Goldschmidt 2026 Abstract
https://doi.org/10.46427/gold2026.34410

A single archaeon rewires long-chain fatty acid methanogenesis

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Anaerobic degradation of complex organic compounds to methane and carbon dioxide is a common process in deep subsurface biosphere. This process has long been considered to require syntrophic cooperation, with methanogens confined to the terminal utilization of simple C_1 and C_2 substrates. Thermodynamic considerations, multi-omics analyses and microcosm experiments suggested the presence of archaeal lineages for direct coupling of complex substrate degradation to methanogenesis. However, experimental validation in pure culture was lacking. Here we report the isolation of a thermophilic archaeon, *Methanoglobus dolicholipophagus* AA-75, affiliated with *Archaeoglobi* from a petroleum reservoir. Strain AA-75 converts methanol to methane. It also directly degrades long-chain fatty acids, including stearate and palmitate, to methane and carbon dioxide. We term this metabolism lipotrophic methanogenesis. Genomic, transcriptomic and comparative genomic analyses reveal an integrated lipotrophic methanogenesis pathway that couples β-oxidation to Wood-Ljungdahl pathway, canonical Mtr and Mcr complexes, together with a coordinated intracellular electron transfer system. The methanogenesis pathway also contains a parallel formaldehyde-methanol C_1 metabolic branch functioning as a Mer bypass. Methane produced from stearate is moderately ^{13}C-enriched, distinct from the strong ^{13}C depletion characteristic of classical methanogenesis pathways. These findings demonstrate that methanogens can function as primary degraders of complex organic matter, challenging the classical syntrophic paradigm and calling for refinement of current models of carbon cycling in the deep subsurface biosphere.