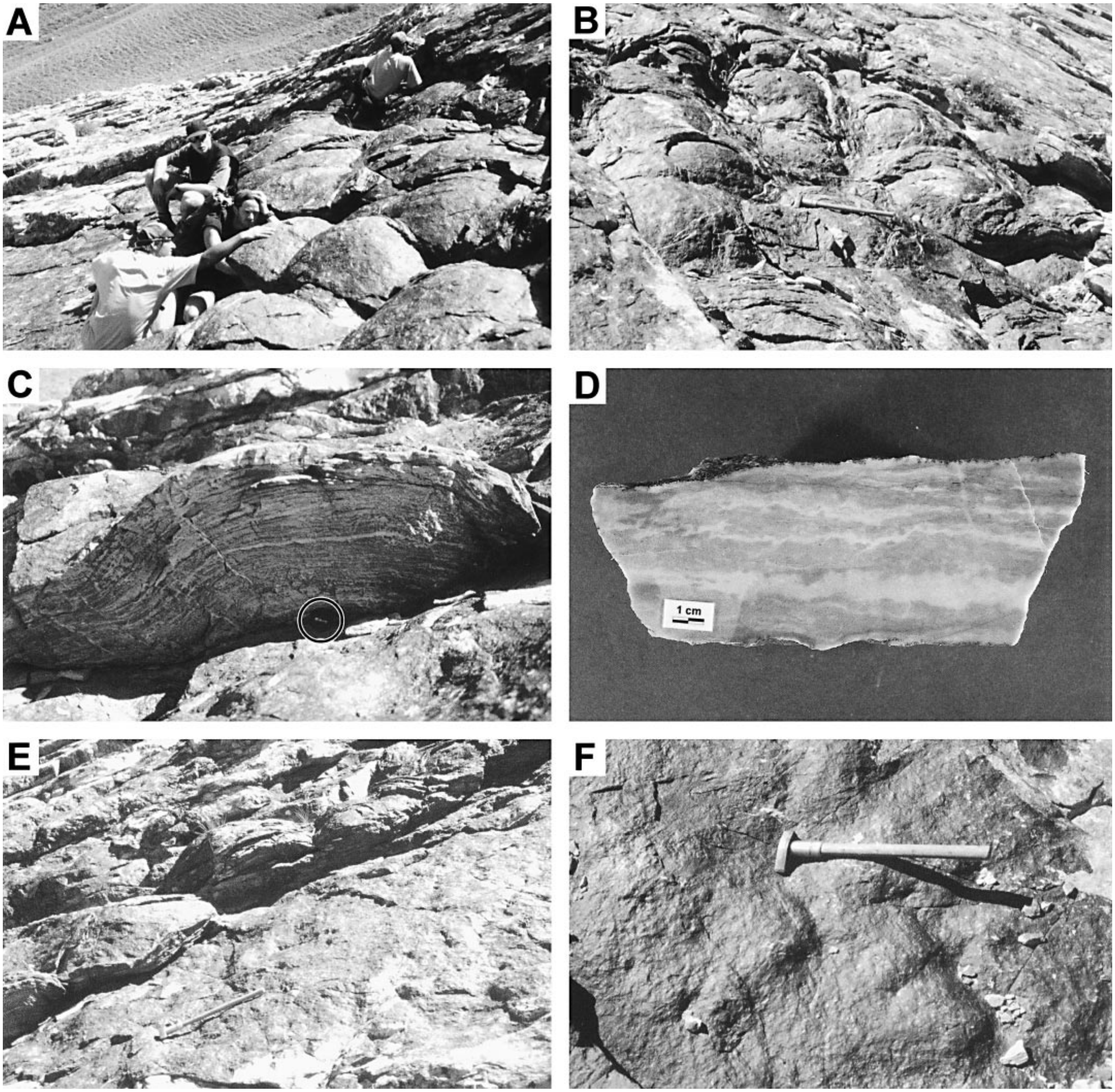

FIG. 4.—**A)** Puzzled structural geologists looking at the regular-shaped siliciclastic domal stromatolites of bed M_c6 (see Fig. 3), viewed towards the east-southeast. Stromatolites are laterally linked hemispheroids (LLH-C) in the classification of Logan et al. (1964); they measure up to 80 cm across and may reach 30 cm in height. **B)** Oblique view of domal stromatolites of bed M_c4 showing their onion-like internal structure and the continuous layering across several domes. Hammer is 57 cm long. **C)** Section of domal stromatolites of bed M_c4. Weathered surface shows alternation of white and gray irregular layers some millimeters thick. Diameter of encircled lens cap is 53 mm. **D)** Polished hand specimen (sample ED97/139) of a domal stromatolite of bed M_c6 in upright orientation. Internal structures consist of an alternation of irregular cloud-like, white and greenish-gray layers up to 1 cm thick. **E)** Irregularly wrinkled bed surface with only minor relief in the lowermost parts of bed M_c4 followed by well-developed domal stromatolites. Hammer is 57 cm long. **F)** Small, asymmetrical domes in the lowermost parts of bed M_c4. Asymmetry was probably caused by preferred trapping of sand grains from sediment-loaded currents in upcurrent direction; paleocurrent direction from right to left. Hammer is 57 cm long.

Mikkim, in the Pin Valley (Fig. 1). Most of the structures occur in FA 2; they are very rare in FA 1. All microbial structures formed initially on loose sand in environments characterized by abundant sand supply. The internal structures are hardly visible on fresh rock surfaces but are much better exposed on weathered surfaces (Fig. 4C).

