KUNGSTRÄDGÅRDEN, A GRANITIC SUBWAY STATION IN STOCKHOLM: ITS ECOSYSTEM AND SPELEOTHEMS

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At a depth of 30 m, Kungsträdgårdens subway station is the deepest station in Stockholm. It is also one of the few with easily accessible walls that are not covered in concrete, but where the Stockholm granite is exposed. On the granite wall a simple but complete and unique ecosystem has developed since the station was constructed in the mid-1970's. The constant artificial light is a unique energy source in this subsurface environment and enables the occurrence of microbial communities dependent on photosynthesis with the primary producers being cyanobacteria, several species of diatoms as well as the bryophyte *Eucladium verticillatum*, not known from other locations in Stockholm. Top predator is the spider *Lessertia dentichelis*, with its only known population in Sweden. Closely associated with the ecosystem are secondary mineral precipitations forming flowstone, coralloids and small stalactites. The most common mineral is calcium carbonate, but there are also sodium sulfate depositions. A significant proportion of the mineralisations has been mediated by the present microorganisms, especially fungi. Characteristic for the microbial communities on the granite wall is that they appear to give rise to local geochemical conditions that influence microbial diversity, mineral precipitation and mineral dissolution, such as diatom ooze with calcium carbonates or a fungal – cyanobacterial community that might be responsible for speleothem formation.

1. Introduction

In most environments, lampenflora is considered as detrimental. This is not the case in the Kungsträdgården subway station in Stockholm, Sweden (Figure 1). As in most of the subway stations in town, Kungsträdgården subway station has an artistic decoration. At Kungsträdgården, the artist Ulrik Samuelson wanted to infer a sense of a (romantic) "granite cave", leaving most of the bedrock in the station exposed and decorating with mascarons from the 17-century palace Makalös (De la Gardie's Palace) that was situated close to the place where the subway station is today, until it was destroyed by fire in 1825. The artist also introduced some plants associated with a romantic view of caves, in particular ivy (*Hedera helix*) that is planted near the entrance to the platform. The station was finished in 1977 as the end station of the newest subway line in the Stockholm Metro system (the "Blue Line"), and was opened for use on October 30th the same year. The platform is one of the deepest in Stockholm, located approximately 34 m underground and 29 m under sea level. The station is entirely constructed in about 1.8 Ga old granite (Ivarsson and Johansson 1995) (thus the artist's "granite cave"). As in caves, there are rich secondary mineralizations ("speleothems"), forming various flowstones and coralloids (but only a few very small stalactites).

Earlier studies on granite speleothems (Vidal Romaní et al. 2010) have revealed a diversity in speleothem forming minerals (in particular opal-A and pigotite, but not calcite) and a close association with various microorganisms. In the station there is also a small ecosystem first noticed in the early 1980's when the first and so far only population in Sweden of the small spider *Lessertia dentichelis* (Linyphiidae) was discovered in the station (Kronstedt 1992). It is obvious that the ecosystem to a large extent is driven by the energy from the lights on the platform. This prompted our recently commenced research in this artificial "cave", this time with focus on the speleothems, but using a systems approach, trying to survey the station from minerals to top-predator.

Figure 1. Kungsträdgårdens subway station, located more than 30 m below the surface in central Stockholm, Sweden. A large part of the wall is covered with the moss Eucladium verticillatum*. There are also several distinct biofilms and speleothems.*

2. Material and Methods

We sampled the speleothems in several places along the platform, making sure not to handle the specimens with ungloved hands. The specimens were transferred to freezer

(-20 °C) within two hours from the sampling, and stored at the Swedish Museum of Natural History, Stockholm, until later investigation. It was noted that the flowstones were exclusively formed where water was seeping out of the granite. In these places there was also a higher biological diversity, and we collected specimens of animals, moss and biofilms (brown "algae" mats and "calcareous slam"). The animals were stored in alcohol (70% Et-OH), while the moss was dried, and the biofilm samples transferred to freezer. In some places we observed a slightly discolored (yellowish) salt precipitation. This, too, was sampled for later analysis.

The animals and the moss were determined by experts at the Swedish Museum of Natural History, where voucher specimens are stored. Speleothems and the salt were analysed using Environmental Scanning Electron Microscopy (ESEM) coupled with Energy Dispersive Spectometry (EDS).

Diatoms were sampled from the walls of the station, using a common spoon and spatula. Samples were cleaned in 30% H_2O_2 and 10% HCl and then mounted using Naphrax™ for light microscopy analyses (using a Leitz orthoplan light microscope at 1,000× and oil immersion), and dried directly onto the stub for Scanning Electron Microscopy (SEM) analyses. The samples were analyzed with the aim of identifying everything to species level by one of us (LNI). Additionally, 400 valves were counted in each sample to estimate the relative abundance of species.

