

GEOCHEMISTRY

Earth's persistent thermostat

The dependence of rock weathering on temperature helps to steer Earth's climate

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For billions of years, Earth's surface climate has varied in temperature within a relatively narrow range, allowing liquid water to persist and ensuring the habitability of our rocky planet. The breakdown of rocks during weathering is thought to be central in keeping the planet warm enough, and not too cold, by providing a stabilizing feedback in the carbon cycle. On page XXX of this issue, Brantley *et al.* (1) reconcile measurements from the laboratory with those made across landscapes in soils and rivers, to quantify the overall temperature dependence of this important feedback mechanism. They find that this process only works to stabilize temperatures when minerals are supplied quickly enough by erosion and if rainfall can quench the thirst of the weathering reactions. Thus, the role of weathering in steering Earth's climate is likely to have changed as continents shifted and collided.

Carbon dioxide (CO₂) is a greenhouse gas that plays a major role in controlling the temperature at Earth's surface. Every year, volcanoes release ~0.1 petagrams of carbon (PgC) per year ($\times 10^{15}$ gC yr⁻¹) as CO₂ from the interior of the planet. Although this appears small compared to the ~44,000 PgC that the atmosphere and oceans contain, over Earth's long history this volcanic leak of carbon quickly adds up: In just a million years, volcanoes would release enough carbon to almost triple the atmosphere and ocean carbon stores. Left unchecked, this build-up of CO₂ would lead to runaway warming (2).

Instead, CO₂ is removed from the atmosphere when specific minerals in rocks are chemically broken down, or weathered. The carbonic acid formed by mixing CO₂ with rainwater can dissolve silicate minerals. The weathering reactions remove CO₂ from the atmosphere and create bicarbonate, a dissolved form of carbon, which is flushed from soils into rivers and onward to the ocean. There, the weathering products are used to make new carbonate minerals that lock up the carbon. Altogether, the net impact of silicate weathering is removal of CO₂ from the atmosphere. Prior research has revealed that the amount of CO₂ removal may be sensitive to temperature (3). If the surface of the planet is too warm, silicate weathering can remove more CO₂. If it were too cool, silicate weathering becomes more subdued and atmospheric CO₂ will build up. In this way, silicate weathering could act as Earth's thermostat (see the figure), keeping the climate hospitable for life to thrive (2, 3).

The global temperature sensitivity of silicate weathering has remained difficult to quantify. This is because not only temperature matters. Minerals need to be supplied to be weathered, often by eroding fresh rocks and breaking apart new minerals (4, 5). Water is important too, needed for the reactions and to wash away the reaction products (4, 6). A second challenge has been to reconcile laboratory-based measurements made over months (7), with chemical weathering rates measured in soils (8) and captured in the dissolved loads of rivers (4, 6, 9), which can record reactions happening over hundreds to thousands of years.

Brantley *et al.* use a thermodynamic framework to assess the temperature dependence of silicate weathering rates. Grounded in the Arrhenius equation that describes the relationship between reaction rate and temperature, they combine the numerous laboratory assessments with global soil profiles and river catchments. All of these datasets show an increase of silicate weathering with temperature, although the field rates increase more with temperature than experiments in the lab. This can be explained by an array of processes that happen in landscapes – including physical mechanisms such as fracturing, the formation of new minerals during weathering, and the role of microorganisms. Notably, they show that many locations around the world have a weak link between temperature and silicate weathering because either there is not enough mineral supplied to weather, or they do not have enough water.

A convergent theme of the study of Brantley *et al.* and prior work (4, 6, 9) is that only if minerals are supplied fast enough can the silicate weathering thermostat work. Where erosion is low, the temperature sensitivity is muted, or apparently non-existent. Chemical weathering models and proxies of CO₂, climate, weathering, and erosion also provide support for these conclusions (10). For example, recent work has suggested global erosion could have doubled over the last 10 to 15 million years and made the Earth's surface a more sensitive thermostat – supplying minerals and making reactions more sensitive to temperature and water supply (10), which affects climate and atmospheric CO₂.

The important role for erosion in the silicate weathering thermostat means that other factors complicate how it may steer Earth's climate. This is because erosion can supply other phases to the weathering zone (11) that release CO₂ when they breakdown. These phases include ancient organic matter in rocks and sulfide minerals that can be oxidized during weathering (12, 13). These erosion and weathering-induced CO₂ emissions are globally important because they release as much CO₂ as volcanoes. In addition, recent work shows that the CO₂ release may increase with temperature (13). This seems to oppose CO₂ removal by silicate weathering. In addition, any holistic consideration of the long-term carbon cycle must also account for fluxes and drivers of CO₂ removal by organic matter burial, as has been suggested for the Himalayan erosional system (14). More research is needed to assess how the organic carbon cycle impacts the thermostat settings.

Unfortunately, the natural silicate weathering process is too slow to help mop up the very large excesses of CO₂ released each year from human activities (~9.6 PgC yr⁻¹). However, deliberately increasing silicate weathering by grinding up silicate minerals and applying them at a large scale to agricultural areas may provide a way to help reach net zero (15). It remains unclear whether the logistical challenges can be met for this enhanced weathering to contribute to CO₂ drawdown, but research into the fundamentals of mineral weathering reactions will be essential to make decisions and assess the water demands of sustaining the reactions (1).

The temperature dependence of silicate mineral weathering provides a persistent thermostat to guide Earth's long-term climate. However, changes in patterns of erosion, water supply and organic carbon cycling have likely changed the thermostat's settings as the continents have drifted and collided over millions of years. Geochemical approaches in the laboratory, field and in silico are crucial to further untangling the dynamics of the carbon cycle on Earth and other rocky planets.

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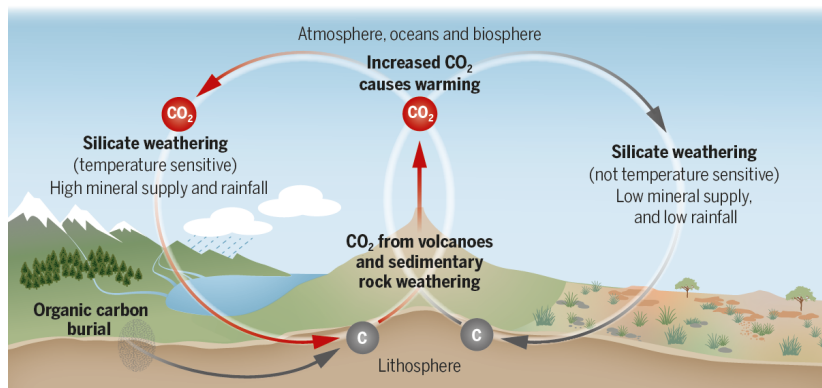
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20 **Silicate weathering thermostat**

21 Over millions of years, atmospheric carbon dioxide (CO₂) is supplied by volcanic eruptions, as well as during
22 sedimentary rock weathering. If CO₂ increases (red arrow), parts of Earth with high erosion and rainfall can
23 increase CO₂ removal by silicate weathering. This provides a stabilizing feedback on climate over millions of
24 years. However, if temperatures are cooler, mineral supply is limited, and rainfall is low, then silicate weathering
25 fixes less CO₂ in the lithosphere.



26 **Figure 1: Silicate weathering removes atmospheric carbon dioxide (CO₂) added from the lithosphere. If CO₂ increases (red arrow), parts of Earth with high erosion and rainfall can increase CO₂ removal by silicate weathering. This returns more carbon back to the atmosphere and provides a stabilizing feedback on climate over millions of years (1).**