Fluvial Tufa Formation in a Hard-Water Creek
(Deinschwanger Bach, Franconian Alb, Germany)

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Summary

Cyanobacteria-dominated biofilms involved in tufa deposition in the hardwater creek Deinschwanger Bach, Bavaria, were investigated with regard to their effect on the carbonate equilibrium and fabric formation. Current tufa deposition is evident by up to 1.5 mm thick crusts that have formed on substrate plates placed in the creek for 10 months. Hydrochemistry data indicate that carbonate precipitation along the creek is physicochemically driven by CO₂ degassing, whereas photosynthetic carbon assimilation is without detectable effect on the macroscale carbonate equilibrium. However, stable isotope data indicate a minor photosynthetic effect, but only for the lower creek section where the pCO₂ already drops to the two-fold of the atmospheric level. Though the initial process of external nucleation on cyanobacterial sheaths in the lower creek section might be promoted by a photosynthetically-induced microscale pH gradient, the effect is not strong enough to cause a CaCO₃ impregnation of the sheaths. The fabric of the laminated tufa crusts in the creek reflects the temporal alternation of porous microsparitic Phormidium incrustatum - Phormidium foveolarum - diatom biofilms in spring, micrite-impregnated Phormidium incrustatum - Phormidium foveolarum - diatom biofilms in summer-autumn, and detritus-rich non-calculated diatom-biofilms in winter. By contrast, exopolymer-poor surfaces of cascade tufa mosses show large, cuboidal spar crystals. Non-photosynthetic bacteria, which occur in large numbers in Phormidium incrustatum - Phormidium foveolarum - diatom communities, thrive on extracellular polymeric substances (EPS) and dead cells of the cyanobacteria and are unlikely to promote CaCO₃ precipitation.

1 CALCAROUS TUFA FORMATION AT COOL SPRINGS AND IN CREEKS

Calcareous tufa deposits of springs and creeks are a common feature of karst regions such as the Franconian and Swabian Alb (e.g., Stirn, 1964; Grüninger, 1965). Karstification driven by soil-derived CO₂ leads to the formation of Ca²⁺-rich, high-pCO₂-groundwaters which rapidly degas when the aquifer discharges to the subaerial environment (see, e.g., Bogli, 1978). Calcareous tufa refers to porous, poorly friable carbonate rocks which form at such non-thermal springs and creeks. Low-Mg-calcite is usually the main mineral component (e.g., Trion & Müller, 1968) because of generally low Mg²⁺/Ca²⁺ ratios of karst waters.

The formation of calcareous tufa at springs and creeks is generally considered to be largely inorganic, i.e. physicochemically driven by CO₂ degassing rising CaCO₃ supersaturation (e.g. Herman & Lohr, 1987, 1988). In addition, mosses and plants that populate springs and creeks provide large surfaces, thereby enhancing CO₂ degassing. Cyanobacteria are considered to provide suitable nucleation sites by their sheaths (Pentecost, 1985; Pentecost & Riding, 1986). In addition, their sticky sheaths should trap and bind detrital carbonate particles, which further grow inorganically within the supersaturated environment. The potential influence of metabolic CO₂ fixation by plants and cyanobacteria is mentioned in almost any study on tufa systems. Pia (1926, 1933) and Wallner (1934ab, 1935) denoted some tufa deposits as "physiologically precipitated" or "phytogen", caused by CO₂ assimilation. Golubic (1973) noted that CaCO₃ precipitation in the upper part of a river flow is largely inorganic, whereas biogenic precipitation may increase downstream when equilibrium conditions with regard to atmospheric pCO₂ are reached. Indeed, tufa depositing springs and creeks show only

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minor diurnal changes in pH (Grüninger, 1965; Usdowski et al., 1979). Calcite precipitates of a tufa depositing creek north of Göttingen show δ13C values close to that of the dissolved carbonate species, thus, indicate a rapid precipitation to cause this isotopic disequilibrium (Usdowski et al., 1979). Further, photosynthetic rates of cyanobacteria measured by 14C uptake were too low to account for CaCO3 deposition rates observed in tufa systems (Pentecost, 1978). Only about 1-5% of the CaCO3 could have formed as a result of cyanobacterial CO2 uptake in the case studies investigated by Pentecost (1978). Nonetheless, under conditions of low discharge photosynthesis determines the diurnal variations in δ13C in dissolved inorganic carbon in creeks (Spiro & Pentecost, 1991).

All these observations clearly point to a negligible role of photosynthetic CO2 assimilation in shifting the carbonate equilibrium to cause CaCO3 precipitation in fluvial tufa systems (e.g., Grüninger, 1965: 88). This view has recently been confirmed by a comprehensive study on water chemistry and tufa precipitation of two hardwater creeks near Bad Urach, Swabian Alb, South Germany (Merz-Preiß & Riding, 1999).

