DISEQUILIBRIUM IS NEEDED FOR LIFE TO EXIST

This issue’s theme is on the importance of large igneous provinces (LIPs) driving global environmental change. As discussed in this issue’s articles, these massive but short-lived magmatic events profoundly impacted the evolution of life through mass extinctions and, in some cases, changing the long-term climatic state of our planet. LIPs are a reminder that the whole Earth, from the core to the crust to the atmosphere, ocean, and life are interconnected, but more specifically, the dynamics of the Earth’s interior plays a key role in facilitating life.

For life to exist, disequilibrium must exist. Disequilibrium gives rise to energy gradients. At the most basic level, life can be seen merely a means of facilitating the flow of energy across these gradients. For example, life-sustaining energy can be accessed from redox potentials between reduced volcanic gases and the oceans and atmosphere. Temperature gradients in hydrothermal environments also provide life-giving energy. But for most of Earth’s history, the most important source of life-giving energy comes from the Sun, accessed through the biochemical reactions associated with photosynthetic organisms. From photosynthesis, the Sun’s energy is captured and stored in the form of reduced carbon, which is then distributed across the planet to sustain non-photosynthetic life, even in places where the Sun does not shine, e.g., the deep sea or in soils.

Enhancing Reaction Rates With Water

Gradients in energy alone, however, are not sufficient for life. The transfer of energy down gradients is kinetically rate-limited. Chemical reactions that permit energy to flow cannot happen if it is too cold. In fact, most redox reactions are too sluggish even at the surface temperatures of Earth today. But reaction rates can be enhanced if atoms can be mobilized. This is why water is essential. Water is a solvent and it flows, providing a rapid means of moving electrons, reactants, and products over distances far greater than solid-state diffusion. Biochemical reactions and compounds also require certain trace elements, known as nutrients. Water allows life to access nutrients and transport them to where they are needed.

But water in a liquid state is not a given. This is why Earth is presently unique in the Solar System. Too cold, water would be frozen, unable to transport nutrients. Too hot, water would be in the form of steam in the atmosphere, inaccessible to life. There is only a narrow window of temperature in which liquid water can persist on our one-­bar planet. Earth’s surface is kept from freezing by the combination of radiative temperature in which liquid water can persist on our one-­bar planet. Volcanism also returns water to the surface, which would otherwise be subducted back into the mantle. Mountain building and erosion provide new nutrients to the surface as well as the mafic and calc-­silicate minerals that weather and eventually allow for the sequestration of CO2 in the form of carbonates. Without the latter—a negative feedback to volcanic inputs of CO2, atmospheric CO2 concentrations would grow unabated, leading to a runaway greenhouse state.

Sustained life thus requires internal and external sources of energy (the Sun), the ability to refresh the surface with life-­essential elements (tectonics), and an internally regulated climate (weathering). This delicate balancing act has somehow been maintained on our planet for billions of years. In detail, our baseline climate fluctuates on long and short timescales, depending on how inputs of CO2 and the sensitivity of negative feedbacks (weathering/carbonate deposition and organic carbon burial) vary with time as Earth’s interior dynamics evolves.

WHAT CONTROLS THE DIVERSITY OF LIFE?

Ecologists view the diversity of life as being controlled by the number of niches within an ecosystem, but from a geologist’s perspective, ecosystems are part of the interconnected planetary system and exist only by the availability and accessibility of energy as controlled by geology and climate. Ecological niches are energy niches. When energy gives forth to life, life itself becomes its own intermediary source of energy, giving forth to even more energy niches and pathways. An ecosystem, teaming with life, is born.

The diversity of life is controlled by the “landscape” of energy (referred to as the “fitness landscape” by ecologists). When the environment changes, the energy landscape changes, and via natural selection, life evolves and diversifies (Futuyma and Kirkpatrick 2022). If environmental change occurs too quickly, such that genetic drift is unable to keep up, mass extinction occurs (which is why we worry about the rapid environmental changes in the Anthropocene). In the aftermath, a new ecosystem with a new set of characters will inevitably arise, even if the environment returns to its previous steady state.