The lack of carbonate or carbonaceous material inhibited the preservation of microbial material itself, and therefore only the morphology and internal fabrics of the microbial structures are used to demonstrate their microbial origin. Additionally, the lack of organic material or structures on the microscale excludes information about the microorganisms involved in the formation of the different microbial structures. Generally, the nature of the underlying substrate (Reid et al. 1995), the environmental setting (Gebelein

1969; Moore and Burne 1994), and the alternation of periods of clastic deposition and nondeposition (Reineck and Gerdes 1997; Lee et al. 2000) are much more important for the final shape of microbial structures than is the microbial composition.

Siliciclastic Domal Stromatolites

Siliciclastic domal stromatolites, which are the most conspicuous microbial sedimentary structures in the Muth Formation (Fig. 4), have been found in three lithostratigraphic sections. In section A–A′, they occur at 170 m, 185 m, and 190 m within FA 1, associated with planar laminated beds, asymmetrical ripples, and herringbone cross stratification. They show gently undulating lamination, are some 20–40 cm wide and 10–15 cm high, and are made up of medium-sand-size quartzites.

The most spectacular domal siliciclastic stromatolites are found in the sections C–C′ and D–D′ (Figs. 2, 3), associated mainly with planar laminated beds. Both sections consist of pure, medium-sand-size quartzites and have been correlated with each other by the prominent domal siliciclastic stromatolites of beds M_c6 and M_d19 (Fig. 3). The stromatolite beds show a slight increase in thickness towards the south to southeast.

In section C–C′, domal siliciclastic stromatolites are found in two intervals showing a similar succession of sedimentary structures (Fig. 3). Both intervals start with irregular crinkled bedding surfaces at the base (Fig. 4E), grading into small asymmetric, irregularly spaced, domal buildups with little relief (Fig. 4F). The latter can be described as spaced laterally linked hemispheroids (LLH-S; Logan et al. 1964). These structures become larger and more regular upwards and are gradually followed by large, regularly distributed, close laterally linked hemispheroids (LLH-C) (Fig. 4E).

Stromatolite domes in the upper part of both stromatolite successions in section C–C′ are up to 80 cm in diameter and some 30 cm high (Fig. 4A). They have smooth outlines, with hemispheroidal shapes in vertical section and subcircular outline in plan view (Figs. 4A, B). Dip angles of the slopes of the domes are up to 43° (corrected for regional bedding tilt) in their steepest parts. The vertical stacking pattern of the domes is random; domes do not follow domes and troughs do not follow troughs, and thus no columnar growth pattern formed. Both domal stromatolite horizons in section C–C′ are separated by a thin planar laminated bed. There is no evidence for erosion at its base; this bed covers the underlying domes like a blanket, leveling the relief. In bed M_d3 of section D–D′ (Fig. 3), a similar succession of small, irregular domal stromatolites grading into large, regular domes has been observed. However, in contrast to both stromatolite beds of section C–C′, at the top of the bed the domal structures show the reverse trend, becoming smaller and irregular again.

The internal structure of these siliciclastic stromatolite domes resembles onion-skin-like layers which are continuous across adjoining domes (Figs. 4A–4C); they range from some millimeters up to one centimeter in thickness. Their crude lamination (Braga et al. 1995) in hand specimen is composed of weakly defined, diffuse, wavy, white and grayish-greenish layers, irregularly alternating with each other (Figs. 4C, 4D, 5A). In thinsections the white layers are made of pure quartzites with blocky syntaxial quartz cement with grain boundaries shown by dust rims (Figs. 5C, D). The grayish-greenish layers comprise quartz grains with a very fine-crystalline matrix of microquartz with some sericite; the microquartz appears slightly brownish in plane-polarized light and finely speckled in crossed-polarized light (Figs. 5E, F). XRD analysis of a gray layer in sample ED97/139 showed very small amounts of white mica besides quartz (all samples are housed in the collection of the Department of Geological Sciences, University of Vienna). Both layers are grain-supported with moderately to well-rounded quartz grains and show about the same mean grain sizes. Nevertheless the gray layers are slightly enriched in finer sand sizes, thus reducing the sorting. Detrital grains commonly constitute more than 60 vol. % of the layers (Figs. 5D, F). In general, detrital white micas are small and rare; they are slightly more abundant in the grayish layers, showing random spatial orientation (Schieber 1999). The total organic carbon content is only 0.0421 weight % which indicates that even the gray layers are almost free of organic remains.

Analogues and Formation of Domal Siliciclastic Stromatolites.—Despite the scarcity of siliciclastic stromatolites, they have been reported from a wide variety of paleoenvironments throughout Earth's history (e.g., Davis 1968; Gunatilaka 1975; Schwarz et al. 1975; Garlick 1988; Witkowski 1990; Martín et al. 1993; Bertrand-Sarfati 1994; Braga and Martín 2000; Prave 2002). At first sight the domal siliciclastic stromatolites of the Muth Formation may resemble hummocky cross-stratification, but the steep flanks with dips exceeding the angle of repose of arenaceous subaqueous sediments and the continuous layers suggest a microbial origin for these structures (Schieber 1999). The shape of the stromatolite domes in the Muth Formation (Figs. 4A, B) closely resembles the outline of dolomitic stromatolites of the Middle Proterozoic Mount Shields Formation of Montana (Schieber 1998, his fig. 22) and of the middle Cambrian Karsha Formation of Lahaul, NW Himalayas (Vannay 1993, his plate 3F). Similar domal shapes are also reported from the domal carbonate stromatolites of the Archean Steep Rock Group of northwestern Ontario (Nisbet and Wilks 1989, their fig. 4; Awramik 1991, his fig. 4) and those of the Båtsfjord Formation of northern Norway (Siedlecka 1982, her Fig. 4).