3. Results

Even if our investigation of the subway station has only recently started, we have some noteworthy results. We observed several individuals of the spider *Lessertia dentichelis* (Simon), including egg sacks. Crane flies (Diptera: Tipuloidea) collected were determined to *Tipula lateralis* Meigen (Tipulidae), and the moss to *Eucladium verticillatum* (Brid.) Bruch and Schimp. The crane fly larvae collected could not be identified to species (Figure 2), but it is likely that they are *T. lateralis*. Of diatoms, 12 species have so far been identified. For an overview of the biodiversity in the station, as known today (including previous reports), see Table 1.

The speleothems consist mainly or entirely of calcite. Characteristic for the speleothems are the close associations with biology including cyanobacteria, fungal mycelia and diatoms. Especially fungi appear to play an important role in the formation of speleothems. It is possible to follow a gradual increase of calcite precipitation from non-mineralized fungal mycelia to well-defined speleothems with less presence of active fungal colonies (Figure 3). In between these opposites are various stages of calcite precipitation with direct precipitation on the fungal hyphae as a first stage, successively forming more and more elaborate calcite precipitates in between the hyphae until large parts of the mycelia is completely mineralized. Whether fungi precipitate calcite directly as a result of their metabolism or if calcite is precipitated indirectly as a response to favorable geochemical conditions in the vicinity of fungi is not yet concluded. Furthermore, cyanobacteria have been observed to live in close association with the fungal communities. Results from DNA analyses of both fungi and cyanobacteria are pending.

The EDS analysis of the salt showed that it is composed mainly of Na, S and O, thus tentatively determined as a sodium sulfate salt.

4. Discussion

The ecosystem at Kungsträdgården subway station seems to be more or less self-sufficient, driven by the energy from the fluorescent lamps used for lightening the station, and water from the bedrock. The autotrophs in this system have been identified as cyanobacteria (in close association with heterotrophic fungi), diatoms, and the moss *Eucladium verticillatum*. This moss is a common component of lampenflora in many caves (Mulec 2012). In these the presence of the moss is unwanted, but the population in Kungsträdgården subway station is the only known from the Stockholm area and an important component in the ecosystem. The moss is tufa-forming, and normally grows on limestone; the presence here on a granite wall was thus not expected. However, at a closer examination, it was clear that all individuals were growing on speleothems and not directly on the wall. *E. verticillatum* is commonly associated with tufa deposits (e.g., Pentacost 1987), but it is not known if the moss contributes in any way to the formation of the speleothem.

The diatom flora of Kungsträdgården subway station (Figure 2) is dominated by aerophilous taxa. *Diadesmis perpusilla* (Grunow) Mann and *Diadesmis contenta* (Grunow) Mann are species often found in caves and they are both characteristic of environments with low light availability. Other species found were e.g., *Pinnularia appendiculata* (Agardh) Cleve, *Diploneis ovalis* (Hilse) Cleve, *Amphora normannii* Rabenhorst, *Cymbella laevis* Naegeli, *Nitzschia sinuata* (Smith) Grunow, *Nitzschia amphibia* Grunow and *Caloneis* cf. *aerophila* Bock. *Caloneis aerophila* is a rare species, to our knowledge not previously reported from Sweden. In addition, a small *Caloneis* species was found, which might represent a yet undescribed species. All diatom species found were pennate diatoms with at least one raphe. This indicates the importance of being able to move around on the substrate. The results show a clear biogeography in the metro station. The species composition of the calcareous slam was not the same as of the brown "algae" mat. It is likely that the diatoms found in the calcareous slam in some way contribute to the making of this specialized habitat.

The top-predator in Kungsträdgården subway station has been identified as the small spider *Lessertia dentichelis* (Kronstedt 1992). It seems to have a viable and stable population on the walls of the platform, mostly found in close association with the moss where the nets and egg sacs can easily be spotted. Due to the small size, it is more difficult to observe the adults. The population at the subway station is the only known in Sweden (Kronstedt 1992), but it is possible that it has been overlooked. Kronstedt (1992) reported a microfauna living among the moss, consisting of nematods, annelids, harpacticids, and collembols (Table 1). It is likely that the spider feeds on the collembols and the harpacticids, and that they in turn lives on the diatoms, fungi

Table 1. Organisms identified from Kungsträdgården subway station, Stockholm, Sweden.

