

## Does volcanism cause warming or cooling?

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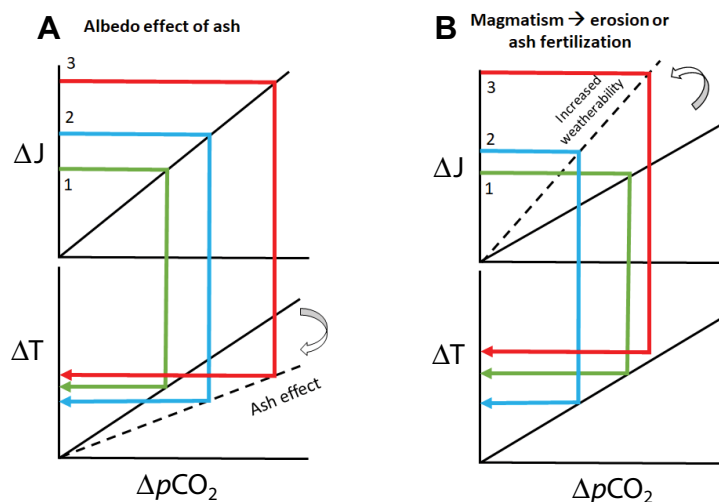
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On million-year time scales, Earth's climate fluctuates between warm and cool baselines. For example, the past 40 m.y. has been relatively cool and characterized by a permanent ice sheet on Antarctica, while the interval between 150 and 50 m.y. ago was characterized by warm temperatures and no permanent ice sheets (Royer et al., 2004; Zachos et al., 2008). What controls these fluctuations is debated, but to first order, the average surface temperature of Earth reflects the balance of incoming solar insolation (energy in) versus planetary albedo and greenhouse gas concentrations (energy out). It is generally thought that over the past billion years, the most important control on long-term climate is variations in greenhouse gases in the atmosphere, namely  $\text{CO}_2$  (Berner, 1991). What controls long-term  $\text{CO}_2$  are variations in geologic inputs and the efficiency of  $\text{CO}_2$  sequestration, the former through volcanic and metamorphic degassing and oxidative weathering of organic carbon, and the latter through silicate weathering (and eventual carbonate precipitation) and organic carbon burial. Importantly, the efficiency of silicate weathering and organic carbon burial is widely thought to scale directly and indirectly with atmospheric  $p\text{CO}_2$ ;  $\text{CO}_2$ 's impact on global temperature and the hydrologic cycle serves as a negative feedback, enhancing (mitigating) carbon sequestration mechanisms given increased (decreased) inputs of  $\text{CO}_2$ . As the residence time of  $\text{CO}_2$  in the exogenic system (ocean-atmosphere-biosphere) is on the order of 10–100 k.y., exogenic carbon contents on million-year time scales are at steady state, where inputs equal outputs (Berner and Caldeira, 1997). Changes in exogenic carbon over greater than million-year time scales thus reflect secular changes in the steady-state baseline, driven by changes in inputs and/or the kinetics of carbon sequestration (Fig. 1).

The current debate is centered around the relative importance of changes in inputs and output efficiencies. Input-driven scenarios mostly invoke changes in volcanic activity, such as

changes in production of oceanic crust or arc magmatism. Output-driven scenarios have focused primarily on collisional orogens in increasing the global efficiency of chemical weathering. For example, Cenozoic cooling is often attributed to enhanced erosion associated with the India-Eurasia collision (Raymo and Ruddiman, 1992).

Another sink-driven hypothesis invokes changes in the efficiency of organic carbon sequestration. The rise of land plants has been suggested to have amplified terrestrial carbon sequestration during the Paleozoic, possibly triggering the Late Paleozoic Ice Age (LPIA), a 100 m.y. interval of icehouse conditions (Ibarra et al., 2019).



**Figure 1.** Schematic diagrams showing the effects on  $p\text{CO}_2$  and temperature through couplings between magmatism and ash-driven albedo (A) and enhanced weatherability through erosion or organic carbon burial through ash fertilization (B). In A, top figure describes an exogenic system at steady state. Vertical axis represents global volcanic inputs or outputs of  $\text{CO}_2$  (J). Horizontal axis represents  $p\text{CO}_2$ . Black line is a representation of a linear silicate weathering feedback, and horizontal lines represent steady-state input or output, with the intersection representing steady-state  $p\text{CO}_2$ . Increases in volcanic inputs lead to increases in steady-state  $p\text{CO}_2$  (1–3; green = reference, red = warm, blue = cool). Bottom panel shows how relative change in  $p\text{CO}_2$  changes temperature, assuming, for simplicity, a linear relationship (solid black line). Increased albedo associated with volcanic ash would decrease the sensitivity of temperature to  $p\text{CO}_2$  (dashed line). Ash inputs unsupported by sufficient volcanic  $\text{CO}_2$  result in cooling (blue line 2), but if  $\text{CO}_2$  outputs are also high, then temperatures may increase (red line 3). B: Effect of enhanced erosion/weathering or organic carbon sequestration driven by magmatism without any change in albedo. Axes are the same as in A. Global weatherability and efficiency of organic carbon burial could increase with during magmatic orogenies (solid line evolves to a system with a stronger climate feedback, as shown by the dashed line). There is a window in which moderate volcanic outgassing (increase in J), if coupled to mountain building, could lead to lower steady-state  $p\text{CO}_2$  and cooling. However, if outgassing outpaces ash inputs on long time scales, warming will be inevitable.

