博士論文

Geochemical and paleontological constraints on microbial evolution of early Proterozoic Earth

（初期原生代の微生物進化に対する地球化学的
および古生物学的制約）

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Abstract

The evolution of early life and its driving forces have long been studied by previous investigators. The expression of eukaryotic microbes is one of the most important changes in the history of life evolution. The eukaryote, having more than 10 times larger body with a complex cell structure than a prokaryote, requires more energy to maintain its body, suggesting that the prokaryote established the ability to generate greater energy than before. Prokaryotes diversified around 2 billion years ago (Ga), followed by eukaryotes emerging indicating that there was a major turning point for early life in that age. However, this is still an open question because evidence of life in the Archaean to Paleoproterozoic era is fragmented due to the lack of fossilized biomaterials and poor preservation. Various geological events such as snowball earth, maximization of magmatic activity, and rise of sedimentation rate of organic matter have been reported in the early Proterozoic era, which may have triggered the diversification of prokaryotes and inducing the emergence of eukaryotes. Such drastic and global changes of Earth's environment caused global changes in material transportation from continents to ocean resulting in the change of flux of bio-essential elements, such as P and metal elements to be taken in the biosphere. However, this hypothesis has not been fully tested, and thus, should be verified.

Therefore, it is necessary to target the global microbial ecosystems of the early Proterozoic era and clarify when and how the acquisition of various functions of microorganisms and the evolution of eukaryotes occurred. To know the evolution of life is equal to understanding the evolution of metabolic systems in the biosphere. As the metabolic reaction is controlled by enzymes, the behavior of trace metals that are utilized in the enzyme is key to solving these questions. It is also necessary to clarify the special elemental circulation caused by the geological events of that era in the strata that recorded the geological events (e.g., magmatic activity and massive organic deposition) of the early Proterozoic era. This will help us to understand the phenomena that are thought to have driven the evolution of microorganisms.

Our primary objective was to constrain the diversification of microorganisms and the timing of eukaryotic outbreaks in the early Proterozoic. In chapter 1, a palynological and geochemical study was conducted on the 1.9 Ga Gunflint microfossils to find more prokaryotic diversity and complexity and examination of potential eukaryotic forms for microfossils preserved in the stromatolite of the Gunflint Formation. As a result, five new morphological microstructures were discovered. New morphological and geochemical data proved the biogenicity of such microstructures. Some microstructures showed early acquisition of dormancy and nutrient storage function. This can be interpreted as the result of adaptation to improve survivability in a fluctuating environment in the 1.9 Ga. Other novel microstructures with spine- or tail-like cell projection showed eukaryotic affinity morphologically. This is the first report that the early eukaryotic evolution coincidentally occurred with prokaryotic diversification in this era.

In chapter 2, we developed a method to solve the problems of conventional microfossil research: to detect trace elements that can be used as a biomarker. The discussion has been ambiguous because the microfossil research conducted so far has not established a method for directly constraining the metabolic mode of microfossils other than morphology. Therefore, by directly detecting phosphorus (P) and enzyme metal (e.g., Molybdenum: Mo) from Gunflint microfossil, we tried to prove that it is a structure of biological origin, and that the enzyme was used. As a result, we succeeded in detecting P and Mo-oxide from the extracted microfossil body by using nanoscale secondary ion mass spectrometry (NanoSIMS). The detection of phosphorus in microfossils provides evidence to support the use of phosphorus in early life and contributes to the elucidation of the origin of phosphorus coexisting with organic matter in geological samples. Mo detection from fossiliferous organic matter means an increase in Mo availability in response to the oxidation of the Earth's surface and the formation of continents followed by the acquisition of Mo-bearing protein by cyanobacteria. Furthermore, it suggested the development of the global nitrogen cycle.

By demonstrating the existence of a special elemental cycle in the era of the “explosive evolution” of microorganisms, it is possible to clarify the relationship between microbial evolution and changes in the global environment. In Chapter 3, a geochemical analysis was performed on the 1.98 Ga Zaonega Formation, Russia, which recorded changes in the marine environment during the early Proterozoic era. Massive sedimentation of organic matter and active volcanism were recognized in this Formation and a part of organic matter was converted into oil due to high heating flux. Thus, this area is considered to be a 'model case' to know a Paleoproterozoic unique elemental cycle and biosphere. Compound-specific measurements of nitrogen isotope ratio of sediments and organic matter were newly performed to clarify the nitrogen cycle in this region. As a result, a positive shift in nitrogen isotope ratio with the distribution of solidified oil was obtained. It was clarified that the nitrogen and other organic compounds were supplied to the biosphere from the oil in that age. This is the first report of an excessive supply of nutrients due to the recycling of petroleum and sedimentary organic matter in the closed basin.

As a summary of this research, it became clear that the change in nutrient element flux due to environmental changes caused by active tectonic, and the diversification of early microbial ecosystems and the evolution of eukaryotes occurred at almost the same time. This indicates that early life evolution was driven by the dynamics of the Earth.