Accepted Manuscript

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PII: S0012-8252(16)30182-9
DOI: doi: 10.1016/j.earscirev.2016.07.007
Reference: EARTH 2289

To appear in: *Earth Science Reviews*

Received date: 11 December 2015
Revised date: 31 May 2016
Accepted date: 20 July 2016

The evolution of Earth's biogeochemical nitrogen cycle

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Abstract

Nitrogen is an essential nutrient for all life on Earth and it acts as a major control on biological productivity in the modern ocean. Accurate reconstructions of the evolution of life over the course of the last four billion years therefore demand a better understanding of nitrogen bioavailability and speciation through time. The biogeochemical nitrogen cycle has evidently been closely tied to the redox state of the ocean and atmosphere. Multiple lines of evidence indicate that the Earth's surface has passed in a non-linear fashion from an anoxic state in the Hadean to an oxic state in the later Phanerozoic. It is therefore likely that the nitrogen cycle has changed markedly over time, with potentially severe implications for the productivity and evolution of the biosphere. Here we compile nitrogen isotope data from the literature and review our current understanding of the evolution of the nitrogen cycle, with particular emphasis on the Precambrian. Combined with recent work on redox conditions, trace metal availability, sulfur and iron cycling on the early Earth, we then use the nitrogen isotope record as a platform to test existing and new hypotheses about biogeochemical pathways that may have controlled nitrogen availability through time. Among other things, we conclude that (a) abiotic nitrogen sources were likely insufficient to sustain a large biosphere, thus favoring an early origin of biological N_2 fixation, (b) evidence of nitrate in the Neoarchean and Paleoproterozoic confirm current views of increasing surface oxygen levels at those times, (c) abundant ferrous iron and sulfide in the mid-Precambrian ocean may have affected the speciation and size of the fixed nitrogen reservoir, and (d) nitrate availability alone was not a major driver of eukaryotic evolution.

Keywords
nitrogen cycle; nitrogen isotopes; Precambrian; evolution

1. Introduction

Nitrogen is a major nutrient that is essential to all life on Earth and it is likely that this is no accident of chemical evolution, for at least three reasons. First, it is an abundant element in the cosmos and in Earth's atmosphere (Henry et al., 2000; Marty, 2012); second, it forms versatile covalent bonds with carbon that are integral to the functioning of organic biomolecules; and third, nitrogen is redox-active in the stability field of liquid water and is thus a potent source