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So far, none of these scenarios alone is sufficient to explain the paleoclimatic record over the Phanerozoic, but this should not be surprising. Tectonics drives both degassing and carbon sequestration, which means that tectonics can warm or cool Earth's surface. In particular, there is a growing appreciation that magmatism and weathering are intimately connected (Jiang and Lee, 2017). Magmatic orogens, such as continental arcs, output vast quantities of CO<sub>2</sub>, but after magmatism ends, these magmatic arcs become regional sinks due to continued weathering, enhancing the global efficiency of weathering and CO<sub>2</sub> drawdown (Lee et al., 2015; Macdonald et al., 2019). To what extent are magmatic outgassing and weathering in phase? Do flare-ups in orogenic magmatism drive greenhouses? Does weathering of these magmatic orogens, after they die, drive icehouses?

Recently, an evaluation of the radiative impacts of explosive volcanism has offered a fresh twist on the debate. Soreghan et al. (2019, p. 600 in this issue of *Geology*) propose that explosive volcanism may trigger and sustain long icehouse intervals. They show that there may be a temporal coincidence between enhanced explosive volcanism and the extent of glaciations during the late Paleozoic, hypothesizing that a sustained increase in sulfate aerosols shading the stratosphere would increase planetary albedo, cooling the planet (Fig. 1). They also suggest that the greater reactivity of volcanic ash fertilizes the oceans and enhances biological productivity and organic carbon burial, cooling the planet further. If Soreghan et al. are correct, then our assumption that volcanism strictly increases atmospheric CO<sub>2</sub>, leading to warming, may need revisiting. However, important questions remain. First, the residence time of aerosols in the stratosphere is on the order of a few years (Robock, 2000). While Soreghan et al. cite relevant work highlighting the attenuation of volcanic cooling via ocean heat transfer, the enhanced glaciation during the LPIA would require tropopause-penetrating volcanic eruptions to occur every few years over tens of millions of years to sustain a long-term icehouse. Detailed studies of ash layers in the Cretaceous Interior Seaway of western North America, a time of a global flareup in arc magmatism, indeed show numerous eruptive events, but even in a 10-m.y.-long sedimentary record, there are only ~200 events (20/m.y.) (Minisini et al., 2017), with only a few large enough to have injected significant amounts of ash and/or aerosols into the stratosphere. Unless the Earth system was al-

ready precariously poised to tip into an icehouse mean-state, it is difficult to envision a world where volcanism could sustain long-term icehouse conditions from increasing albedo alone.

As for the effects of ash, there is growing evidence that ashfall events might lead to enhanced organic carbon burial (Lee et al., 2018). However, recurrence intervals of 10–50 k.y. would be required to maintain long-term low *p*CO<sub>2</sub> levels. While this may not be unreasonable during a global magmatic flareup, what remains to be seen is whether the effects of ash on organic carbon burial can offset the added CO<sub>2</sub> inputs from volcanism. On million-year time scales, it is unlikely that volcanism can cause a long-term decrease in atmospheric CO<sub>2</sub> because ash represents a small component of the total magmatic flux (<1%?). On long time scales, CO<sub>2</sub> inputs likely play a larger role than ash because degassing comes from the overall magmatic flux, which mostly does not erupt (Aiuppa et al., 2017). However, the episodic nature of ash generation may generate interesting behavior on short time scales. That is, it may be possible for individual eruptions to perturb the carbon cycle on time scales of 1–10 k.y., where ash-driven organic carbon burial is unsupported by CO<sub>2</sub> inputs from the same volcanic event. These effects would be manifested as short-term cooling events superimposed upon an otherwise warmer baseline. It would be difficult for volcanic eruptions to sustain long-term continuous icehouse conditions in the late Paleozoic or any other time. On the other hand, if the late Paleozoic ice age was characterized by numerous but short-lived icehouse conditions, volcanic eruptions could have played a key role in their initiation.

More broadly, the nature by which volatiles are exchanged between planetary interiors and their surfaces is rich with complexity. The magnitude and style of magmatism not only controls volatile degassing but also erosion, weathering, radiative balance, and biological productivity. How magmatic processes change through time and with geodynamic states is an area ripe for interdisciplinary research and new discoveries. Soreghan et al.'s work is an example of how investigating these processes from deep time to the present, as well as on Earth and other planets, will force us to rethink how planetary systems operate.

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