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The Cambrian Explosion: Plume-driven birth of the second ecosystem on Earth

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ABSTRACT

The birth of modern life on Earth can be linked to the adequate supply of nutrients into the oceans. In this paper, we evaluate the relative supply of nutrients into the ocean. These nutrients entered the ocean through myriad passageways, but primarily through accelerated erosion due to uplift. In the 'second ecosystem', uplift is associated with plume-generation during the breakup of the Rodinia supercontinent. Although the evidence is somewhat cryptic, it appears that the second ecosystem included the demospongia back into the Cryogenian (~750 Ma). During the Ediacaran–Cambrian interval, convergent margin magmatism, arc volcanism and the closure of ocean basins provided a second pulse of nutrient delivery into the marine environment. A major radiation of life forms begins around 580 Ma and is represented by the diverse and somewhat enigmatic Ediacaran fauna followed by the Cambrian Explosion of modern phyla during the 540–520 Ma interval. Tectonically, the Ediacaran–Cambrian time interval is dominated by the formation of ultra-high pressure (UHP), high pressure (HP) and ultra-high temperature (UHT) orogenic belts during Gondwana orogenesis. Erosion of this extensive mountainous region delivered vast nutrients into the ocean and enhanced the explosiveness of the Cambrian radiation. The timing of final collisional orogeny and construction of the mountain belts in many of the Gondwana-forming orogens, particularly some of those in the central and eastern belts, post-date the first appearance of modern life forms. We therefore postulate that a more effective nutrient supply for the Cambrian radiation was facilitated by plume-driven uplift of TTG crust, subsequent rifting, and subduction-related nutrient systems prior to the assembly of Gondwana. In the outlined scenario, we propose that the birth of the 'second ecosystem' on our planet is plume-driven.

Contents

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1. Introduction

1.1. The Cambrian Explosion: nutrients as the most essential factor

One of the most spectacular events in Earth history, termed the 'Cambrian Explosion' (CE), witnessed the origin of metazoans from unicellular organisms and their subsequent evolution into large multi-cellular animals at the dawn of the Phanerozoic (Gould, 1989, 1995, 1998; Maruyama and Santosh, 2008; Meert and Lieberman, 2008). There are multiple hypotheses and proposed triggers for the CE, but many consider that the most important change that took place was an increase in the oxygen content of the oceans and atmosphere (Gould, 1998; Holland, 2006; Chumakov, 2010). It is thought that oxygen levels increased up to a hundred fold from 1/100 PAL to near present-day levels of 1 PAL near the Ediacaran–Cambrian boundary.

Whereas the increase in oxygen levels is well-documented, a biological enigma remains in that high pO_2 levels alone cannot explain the rapid rise in complexity that is observed in the Cambrian. In particular, we argue that changes in oxygen levels worked in conjunction with a stable supply of essential nutrients to produce the myriad life forms that appeared in the CE. Of utmost importance are the presence of dissolved nutrients such as P, Ca, K, Fe, Mg, Fe, Ca, S, Zn, Mo and others. Nutrients such as Ca, P and Fe are critically important to build the 'hard parts' (bones, shells, teeth) whereas some of the other nutrients are essential for cell metabolism. A continuous supply of these nutrients over time is required to sustain complex life forms.

The abiogenetic origin of primitive life on the early Earth remains a mystery. One of the myriad models for the origin of life considers the interaction of the nascent hydrosphere with mantle rocks to form serpentinites and the subsequent reaction of the vent fluids with CO_2-bearing sea water as part of the 'nutrient' equation (Sleep et al., 2011). The diverse assemblages of microbial fossils found in the 3465 Ma Apex Chert (NW Australia) are thought to represent of the earliest forms of primitive life on the early Earth (Schopf and Kudryavtsev, 2012). Brasier et al. (2013), in a recent study on the Apex basalts, reported the occurrence of pumice clasts with potential biominerals including sulfides and phosphates, together with intimate associations of C, N, P and S. They proposed that these clasts, that also contain catalytic minerals such as titanium oxide, altered clays and zeolites represent an optimum environment for the development of early life.

In addition to proper nutrients, substrates and protective cellular membranes, energy is fundamental to the formation and survival of life. Therefore, consideration of the source and mechanism of various energy yielding pathways is paramount when evaluating the origin and evolution of life. In simplistic terms, solar energy is the dominant external 'power cell' for the planet. Life on Earth took full advantage of this energy source early on with the development of cyanobacterial stromatolites in the Archean. Since the development of the first photosynthetic organisms, a large diversity of primary producers evolved strategies to capture and store solar energy as chemical fuels that are used by other life forms without photosynthetic systems (Ehleringer and Monson, 1993). Lu et al (2012) in a recent study demonstrated that semiconducting mineral photocatalysis, acting as an energy source, promoted microbial growth.

An early study of Brasier et al. (1978) recognized that nutrient supply was one of the most essential triggers for the Cambrian Explosion, although the relationship to elevated pO_2 remained uncertain. Maruyama and Liou (2005) correlated the increase in pO_2 with the deposition of large volumes of sedimentary rocks that prevented the reverse reaction of organic material burial, thereby preserving free oxygen in the atmosphere and maintaining a dynamic equilibria.

Squire et al. (2006) speculated that the abundant nutrient supply leading to the Cambrian Explosion was related to the formation of large collisional mountain belts during the amalgamation of Gondwana at ca. 540 Ma. Based on a compilation of $^{87}Sr/^{86}Sr$ isotopic ratios through time (e.g., Shields and Veizer, 2002), a sharp increase in the rapid and abundant nutrient supply was identified at the onset of the Cambrian (Maruyama and Liou, 2005; Maruyama et al., 2013). The rapid erosion of mountain belts built through continent–continent collisions associated with the formation of supercontinents releases large amounts of nutrients such as iron and phosphorus into the oceans, leading to an explosion of algae and cyanobacteria and enhanced production of O_2 through photosynthesis (Campbell and Allen, 2008). The increased sedimentation also promotes the burial of organic carbon and pyrite, inhibiting the back-reaction with free oxygen and maintaining a sustained increase in atmospheric oxygen as envisaged by Maruyama and Liou (2005).

In a recent work, Peters and Gaines (2012) reached a similar conclusion on the role of nutrients as a trigger for the Cambrian Explosion. Their work suggested that the 'Great Unconformity' resulted from a sudden denudation of a large landmass resulting in a large nutrient supply into the global oceans. The unique appearance of a huge landmass on the Earth during the Neoproterozoic was earlier addressed by Maruyama (1997a) and Maruyama and Liou (2005), who concluded that it was a consequence of the cooling Earth that triggered the initiation of return-flow of seawater into mantle, thereby lowering the sea level and exposing the landmass to enable weathering and transport of nutrient elements into the ocean. The appearance of blueschist facies rocks and low-T eclogites in subduction zones over the last 750 Ma, the extensive hydration of the hanging walls of the mantle wedge, and the hydration of the mantle transition zone were considered as the key evidence for the decreasing volume of ocean water on the Earth's surface since the Neoproterozoic. These aspects are discussed in more detail in a companion paper (Maruyama et al., 2014).

In this work, we address the following major aspects. (1) The location of mountain belts during the formation of Gondwana based on the space–time distribution of collision-type orogenic belts and their P–T estimates. (2) Continental rifts, initially elevated by rising plumes, as the most effective source of nutrient supply. (3) The role of post-collisional up-doming caused by the heated and metasomatized mantle through the effect of the 'second continents' in the mantle transition