Modern examples of domal stromatolites have commonly been reported from intertidal settings. Black (1933) described them from intertidal environments of Andros Island, Bahamas, whilst in Shark Bay they are common in hypersaline, protected, shallow intertidal to lower supratidal areas with reduced wave energy (Logan 1961). Schwarz et al. (1975) described modern examples of domal stromatolites from intertidal environments of the Mauritanian coast.

Several fossil examples of domal siliciclastic stromatolites and their depositional environment have been described from the Late Miocene Sorbas Basin in SE Spain (Martín et al. 1993). From the same area, Braga et al. (1995) reported microbial sediments from a continuous transect, from midshelf to the basin floor. They showed that domal, smooth-sided stromatolites, similar to the LLH-C domes of the Muth Formation, formed at the slope and proximal basin floor, while columnar thrombolites preferably grew at the mid-shelf and the shelf break. Braga et al. (1995) explained the stromatolite growth by episodic but even accretion and the thrombolite formation by episodic but uneven growth in shallower and more turbulent water. Siliciclastic domal stromatolites have also been found in the lowermost shoreface zone in the same basin (Braga and Martín 2000); they show finer grain sizes and shallower synoptic relief in distal directions. Large dolomitic domal stromatolites from the Messinian of Santa Pola, SE Spain, which closely resemble the examples in the Muth Formation, formed in protected intertidal areas (Feldmann and McKenzie 1997).

Benthic cyanobacteria are generally regarded as the main constructors of stromatolites (e.g., Reid et al. 2000; Noffke et al. 2003). There is no clear evidence of the composition of the former benthic community of the Muth stromatolites. However, the comparison with similar modern examples indicates that a multitude of different marine benthic communities, ranging from prokaryotic cyanobacteria to diverse eukaryotic micro and macro-algal communities, might be expected (Golubic 1976; Riding et al. 1991; Lee et al. 2000). In clastic environments like the Muth Formation the species composition appears to be controlled by the rates of sediment supply, because few organism are able to overcome burial in sand. Consequently, the lamination of the siliciclastic stromatolites reflects alternating periods of sediment movement and stasis. These conditions have forced the microbial community to reestablish itself again and again on new sedimentary surfaces (Reineck and Gerdes 1997; Lee et al. 2000), either from phototactic response of the buried organism or from suspended inoculi. The gray layers of the Muth stromatolites (Fig. 5E, 5F) evidence periods with low clastic sedimentation rates, rich in former organic material, whereas the white layers document high sedimentation rates of detrital grains (Lee et al. 2000). Sericite, frequently found in the microquartz cements of