Taxon	Reference	Remark
Mammalia: Hominidae		
Homo sapiens Linnaeus	This Investigation (TI)	temporarily in high density, not stationary; adults and juvenils
Arachnidae: Linyphiidae		
Lessertia dentichelis (Simon)	Kronstedt 1992, TI	several individuals, including egg sacs
Insecta: Diptera: Tipulidae		
Tipula lateralis Meigen	TI	several adults, numerous larvae
Collembola: Hypogastruridae		
Hypogastrura purpurescens (Lubbock)	Kronstedt 1992	
Collembola: Isotomidae		
Proisotoma minuta (Tullberg)	Kronstedt 1992	
Crustacea: Copepoda		
Harpacticidae	Kronstedt 1992	
Nematoda	Kronstedt 1992	
Annelida	Kronstedt 1992, TI	
Plantae: Bryophyta: Pottiaceae		
Eucladium verticillatum (Brid.) Bruch & Schimp	TI	locally abundant on sinter
Heterokontophyta: Bacillariophyceae		
Amphora normannii Rabenhorst	TI	
Caloneis cf. *aerophila* Bock	TI	first record for Sweden?
Caloneis cf. *bacillum* (Grunow) Cleve	TI	
Caloneis sp.	TI	new species?
Cymbella laevis Naegeli	TI	
Diadesmis contenta (Grunow) Mann	TI	low light environments
Diadesmis perpusilla (Grunow) Mann	TI	low light environments
Diploneis ovalis (Hilse) Cleve	TI	
Navicula sp.	TI	
Nitzschia amphibia Grunow	TI	
Nitzshia sinuata (Smith) Grunow	TI	
Pinnularia appendiculata (Agardh) Cleve	TI	
Fungi	TI	
Cyanobacteria	TI	

and cyanobacteria, as well as decomposing parts of the moss. We attempt to follow up on Kronstedt's inventory, trying to identify more components of the microfauna and their roles in the ecosystem.

In the background, but as an integral part in the local environment, are the speleothems (Figure 3). We expected the usual granite speleothem forming minerals (Vidal Romaní et al. 2010); instead we could only identify calcite from the samples. The source of the calcium is not yet identified. The bedrock is granite, but the ceiling is covered in concrete and would be the obvious source. However, most of the speleothems form only some distance below the ceiling, without visible contact with the concrete, and the impression is that the seeping water is the source of the calcium. Granites contain only a fraction of Ca compared to mafic rocks and the groundwater in the Stockholm usually contains small amounts of Ca: 4–6°dH (grad deutscher Härte) where 1°dH correspond to 10 mg CaO/1 litre of water. This can vary locally, especially in the nearby Stockholm archipelago with measured values of 7–13°dH. In such areas Ca precipitations in washing machines, saucepans and pipes can be a problem. Perhaps the degree of CaO is high enough to precipitate speleothems on the granitic walls of the subway station Kungsträdgården, at least with support of microorganisms.

Acknowledgement

We want to thank AB Storstockholms Lokaltrafik (SL) for permission to survey the station and its fascinating environment; especially Gülsüm Kaya at SL must be thanked for support and assistance during the project. Thanks also to Lars Hedenäs and Yngve Brodin, both at the Swedish Museum of Natural History (NRM), who determined the moss and the crane fly, respectively, and to Mario Parise, National Research Council of Italy, for valuable comments on an earlier version of the manuscript. The ESEM/EDS analyses were done at Stockholm University; in particular we would like to thank Marianne Ahlbom at the Department of Geological Sciences for assistance during the ESEM. Some of the light microscopy analyses of the diatomes were done at the Paleobotany department at NRM, and we would like to thank Prof. Else-Marie Friis and Dr. Christian Pott for help with the microscopy. At NRM we had much help from Veneta Belivanova and Yvonne Arremo with the SEM, many thanks to both of you!