However, other studies focussed on potential microscale gradients caused by non-phototrophic bacteria, which possibly modify the carbonate equilibrium within the exopolymer matrix of cyanobacterial colonies and mats (Caudwell, 1987; Pentecost & Therry, 1988; Szulc & Smyk, 1994). Though the presence of several chemorganotrophic and chemolithotrophic bacteria in tufa biofilms has been shown (Szulc & Smyk, 1994), data on their in-situ abundance and metabolic activity in natural samples are still missing. Aerobic heterotrophs isolated from 10 tufa-depositing sites in Europe and North-America failed to cause CaCO3 precipitation in laboratory experiments (Pentecost & Therry, 1988). Most of these isolates were gram-negative, motile rods of the "Pseudomonas"-type. Consequently, the tufa-depositing hardwater creek Deinschwanger Bach has been investigated with regard to hydrochemistry, the effect of biofilm exopolymer matrix on CaCO3 nucleation, fabric formation, and the presence of non-phototrophic bacteria.

2 ENVIRONMENTAL SETTING

The Deinschwanger Bach ("Wurstbach") is a hardwater creek located at the western rim of the Franconian Alb approximately 30 km ESE of Nürnberg (Fig. 1). The Franconian Alb plateau consists of Upper Jurassic carbonate series, which are affected by intensive karstification since the Early Cretaceous. Numerous caves, karst springs, and tufa deposits are known from this area.

The E-W trending valley of the Deinschwanger Bach cuts down from Lower Kimmeridgian limestones ("White Jurassic") down to Aalenian-Bajocian sandstones of the "Brown Jurassic" (Fig. 1). Callovian clays of 2-4 m thickness ("Ornatenton") below the up to 70 m thick Oxfordian-Kimmeridgian limestones are responsible for numerous springs discharging from the karst aquifer. A second major spring horizon is bound to clayey siltstone intercalations ("Disciteston") within the 50 m thick Aalenian-Bajocian sandstones. Large parts of the valley floor are covered by up to 6 m thick Holocene tufa deposits which now form terraces at the incised creek. The formation of Holocene tufas is possibly related to large landslides that might have dammed the creek temporarily (Schmidt-Kaler, 1974).

The main spring of the Deinschwanger Bach discharges 10 - 15 L/sec (Schmidt-Kaler, 1974). It is located at 520 m above S.L. at the eastern end of the valley, approximately 10 m above the Callovian-Oxfordian boundary. The creek is up to 3 m wide and usually less than 50 cm deep. Current CaCO3 deposition starts approximately 1.2 km away from the main spring and ends approximately 2.6 km downstream. In addition, both wooded sides of the valley show several small cascade tufas and wide-spread, swampy areas covered by sheet-like deposits of carbonate encrusted shells of the pulmonate snail Cepaea hortensis.

Four sites have been selected for a detailed study of biofilm calcification and water chemistry (Fig. 1):

(1) The main spring (520 m above S.L.; site 1; Pl. 1/1),
(2) a small tufa cascade at the southern valley side (495 m above S.L.; site 2; Pl. 2/1),
(3) a small barrage of the middle creek, which is incised in Holocene tufa terraces (477 m above S.L.; site 3; Pl. 3/1), and
(4) a low-turbulent, well-illuminated section of the lower creek part (462 m above S.L.; site 4; Pl. 4/1).

All sampling sites, except for the lower creek section, are situated within shady, wooded area.

3 INVESTIGATED MATERIAL AND METHODS

Biofilm and water samples have been taken in spring (01.05.1996; 12.06.1999), summer (22.07.1996), autumn (22.11.1996), and winter (01.03.1997) at the four sites (Table 1). 125 hardpart sections of 21 formalin/glutaraldehyde-fixed, LR-White embedded tufa biofilm samples have been investigated by conventional light microscopy and wide-field deconvolution epifluorescence microscopy. In addition, 30 sections of 11 artificial substrate plates, which have been placed at the four sites for 10 months (22.11.96 - 30.09.97), have been investigated. The 5x5 cm sized plates of Solnhofen limestone, polystyrene, wood, and iron steel were fixed by 15 cm long screws at water-covered places. Fixation and preparation of hardpart sections was done as described in Arp et al. (1998). For details of Wide-field deconvolution epifluorescence microscopy (WDEM) see Manz et al. (2000), 11 smitihin and 9 ultrathin sections of two decalcified samples were prepared for TEM studies (sample preparation see Arp et al., 1999). The ultrathin sections were examined at a Jeol 100 B transmission electron microscope at 80 kV at the Max-Planck-Institute for Biophysical Chemistry, Göttingen.

Electrical conductivity (EC), temperature, pH, and redox potential of water samples were measured in the field. For each samplings site a diurnal cycle (9.00 a.m. to 18.00 p.m.) of water temperature, oxygen, redox potential, conductivity and pH were recorded for each season in 1997. Temperature