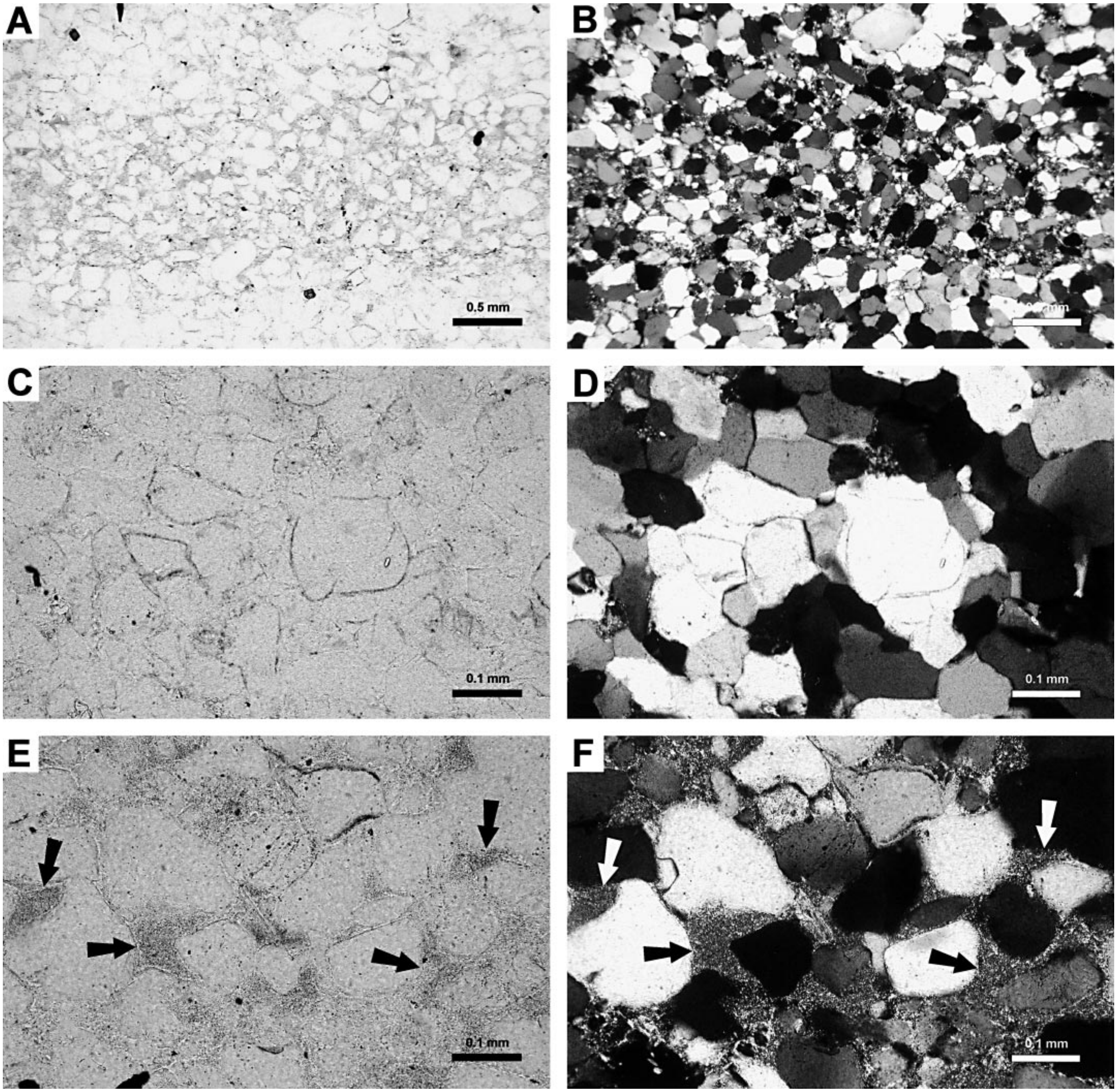

FIG. 5.—Thin-section photomicrographs of a domal stromatolite in upright orientation (sample ED97/139). **A)** Microbial layering shows bright layers of quartz-cemented quartz arenite alternating with gray layers of quartz grains with microquartz and sericite matrix (plane-polarized light; compare with Fig. 4D). The white layers record periods of more intensive sedimentation, whereas the gray layers represent layers with former higher organic content. **B)** Same as Part A but with crossed nicols. **C)** Detail of a bright layer, with euhedral quartz cement overgrowing detrital quartz grains defined by dust rims (plane-polarized light). **D)** Same as Part C but with crossed nicols. **E)** Detail of a gray layer showing detrital quartz grains cemented by slightly brownish microquartz (arrows) with a rough appearance in plane-polarized light. Matrix of microquartz with some sericite. **F)** Same as Part E but with crossed nicols. Small bright minerals, finely dispersed in the microquartz, are sericite, resulting in a speckled appearance of the cement.

the gray layers, is a common mineral in fossil microbial layers. It might have been derived from clay minerals originally trapped and bound by the microbiota and/or from biogeochemical processes within the microbial mat, which can have an important influence on the formation of clays (Krumbein and Werner 1983).

Logan et al. (1964) mention four possibilities for how microbial mats may form domal structures: (1) overgrowth of preexisting irregularities, (2) lateral growth expansion (Black 1933), (3) preferred accretion of material at the crest, and (4) ascending intraformational gases from decayed organic material accumulating underneath dense microbial mat layers.

Domal stromatolites in the Muth Formation show some layers that are thicker in the troughs than at the crests. This highlights the competition of detrital sedimentation with preferred accretion of material on the crests, which usually shapes laterally linked hemispheroids into individual domes

(Logan et al. 1964; Noffke et al. 2001b). As a result, the random vertical stacking pattern of the domal stromatolites in the Muth Formation, showing continuous layers across several neighboring domes (Figs. 4A, B), contrasts strongly with the structure of individual columnar stromatolites (e.g., Logan 1961; Reid et al. 1995), even if they grew closely (Burne and Moore 1993).

The observed development of planar microbial mats grading into asymmetric domes and finally into well-developed domal stromatolites can be explained by repeated alternating periods of sediment movement and stasis and the microbial response to these conditions (Lee et al. 2000). At the beginning, microbial communities become established on the sediment. By baffling, trapping, and binding, the microbes accumulate sand grains (Black 1933). These sites of enhanced sediment accumulation are subsequently overgrown by new generations of sediment-stabilizing microbial mats. Those again baffle, trap, and bind the sediment, which is transported by bottom currents crossing the sea floor. Because, benthic microbial systems need ecological time spans to become established on sediment surfaces, the periods of low or zero sedimentation are crucial for their existence in siliciclastic environments (Lee et al. 2000). The preferred accumulation of sediment on bed irregularities in upcurrent direction results in the formation of asymmetric domes (Hoffman 1967; Gebelein 1969; Noffke 1998; Schieber 1999). With increasing size these asymmetric domes tend to become more regular and evolve into symmetrical domal stromatolites.

Microbial Gas Pits

Microbial gas pits (Reeves 1963) form doughnut-shaped structures on upper bedding surfaces of planar laminated beds (Fig. 6A, B). A single example was found in the upper part of section A–A′ (Fig. 2), but they are abundant in sections C–C′ and D–D′ (Fig. 3). Microbial gas pits and domal stromatolites were never found together on the same bedding surface.

