Origin and Evolution of Biological Nitrogen Fixation

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Abstract

The origin and evolution of life on Earth was impacted by the availability of fixed nitrogen. The advent of biological nitrogen fixation represents a key step in the evolution of life on Earth facilitating the proliferation of life as abiotic sources of fixed nitrogen presumably dwindled. The ability to fix nitrogen is distributed throughout a small number of phylogenetically diverse bacteria and some methanogenic Archaea. The widespread phylogenetic distribution of diazotrophy provides little insight into the environmental underpinnings that define the limits and diversity of biological nitrogen fixation and would provide key insight into the evolution of diazotrophy. Degenerate primers targeting the known diversity of the nitrogenase protein-encoding gene (nifH) were designed and employed to investigate the physical and chemical parameters that underpin the distribution and diversity of nifH in thermal springs of Yellowstone National Park. Collectively, these studies provide new insight into environmental constraints that underpin the distribution, diversity, and activity of diazotrophs in geothermal environments. Furthermore, this study extends the upper temperature limit for nitrogen fixation in a terrestrial environment, and arguably represents the most extreme environmental conditions that support nitrogenase activity. As a result, a clear picture of the sequential evolution of Mo-dependent and alternative forms in extant organisms has emerged.

Nitrogenase

N₂ + 8H⁺ + 8e⁻ + 16MgATP → 2NH₂ + H₂ + 16MgADP + 16P

Electron Transfer Pathway

Nitrogenase FeMo-cofactor biosynthesis

Phylogenetic Occurrence of Mo-Nitrogenase

Mo-Nitrogenase do not occur in deeply-branching lineages

Gene Duplication and Gene Fusion Events

Insight into Nitrogenase Evolution

Are Alternative Nitrogenases Ancestors of Mo-Nitrogenase?

Phylogenetic analysis and structural evolution of HDK

nif-encoded HDK form two distinct lineages:
1. Hydrogenotrophic methanogens at the base of the tree
2. More recently evolved NifH/DHK homologs

Vnf and Anf nested within the 2 Nif sublineages
Vnf and Anf were derived from Nif

Are Mo-Nitrogenases Ancient Enzymes?

A number of inconsistencies with these enzymes being ancient
Complex maturation machinery required for FeMo
More complex enzymes as ancestors of less complex enzymes not the simplest explanation
Absence of more universal occurrence, especially in deeply-branching organisms

Nif ancestral to Anf/Vnf/Nif and Bch

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