Methanogenesis under extreme environmental conditions in permafrost Soils: a model for exobiological processes?

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INTRODUCTION

Permafrost within the solar system exists on seven planets as well as several moons, which are characterized by cold environmental conditions. Of special interest to present-day research in astrobiology is the comparability of environmental and climatic conditions of the early Mars and Earth. Martian and terrestrial permafrost areas show similar morphological structures, suggesting that their development is based on comparable processes. New high-resolution images of the Mars Orbiter Camera (MOC) imply water in liquid form or as ground ice on Mars, which is an essential bio-physical requirement for the survival of micro-organisms in permafrost. Terrestrial permafrost, in which micro-organisms have survived for several million years (Rivkina et al. 1998), is an ideal model for comparative system studies regarding the evolution, adaptation and survival strategy of microorganisms under extreme conditions.

METHANOGENESIS

The microbial methane production (methanogenese) is the terminal step during the decomposition of organic matter in permafrost soils. Responsible for the methane production is a small group of highly specialized microorganisms, called methanogenic archaea, which are considered to be one of the initial organisms from the beginning of life on Earth. They are regarded as strictly anaerobic microbs, which can grow and survive only under anoxic conditions, like in wet tundra environments. Compared to Martian conditions, such a metabolism would be favourable because the atmosphere on Mars is dominated by CO_2 (95.3 %). Furthermore, they are characterized by litho-autotrophic growth, whereby energy is gained by the oxidation of hydrogen, and carbon dioxide can be used as the only carbon source (Deppenmeier et al. 1996). Organic compounds, which were not verified on Mars, are not required for growth. The special metabolism qualities of the methane-forming archaea are the reason that they are regarded as *key organisms* for further investigation in the adaptation strategies and long-term survival in extreme environments such as those with terrestrial permafrost (Wagner et al. 2001).

MICROBIAL METHANE PRODUCTION UNDER EXTREME CONDITIONS

The field investigations were carried out on the Samoylov island (N 72°, E 126°) located in the Lena Delta/Siberia. The study site represented an area of typical polygonal patterned grounds with ice wedges. The permafrost soils were classified as *Glacic Aquiturbels* and *Typic Historthels* with a maximum thaw depth between 30 and 55 cm. The average air temperature was −14.7 °C with a min. of -47.8 °C in January and a max. of +18.3 °C in July.

The investigation of *in situ* methane production revealed methane formation in the boundary layer to the permafrost at temperatures between 0.6 and 1.2°C (Fig. 1) with a rate of about 1.0 nmol CH_4 h^{-1} g^{-1}. Without any additional substrate, the methane production varied between 0.3 and 4.7 nmol CH_4 h^{-1} g^{-1} (Fig. 2). The highest activity could be determined in the peat layer of the upper soil at an average temperature of 10 °C. Nevertheless, the comparison of different vertical profiles to the methane production showed that the activity of the micro organisms is independent of the soil temperature. After addition of methanogenic substrates (acetate, H_2), the activity drastically increased. The methane production in the peat layer with H_2 as substrate was about 2 times higher (13.0 nmol CH_4 h^{-1} g^{-1}) compared with acetate (7.2 nmol CH_4 h^{-1} g^{-1}) as substrate, while above the permafrost table the activity was in the same order of magnitude (approx. 1.5 nmol CH_4 h^{-1} g^{-1}) with both substrates. Even the incubation of soil material from the active layer with H_2 as a substrate showed a significant methane production rate at −3 °C (0.1 – 11.4 nmol CH_4 h^{-1} g^{-1}) and −6 °C (0.08 – 4.3 nmol CH_4 h^{-1} g^{-1}). The existence of a methanogenic community, which has adapted well to the low *in situ* temperature of permafrost soils is assumed by our results.

In accordance with Panikov (1997), psychrophilic bacteria have a significant part in the microbial community in cold environments like permafrost soils. However, the isolation and characterization of methanogenic archaea from permafrost soils should clarify the possible growth characteristic (psychrophile or psychrotroph) and the ecological significance of these organisms.

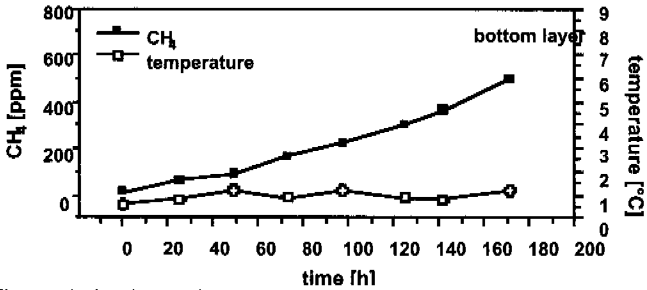

Figure 1. *In situ* methane production in the boundary layer to the permafrost in the soil of the polygon depression.

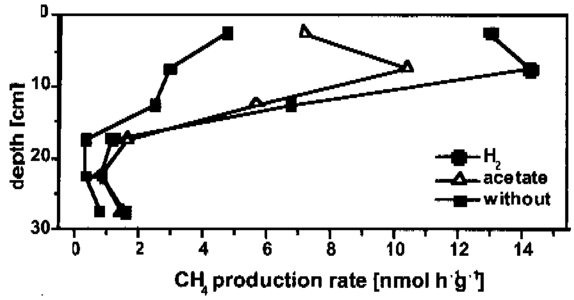

Figure 2. Vertical profile of methane production rates without any additional substrate as well as with H_2 and acetate in the soil of the polygon depression.

First results concerning the diversity of methanogenic microflora by fluorescence *in situ* hybridization (FISH) indicated that H_2-using genera like *Methanobacterium* and *Methanomicrobium* dominated over methylotrophic and acetotrophic methanogenic archaea. Enrichment cultures, which were dominated by the genera *Methanosarcina*, showed that these organisms grow not only with the preferred substrate methanol but also with CO_2 and H_2 as the only carbon and energy source.

CONCLUSIONS AND FUTURE PERSPECTIVES

Methanogenic archaea, which can live solely on the basis of water, minerals, carbon dioxide and hydrogen, survived in terrestrial permafrost for several millions of years. Since they are still active, they had to develop different strategies to resist extreme conditions like salt stress, physical damage by ice crystals and background radiation. The presented results demonstrate an essential basis for the understanding of the origin of life. The studies can be used as a model for exobiological processes to find traces of life in extraterrestrial habitats and to look for possible protected niches e.g. on Mars.

Apart from the presented studies, simulation experiments with permafrost microcosms can supply important results for the understanding of microbial life under extreme conditions (Wagner et al. 2003). Simulation of the freezing-thawing cycle can help to understand the problem in which way the microbial population will be influenced by the natural permafrost system and by the interaction of the combined parameters.

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