Microbial gas pits are circular in plan view and show well-defined, doughnut-shaped rings rising above the bedding surface, with a bowl-shaped central depression (Figs. 6A, B). They have smooth outlines, with relatively gentle slopes towards the bedding surface, as well as towards the central depression, which is usually slightly below the bedding surface (Fig. 6B). The outer diameter of the structure ranges between 12 and 70 cm; the diameter of the central pit usually is some 1/5 to 2/3 of the outer diameter. The largest microbial gas pit has a 70 cm outer diameter, and a 31 cm inner diameter, and is raised 7 cm above the bedding surface, with the bottom of the pit c. 5 cm below the bedding surface. The sediment of the microbial gas pits and the surrounding beds consists of the same pure quartzite. Except for one example (Fig. 6B), doughnut-shaped rings usually do not show superposition. One microbial gas pit has a flattened top (Fig. 6A), whereas wave ripples have formed on the surface of another doughnut-shaped ring.

In the lower parts of section D–D′ microbial gas pits and the trace fossil *Taenidium barretti* are commonly found on the same bedding surface (Fig. 3). Most of the traces form horizontal burrows at the bedding surfaces and possibly were produced by myriapods (Draganits et al. 2001). On the upper bedding surface of bed M_d2, doughnut-shaped structures are associated with small microbial gas domes.

Analogues and Formation of Microbial Gas Pits.—Fossil examples of structures resembling microbial gas pits are rare. Gas pits in Cambrian sandstones from the Grand Canyon (McKee and Resser 1945, plate 7) are very close analogues to those in the Muth Formation (Fig. 6A), in size, shape, and the type of sediment.

Modern analogues are more common. ''Fairy rings'' (Gerdes et al. 1993, plate 13/8) are small concentric ripples on muddy surfaces that formed by ascending gas bubbles in very shallow water. They differ from the pits of the Muth Formation in their larger number of rings and their very small relief. Gas rings from playa mud in Texas have several concentric rings with little relief and raised central parts; they probably also formed by ascending gas (Reeves 1963). Gas pits found in lacustrine mud (Maxson 1940, his fig. 5) are bowl-shaped depressions lacking elevated rings on the bedding surface. Pit and mound structures are much smaller, usually only a few millimeters across (Shrock 1948). ''Washbowl structures'' (Burne and Moore 1993, his fig. 3A) and ''pustular doughnuts'' (Moore and Burne 1994) are reported from modern thrombolites near the shore line of Lake Clifton (western Australia). The former are explained by preferred lateral growth of the microbial structures, with the vertical growth being restricted by the water level. The latter are interpreted to form during an abrupt rise of the sea level.

Three mechanisms seem plausible for the formation of the doughnut-shaped structure in the Muth Formation: (1) extrusion of fluidized sand (e.g., by groundwater springs); (2) digging by organisms, and (3) ascending gas.

(1) Large, vertical sandstone pipes with bowl-shaped spring pits at their upper termination have been found in the Muth Formation (Draganits et al. 2003, figs. 5a, 5b). However, the spring pits have deeper central depressions compared to microbial gas pits and the observed fluidization structures do not form doughnut-shaped structures on the bedding surfaces. The microbial gas pits do not show any pipe-shaped conduits below (Figs. 6A, B), and the relatively steep rims of the doughnut rings suggest microbial stabilization of the sand.

(2) *Taenidium barretti* associated with microbial gas pits in the Muth Formation, commonly found on the same bedding surface (Fig. 3), are up to 8 cm in diameter (Draganits et al. 2001, their fig. 9B). Although the producers of these traces theoretically might have been able to produce circular depressions on bedding surfaces, these trace fossils are much smaller than most microbial gas pits. Further, the microbial gas pits lack pipe-shaped digging traces underneath.

(3) Microbial gas pits in the Muth Formation are commonly associated with wrinkled bedding surfaces (wrinkle structures), which indicate the former existence of microbial mats (Hagadorn and Bottjer 1997; Schieber 1998). The gas pits are interpreted as collapsed microbial gas domes, in which the microbial mat of the roof leaked because of desiccation and/or increased degradation of crest biomass. The occurrence of microbial gas pits together with a microbial gas dome on the upper bedding surface of bed M_d2 in the Muth Formation underlines a genetic relationship of both structures. The trapped gas escaped before the structure was completely cemented, and the microbial mat of the roof collapsed into the hollow below. The formation of the doughnut-shaped rings, raised above the bed surface, indicates that the lower part of this structure (closer to possibly ascending pore water) was already cemented when the roof collapsed. The gas channels underneath these structures are too small and/or too diffuse to be recognized. The repeated burial of organic material, essential for the subsequent formation of microbial gas, is facilitated in siliciclastic environments by common alternations of deposition and nondeposition (Reineck and Gerdes 1997). The flat-topped shape of one microbial gas pit (Fig. 6A) indicates that it possibly formed in very shallow waters and temporal emergent conditions.

Comparable structures formed by ascending intraformational gas accumulating underneath dense microbial mats are a common feature on modern tidal flats (Goemann 1939, his fig. 2; Noffke et al. 2001b, their fig. 3). Gerdes et al. (1993, their plate 13/1 and 2) shows modern examples of domal structures from saltern basins on Lanzarote Island. Both examples are noncollapsed and show a significant hollow underneath the microbial mat cover. These domes formed in the lower supratidal area, where the ascending flood current penetrates the sediments and pushes intrasedimentary gases upward.

