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Celebrating 50 Years

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Geology was somewhat of an upstart in 1973 ("a new venture in earth science reporting"). In celebration of its 50 years of publishing, the journal has invited recent Donath medalists to submit essays on what might be in store for the geosciences in the next 50 years. The following is from the 2020 medalist, Christopher J. Spencer.

Biogeodynamics: Coupled evolution of the biosphere, atmosphere, and lithosphere

Christopher J. Spencer[1]

[1]Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, Ontario, K7L 3N6, Canada

There is broad consensus that tectonic and magmatic processes play a role in the evolution of life and the composition of the atmosphere. Tectonic and magmatic processes provide a suite of bio-essential nutrients that are carried into the hydrosphere through sedimentary processes. Tectonic processes facilitate the subsequent recycling and concentration of these nutrients for continued biospheric utilization. The burgeoning field of "biogeodynamics" aims to test hypotheses about such connections (Fig. 1). The past 50 years brought the plate tectonics revolution into full swing. The next 50 years are in a prime position to expand phylogenic consensus, augmenting secular evolution of geologic processes and expanding the links between the disparate processes controlling the evolution of the biosphere, atmosphere, and the solid Earth.

The past 50 years have also focused considerable attention on defining secular change in geologic processes. The uniformities of law and process are unequivocally accepted by the geologic community and uniformity of rate (gradualism) is largely rejected (Gould, 1965). However, the uniformity of state (that is, the lack of secular change in geologic processes and resulting phenomena) continues to be debated even when it comes to first-order processes such as the onset of plate tectonics or advent of oxygenic photosynthesis. There are "tectonic uniformitarianists" who argue for the emergence of effectively modern-style plate tectonics during the Hadean (Harrison et al., 2017; Rosas and Korenaga, 2018) and others who broadly ascribe to an onset either during the Archean (Shirey and Richardson, 2011; Nutman et al., 2015) or Proterozoic (Stern, 2018). As for oxygenic oxygenation, there are the "whiffers" who posit an early evolution of atmospheric photosynthesis that is decoupled from the Great Oxygenation Event (Anbar et al., 2007; Lyons et al., 2014) and those who contend the early "whiffs" of oxygen are the product of alteration (Slotznick et al., 2022) and hypothesize a direct link between the rise of atmospheric oxygen and evolution of oxyphotobacteria (Fischer et al., 2016; Soo et al., 2017).

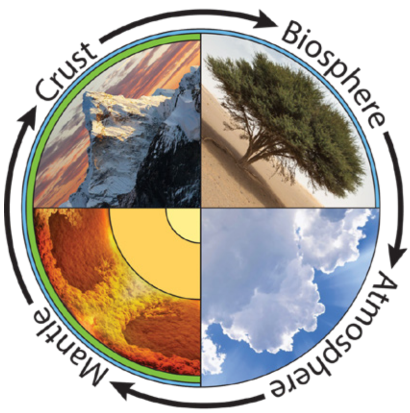

Figure 1. The field of biogeodynamics posits the interconnection between the mantle, crust, biosphere, and atmosphere. Images from the Creative Commons.

The primary connection between bioproductivity and tectono-magmatism is largely related to rock-bound nutrients delivered to the oceans through weathering and erosion processes (Cox et al., 2018; Zerkle, 2018). Additionally, plate tectonic processes provide environmental pressures through continental redistribution, opening and closing oceans, and growing mountain ranges which all carry the potential to isolate and stimulate populations. Chemical exchange between the atmosphere, hydrosphere, and biosphere with the lithosphere results in traceable changes in sedimentary composition throughout geologic time (Smit and Mezger, 2017). In this way, sedimentary rocks are the direct harbinger of interactions between the biosphere, hydrosphere, and atmosphere with the lithosphere. Sedimentary deposition along continental margins and within ocean basins ultimately leads to a sizable fraction of sedimentary material becoming incorporated into magmatic systems during convergent tectonics (Liebmann et al., 2021).

In my unabashedly biased view, the mineral zircon continues to provide important contributions to biogeodynamic discussions. Through thermochronology, geochronology, trace element concentration and Hf, O, and Li isotopic compositions, zircon can provide insight into mountain formation and denudation, sedimentary provenance and burial, metamorphism and magmatic recycling, and long-term tectonic cycles. Recent work has sought to directly tie the zircon record to the increase of continental freeboard (Reimink et al., 2021) which is temporally correlated with atmospheric oxygenation (Spencer et al., 2019). Nevertheless, various oft-overlooked accessory mineral species are gaining more of the limelight as advances in mineral liberation and mass spectrometry expand avenues for their analysis. Apatite, rutile, monazite, garnet, titanite, and allanite have great potential to augment our understanding of biogeodynamics. In particular, apatite has a special connection between magmatism and metamorphism with biological productivity in terms of a riverine phosphorus source (Hao et al., 2021) but also

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as a direct recorder of phosphate burial and diagenesis (Lumiste et al., 2019).

A fundamental question is how much life shaped geologic processes and how much geologic processes have influenced the evolution of life (DePaolo, 2008). Was the origin and evolution of life directly coupled to and therefore traceable through the secular change in geologic processes, or did geology play a passive role in the biosphere? Although there is a clear correlation between various geologic processes and the evolution of the biosphere and atmosphere, the causality of these connections is sometimes tenuous or at the very least would benefit from greater shoring.

The next steps in addressing whether evolution of life and atmosphere is coupled to the lithosphere will require synthesizing wide arrays of data spanning disparate disciplines and methodologies. This includes continued exploration of novel isotopic proxies that hold significant promise in testing biogeodynamic hypotheses. Advances in isotopic analysis hold significant promise in expanding our understanding through nitrogen, selenium, zinc, copper, and triple oxygen isotopes.

In addition to the isotopic investigations, biogeodynamic hypotheses are also being tested in fields as diverse as paleomagnetism and phylogenetics. Earth's magnetic field plays an important role in protecting the biosphere from cosmic radiation and solar wind; however, recent research has proposed how fluctuations in the magnetic field had a direct influence on the evolution of life on Earth (Bono et al., 2022). This is intuitive as the magnetic field shields the biosphere from harmful radiation. Nevertheless, establishing the paleointensity of the magnetic field is no trivial task and requires only the highest quality data to constrain secular changes in the magnetic field (Bono et al., 2022).

Phylogenetics play a vital role as calibrations of molecular clocks point to the approximate time at which taxa divergence occurred. In particular, the relationship between the evolution of oxygenic phototrophs and the Great Oxygenation Event remains unclear, with some proponents for an early Archean emergence of oxygenic photosynthesis (Cardona et al., 2019) and others arguing for a causal relationship between oxygenic phototrophs with the Great Oxygenation Event (Fischer et al., 2016; Soo et al., 2017). Further work is under way that aims to unify the geologic record with phylogenetics that will undoubtedly lead to further insight into the possible coupling between the biosphere, atmosphere, and lithosphere.

Suffice it to say that the future is bright when it comes to our understanding of the coupled evolution of the biosphere, atmosphere, and lithosphere. With new tools applied to old problems and new problems tested with compiled data, the next 50 years is sure to see the field of biogeodynamics breaking the boundaries of the scientific status quo.

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