What Controls Long-term Climatic States on Earth?

To understand how life has evolved on Earth thus requires us to understand what controls long-term steady states (>million-year timescales) and what controls catastrophic events that knock the system out of steady state. Over most of Earth’s history, changes in Earth’s long-term climate likely correlates with changes in the long-term CO2 content of the atmosphere. This balance is controlled by deep Earth inputs (volcanic and metamorphic degassing) and negative feedbacks (where outputs correlate with pCO2), which relate to the efficiency of carbonate and organic carbon burial (the former linked to silicate weathering and the latter to biological productivity) (Walker et al. 1981). On long timescales, inputs and outputs are roughly balanced (Figs. 1 and 2). Thus, a warm climatic baseline arises if inputs are high or the efficiency of weathering is low (Lee et al. 2019). Cool climates arise if inputs are low or the efficiency of weathering is high (Caves et al. 2016). The Earth can shift from one baseline to another if there are fundamental shifts in how the Earth operates. For example, if ridge activity increases, all else being equal, there would be a shift to being warm. If large amounts of mafic crust are emplaced or exposed at the surface, the higher weatherability of such lithologies could enhance the silicate weathering feedback, moving the Earth into a cold baseline.
Baseline Climates Near Threshold are Sensitive to Perturbations

Tectonic processes, however, are slow and should lead to long periods of stasis or gradual change in fauna. Rapid diversification or mass extinctions require short-lived perturbations that lead to catastrophic environmental change (see also Galloway and Lindström 2023 this issue; Gaynor et al. 2023 this issue; Grasby and Bond 2023 this issue; Svensen et al. 2023 this issue). Most mass extinctions appear to be related to eruption of large igneous provinces (LIPs), but the reverse is not true, as not all LIPs lead to a mass extinction (see also Deegan et al. 2023 this issue). Why? Much of this can probably be explained if negative feedbacks are not linear (Fig. 1). For example, one could envision that below some threshold temperature, chemical weathering becomes too slow, such that at low atmospheric CO$_2$, the negative weathering feedback (where higher pCO$_2$ leads to higher weathering rate) and stable climate. Green high- and low-temperature regimes are where weathering sensitivity to pCO$_2$ breaks down (due to kinetic limitations or availability of substrate), such that small changes in inputs become amplified in pCO$_2$. Climatic state 1 is stable, but risk of runaway greenhouse or icehouse is high at thresholds 2 or 3, respectively. Modified from Lee et al. (2019).

**SUMMARY**

In summary, Earth’s long-term climate is fundamentally tied to deep Earth processes through the whole Earth carbon cycle. The slow fluctuations in interior dynamics of our planet dictate climatic baselines through changes in volcanic activity and weathering efficiency. When negative feedbacks are strong, the planet has healing power and is robust to short-lived perturbations. LIPs lead to environmental catastrophe if baseline climate is already close to threshold. It is on this backdrop that the evolution of life progressed and faltered.

**REFERENCES**


Galloway JM, Lindström S (2023) Impacts of large-scale magmatism on land plant ecosystems. Elements 19: 269-295


Grasby SE, Bond DPF (2023) How large igneous provinces have killed most life on Earth—numerous times. Elements 19: 276-281


Macdonald FA, Swanson-Hysell NL (2023) The Franklin Large Igneous Province and Snowball Earth initiation. Elements 19: 296-301


Svensen HH, Jones MT, Mather TA (2023) Large igneous provinces and the release of thermogenic volatiles from sedimentary basins. Elements 19: 282-288


**ABOUT THE AUTHOR**

Cin-Ty Lee is a professor of geochemistry at Rice University, USA. His research focuses on the evolution of magmas, the formation of continents, and the cycling of elements between the deep Earth and its surface. He is also working on bioacoustic monitoring of nocturnal bird migration and analyzing soundscapes to monitor the health of ecosystems.