Small gas pits occurring within larger doughnut-shaped structures represent a second generation, caused by the ''pumping'' of the tidal flushes. The fact that microbial gas pits and domal stromatolites are not found on the same rock bed demonstrates their facies-related distribution pattern: whereas gas pits occur in a narrow zone of the lower supratidal area, domal

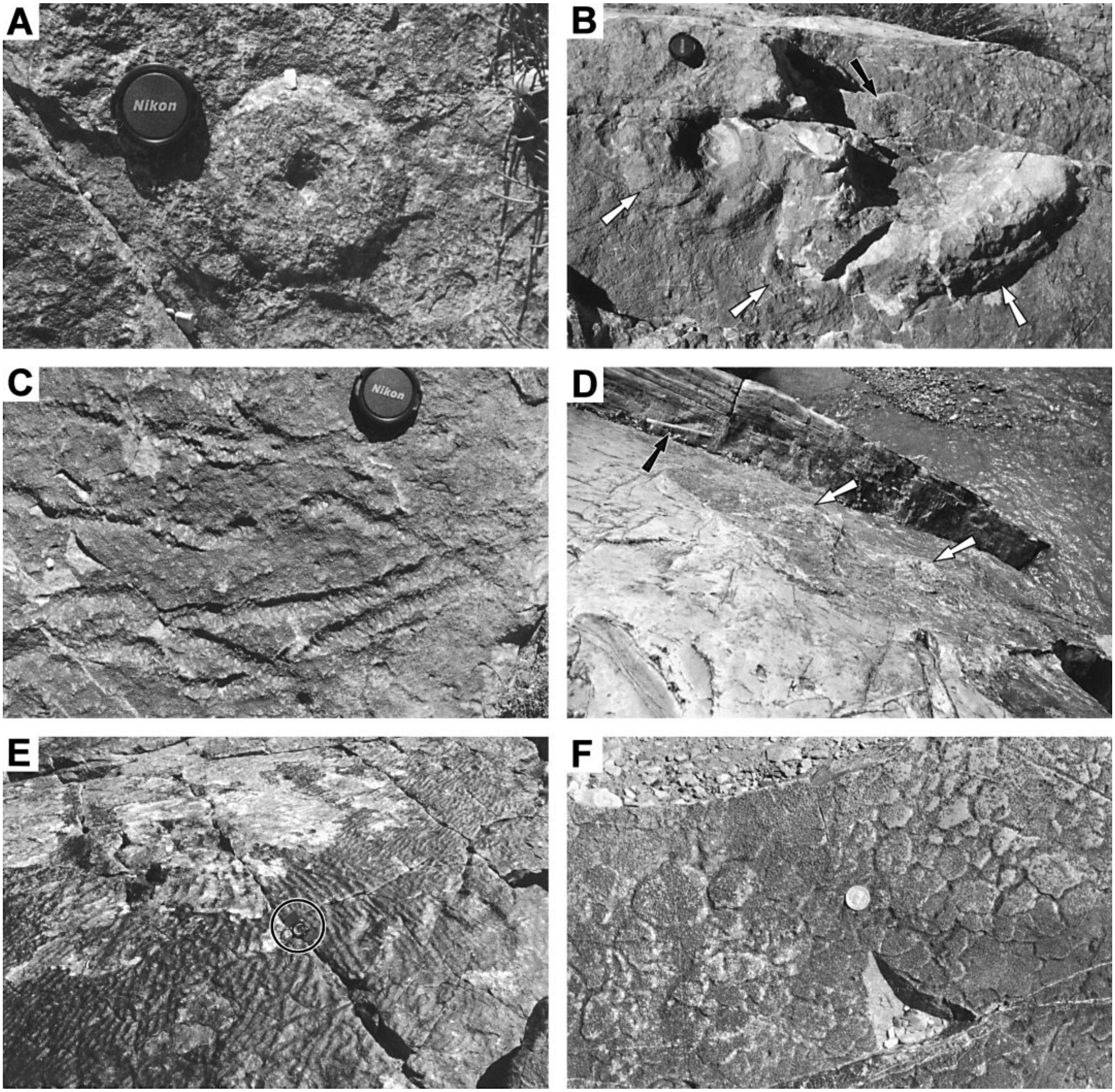

FIG. 6.—**A)** Plan view of a microbial gas pit on the irregularly wrinkled, upper bedding surface of bed M_d6 (see Fig. 3). The structure is sharply defined and shows a small, circular, central depression. Its upper part is flat-topped. Lens cap diameter 53 mm. **B)** Vertical view of three superposed microbial gas pits (white arrows) on the upper bedding surface of bed M_d6. The two larger ones rise gently from the irregularly wrinkled upper bed surface, forming doughnut-shaped structures with a central bowl-shaped depression extending below the bedding surface. Black arrow points to a small microbial gas pit on the upper bed surface of bed M_d5 below. Lens cap diameter 53 mm. **C)** Abundant *Taenidium barretti* on the irregularly wrinkled upper bed surface of bed M_d7 (see Fig. 3). Lens cap diameter 53 mm. **D)** Oblique view of a bed surface (at 235 m of section A–A′; see Fig. 2) showing irregular domes (white arrows), some 60 cm in diameter and up to 15 cm high. The surface of the domes is much rougher than the surfaces of the domal stromatolites (see Fig. 4A). Hammer (black arrow) is 57 cm long. **E)** Multidirected ripple marks on an upper bedding surface at 265 m of section A–A′ (see Fig. 2). Encircled compass is 8 cm long. Such chaotic-like patterns of ripple marks result from the interference of microbial mat growth and a series of subsequent reworking events. **F)** Polygonal shrinkage cracks forming irregular polygons with raised rims on the lower part of a foreset surface at 265 m of section A–A′ (see Fig. 2). Coin diameter 26 mm.

stromatolites are characteristic of subtidal environments, which are ruled by stronger currents and more intense wave action.

