Cyanolithic tufas at Lingenau (Vorarlberg, Austria): Patterns and rates of tufa formation, and implications for the „late Holocene tufa decline“

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At Lingenau (Vorarlberg, Austria), cyanolithic tufa of *Rivularia* type presently forms at rates of a few mm/a, but larger areas of relictic tufa and of ephemerally active tufas indicate that the short-term rate of tufa accumulation is a poor indicator of long-term rate.

The tufa of Lingenau overlies a tilted and truncated succession of marls, sandstones and conglomerates of the Weissach Formation (Molasse Zone). The springs that nourish tufa deposition emerge a few meters upslope the brink line of bedrock cliffs; the cliffs comprise the flanks of the incised valley of river Subersach. Active tufa deposition is mainly nourished by a single spring that emerges by calmly welling out. Over the year, the spring shows little changes, each, of shedding, pH, alkalinity and conductivity. About three meters downslope of spring emergence, the water descends a waterfall with tufa curtains and, downstream of the waterfall, with rimstones and shelfstones. Farther downstream, along a steep reach of the creek, phytoclastic tufas accumulate. Finally, the water cascades down into the Subersach via low, stepped cliffs veneered by waterfall tufa. The entire waterfall-creek system is well-lit and faces towards the south. The precipitated tufa consists practically entirely of cyanolithic calcite of type *Rivularia*. In the waterfall tufa as well as in rimstones and shelfstones, the tufa consists of laminae typically between 3–6 mm in thickness. Laminae are subparallel to their substrate.

Up-section, individual tufa laminae start from a sub-millimetre thick lamina of micrite to microsparite. Above, a fringe of crystals of calcite of elongate to „club-like“ shape is present. In SEM, viewed from above, all of these crystals contain a subcircular hollow in their centre. Higher up, these crystals branch into „bushes“ of calcite crystals. These bush-like calcites are up to about 8 mm in thickness, and comprise the main portion of a single tufa lamina. In longitudinal section, the calcite-fringed „branches“ of the crystal bushes show a hollow tube along their centre. Within the bushes, clusters of „branches“ are encased by calcite of uniform optical orientation, such that the crystals that build the bushes are a few millimeters to nearly 10 mm in length. Excavation of laminated tufa and placing of both natural and artificial substrata into the tufa-precipitating creek showed that *Rivularia* tufa forms readily anew on the excavated surface and on the substrata. Where tufa was artificially excavated in late winter, a lamina of *Rivularia* tufa up to about 8 mm in thickness formed during spring and summer, over nearly 8 months. Similarly, on all of the artificial substrata, layers up to nearly 10 mm in thickness of *Rivularia* tufa had formed within nearly 8 months. In all its macro- and microscopic characteristics, the

Rivularia tufa from the artificial substrata and on the excavation surface is identical to the natural tufa. Precipitation of *Rivularia* tufa thus proceeds actively and at a moderate rate typical for tufa deposition.
At Lingenau, the area of active tufa deposition is much smaller than the area of both relictic and fossil tufa. Some springs and seeps situated adjacent to the present perennial tufa-depositing spring, however, do shed (with up to an estimated 0.5–2 l/s) only during spring (snowmelt) and after heavy summer rains, whereas for the rest of the year, these are inactive. These ephemeral springs also are associated with actively-forming *Rivularia* tufa. At Lingenau, thus, formation of tufa is „pulsed“ in frequencies ranging from weeks to months (ephemeral springs) to seasonal (annual tufa lamination) to, perhaps, decennial to millennial (relictic waterfall tufas, and fossil tufas). If tufa deposition since 10 ka bp occurred at a rate of about 5 mm/a, and always was nourished by the same spring, a deposit 50 m in thickness should have formed. This is evidently not the case, as both the active and the relictic waterfall tufas are riddled by rock outcrops, and the tufa cover at many locations is less than about 10–20 cm in thickness. The observations indicate that only part of the total tufa deposit was active at a time, or that intervals of tufa deposition had changed with intervals of no tufa formation and/or erosion. An overall inverse relation between total size of a tufa deposit and area of active tufa precipitation has been found at a number of other locations, too. This suggests that tufa formation is inherently non-continuous, or episodic, both in space and time. An apparent late Holocene decline in tufa deposition (inferred by other authors) hence, in part or entirely, results from a typical pattern of tufa accumulation. Short-term rates of tufa deposition can hardly be extrapolated to deduce long-term rates, i. e. the accumulation of tufa follows the same principle than all other sedimentary rocks on Earth. To recognize a potential environmentally-induced tufa decline prerequisites distinction of „normal“ stratigraphic incompleteness from a genuine decline of tufa formation over the entire Late-Glacial to Holocene interval.