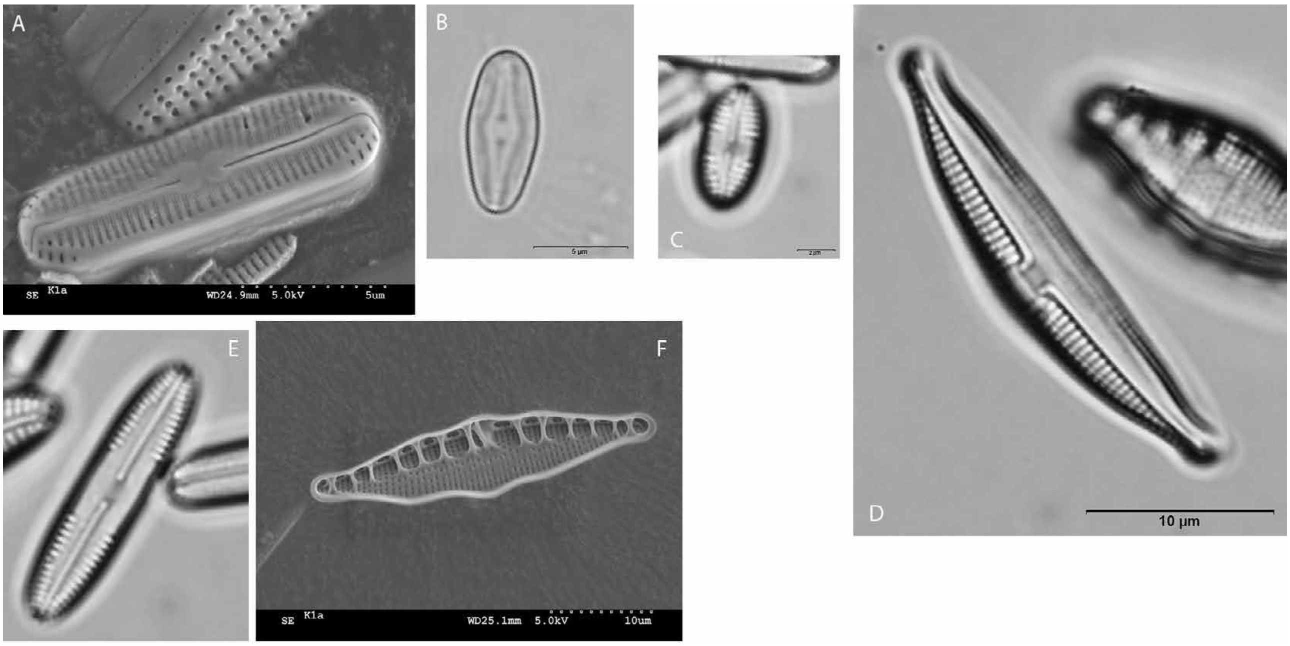

Figure 2. Some of the species from the diatom flora of Kungsträdgården subway station, Stockholm, Sweden. A: Diadesmis contenta *(Grunow) Mann. B:* Diadesmis perpusilla *(Grunow) Mann. C:* Caloneis *sp. D:* Amphora normannii *Rabenhorst. E:* Caloneis *cf.* aerophila *Bock. F:* Nitzschia sinuata *(Smith) Grunow.*

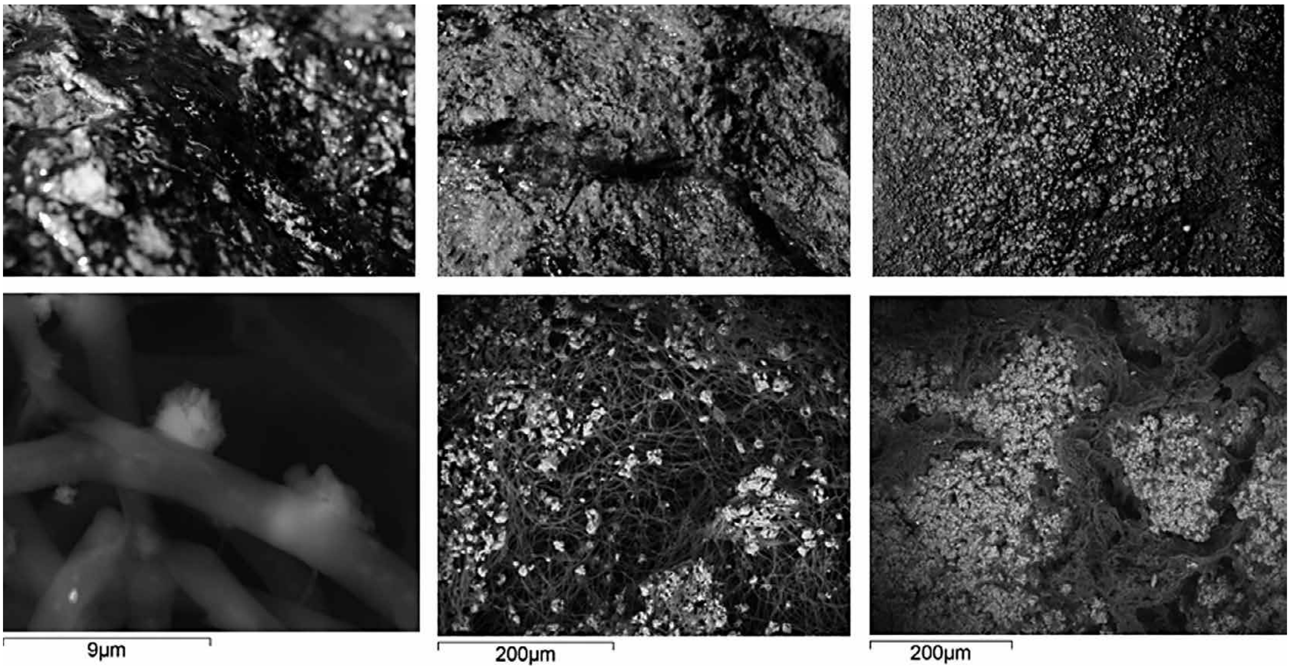

Figure 3. Microphotographs and ESEM images showing gradual increase (from left to right) of calcite precipitation on fungal hyphae with the final result of speleothem formation.

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