Microbial Gas Domes

In upper levels of section A–A′, enigmatic domes have been found on bedding surfaces of planar laminated beds alternating with large-scale cross-beds of FA2 (Draganits 2000). These randomly distributed structures are gently rising mounds, reaching c. 80 cm in diameter and some 30 cm in height (Fig. 6D). Usually, they are a meter or more apart. The domes are hemispheroidal in vertical sections and show circular outlines in plan view. They have slightly steeper slopes and somewhat rougher surfaces than the domal siliciclastic stromatolites of section C–C′.

In cross sections, the domes comprise massive quartzite lacking any internal structures. Some pyrite occurs rarely in these structures. In section A–A′, they are commonly associated with crinkled bedding surfaces and *Taenidium barretti*. In section D–D′, small domes are associated with doughnut-shaped microbial gas pits on the upper bedding surface of bed M_d2.

Analogues and Formation of Microbial Gas Domes.—Because no internal structures are evident, the formation of microbial gas domes in the Muth Formation remains uncertain. Their morphology resembles those of nebkha dunes (Hesp 1981; Ash and Wasson 1983), but they are commonly associated with wrinkled bedding surfaces and in one example with microbial gas pits. The mounds are interpreted as microbial gas domes that rose from ascending gas, originating from degrading buried organic material that accumulated underneath sealing microbial mat layers atop. In contrast to microbial gas pits they did not collapse because of stabilization by early cementation. Braga et al. (1995) termed microbial sediments without internal structures ‘‘leiolites.’’

Multidirected Ripple Marks

Multidirected ripple marks (Noffke 1998) were found on an upper bedding surface at 265 m of section A–A′, in FA 2. The bedding surface is covered with patches of ripples, each patch showing a different ripple orientation (Fig. 6E). The slightly asymmetric ripples have rounded, flattened crests with irregularly undulating crest lines.

Analogues and Formation of Multidirected Ripple Marks.—Noffke (1998, her fig. 2) presents modern examples of multidirected ripple marks from Mellum Island, Germany. Patches of rippled surfaces with different orientations of the ripple crests record the interference of microbial mat growth and repeated reworking events. The ripple marks were stabilized by microbial communities against erosion by storm currents or high-water spring tides.

Polygonal Shrinkage Cracks

The lower part of a foreset surface of bed M_a566 in section A–A′ shows irregular polygonal fracture patterns (Fig. 6F). The surface is broken into irregular but relatively isometric fragments, 2–6 cm in size, with slightly raised, pillow-like rounded rims. This bed also contained abundant arthropod trackways (Draganits et al. 2001).

Analogues and Formation of Polygonal Shrinkage Cracks.—Desiccation structures are common surface features in episodically subaerially exposed intertidal areas. The desiccation structures in the Muth Formation closely resemble modern desiccated microbial mats from Bretagne salterns (Gerdes et al. 1993, their plate 12/1) and from lower supratidal areas of Tunisia (Noffke et al. 2001a, their plate 7, figs. 5, 7). The occurrence in medium-sand-size quartzite of the Muth Formation, and their different appearance, excludes simple explanations as mud cracks. In the Muth Formation, the sand-size sediment, the irregular fracture pattern with relatively isometric fragments, and the slightly raised, pillow-like rounded rims (Fig. 6F) indicate a formation by desiccated microbial mats (Gerdes et al. 1993). These characteristic rims have been termed ‘‘crack tapestry’’ by Gerdes et al. (2000).

DISCUSSION

General Characteristics of the Microbial Structures in the Muth Formation

The pure quartzite of the Muth Formation may appear hostile to microbial life, although cyanobacterial communities can adapt to such conditions (Decho 2000; Noffke et al. 2002). Almost pure quartz sand can support benthic cyanobacterial growth, because, (1) translucent quartz sand permits light to penetrate deeper into the sediment compared with carbonate sand, thus permitting benthic cyanobacteria to grow within sediments (Noffke et al. 2003), (2) the grains are small enough to enable capillary water to ascend from below and keep the surface moistened during possible emergent periods (Gebelein 1969; Gerdes and Krumbein 1994), (3) sand grains of this size can be baffled, trapped, and bound by cyanobacterial filaments into the microbial layer (Noffke et al. 2001b), (4) deposition of sand at low sedimentation rates stimulates upwards growth of microbial layers (Gerdes and Krumbein 1994), and (5) sand deposition may produce enough sediment stress to suppress other organisms, given that the nondeposition intervals during repeated sediment movement and stasis are long enough for the establishment of simple organisms like cyanobacteria, but too short for complex species (Riding et al. 1991; Reid et al. 1995; Lee et al. 2000).

The lack of organic matter in the Muth stromatolites can be explained by anaerobic and/or aerobic microbial decomposition (Lee et al. 2000), and elutriation in the originally highly permeable arenaceous sediment. Very rare occurrences of pyrite possibly represent indications of former organic material. Carbonate cements, which usually cause early lithification, which is essential for the accretion and preservation of coastal stromatolites (Logan 1961; Riding 2000), are not preserved in the Muth Formation stromatolites. However, the microcrystalline quartz cement of the gray stromatolite layers (Fig. 5F) is much finer grained than the blocky quartz cements usually found in the Muth Formation. The extremely fine crystalline texture of the microquartz is indicative of diagenetic replacement of former carbonate cements by quartz (Adams et al. 1984; Tucker 2001). This observation is an important indication of the former existence of early carbonate cements in the stromatolites, which may explain the preservation of the domal stromatolites in the siliciclastic, high-energy environments of the Muth Formation.

Climate

Owing to the virtual lack of significant fossils in the Muth Formation, climatic reconstructions are challenging. Climate indications from the rich faunal communities of the Pin Formation are inapplicable, because of the extensive depositional gap between the Muth and Pin formations, whilst information from faunas in the Lipak Formation above is of little value because of pronounced variations in climate during its deposition (Streel et al. 2000).

At larger scales, paleogeographic reconstructions of the Indian subcontinent during the Early Devonian indicate a position at c. 30° S (Stampfli and Borel 2002) or even at slightly lower latitudes (Li and Powell 2001). On the basis of modern analogues of atmospheric circulation models, subtropical-arid climate conditions seem likely for the paleolatitude of the Muth Formation.

Microbial mats have been described from a broad climatic range, from temperate to tropical and from humid to arid (Gerdes and Krumbein 1994; Gerdes et al. 2000; Noffke et al. 2003). The probability of fossilization of these ‘‘potential stromatolites’’ (Krumbein 1983) varies not only with the rate of early cementation, controlled by climatic conditions (Braga and Martín 2000; Noffke et al. 2003), but also by local water chemistry (Moore and Burne 1994). Early carbonate cementation of siliciclastic stromatolites, essential for the preservation of microbial buildups, is limited to tropical to subtropical marine environments, where water temperature and carbonate saturation favor microbial calcification (Gerdes and Krumbein 1994; Noffke et al. 2003). Braga and Martín (2000) regard arid to semiarid tropical to subtropical areas with their discontinuous water supply (less siliciclastic input combined with higher carbonate saturation of the seawater) more favorable to produce siliciclastic stromatolites than humid tropical settings. The possibly subtropical-arid paleoclimate during the deposition of the Muth Formation may thus have supported the formation of siliciclastic stromatolites. The occurrence of polygonal shrinkage cracks strongly hints at semiarid paleoclimate conditions (Noffke et al. 2001a).

Relationship between Trace Fossils and Microbial Structures

Abundant trace fossils were found in the meager quartzites of the Muth Formation. They are dominated by arthropod trackways, especially by *Palmichnium antarcticum,* probably produced by stylonurid eurypterids. Rarer *Diplichnites gouldi* and bedding-parallel *Taenidium barretti* were probably produced by myriapods (Draganits et al. 2001); the latter are abundant on wrinkled bedding surfaces. They are also commonly found on the same surfaces with microbial gas domes in section A–A′ (Fig. 2) and are common on bedding surfaces together with microbial gas pits in section D–D′ (Fig. 3). Hagadorn and Bottjer (1999) report *Diplichnites* trackways and many bedding-parallel burrows on wrinkled bedding surfaces of suspected microbial origin from the Precambrian–Cambrian boundary; they relate the bedding-parallel burrowing with the feeding behavior of their producer. The analogues, bedding-parallel *Taenidium barretti* in the Muth Formation, may also be feeding traces within microbial mats. Environmental pressure by grazing and burrowing organisms has been used to explain the ''crisis'' in stromatolite abundance and diversity at the end of the Proterozoic (Garrett 1970). The Muth example and additional reports on the co-occurrence of microbial structures with grazing and burrowing fauna (e.g., Moore and Burne 1994; Hagadorn and Bottjer 1999) may indicate that they can coexist. Again, early cementation is obviously important for the preservation of microbial structures (Logan 1961; Moore and Burne 1994).

CONCLUSIONS

Several types of microbially induced sedimentary structures were found in the quartzites of the Lower Devonian Muth Formation (NW Himalayas). They were formed in shallow marine, coastal environments and include siliciclastic domal stromatolites from shallow subtidal to intertidal settings, as well as microbial gas pits, microbial gas domes, multidirected ripple marks, and polygonal shrinkage cracks from lower supratidal environments. The microbial structures were found in intervals of the formation associated with physical sedimentary structures that indicate at least temporally emergent conditions. These observations support the interpretation of a peritidal setting for the microbial structures within a wave-dominated, barrier-island depositional environment of the Muth Formation. Additionally, the polygonal shrinkage cracks indicate semiarid paleoclimates.

The siliciclastic structures in the Muth Formation indicate that benthic microbial communities are able to survive even in strongly siliciclastic environments, provided that intervals of low or zero sedimentation during repeated sediment movement and stasis are long enough for microbial organisms to become reestablished on sediment surfaces.

The replacement textures of the microquartz matrix between the clastic quartz grains in the stromatolites is an important indication of the former existence of syngenetic carbonate cements, which may explain the preservation of the siliciclastic microbial structures in the high-energy environments of the Muth Formation.

The stromatolites in the Muth Formation commonly contain more than 60 vol. % siliciclastic grains. This fact demonstrates the existence of microbial activity in environments of higher sedimentary stress than generally thought and thus extends our knowledge of the capability of benthic microbial organisms to settle in shallow marine environments.

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