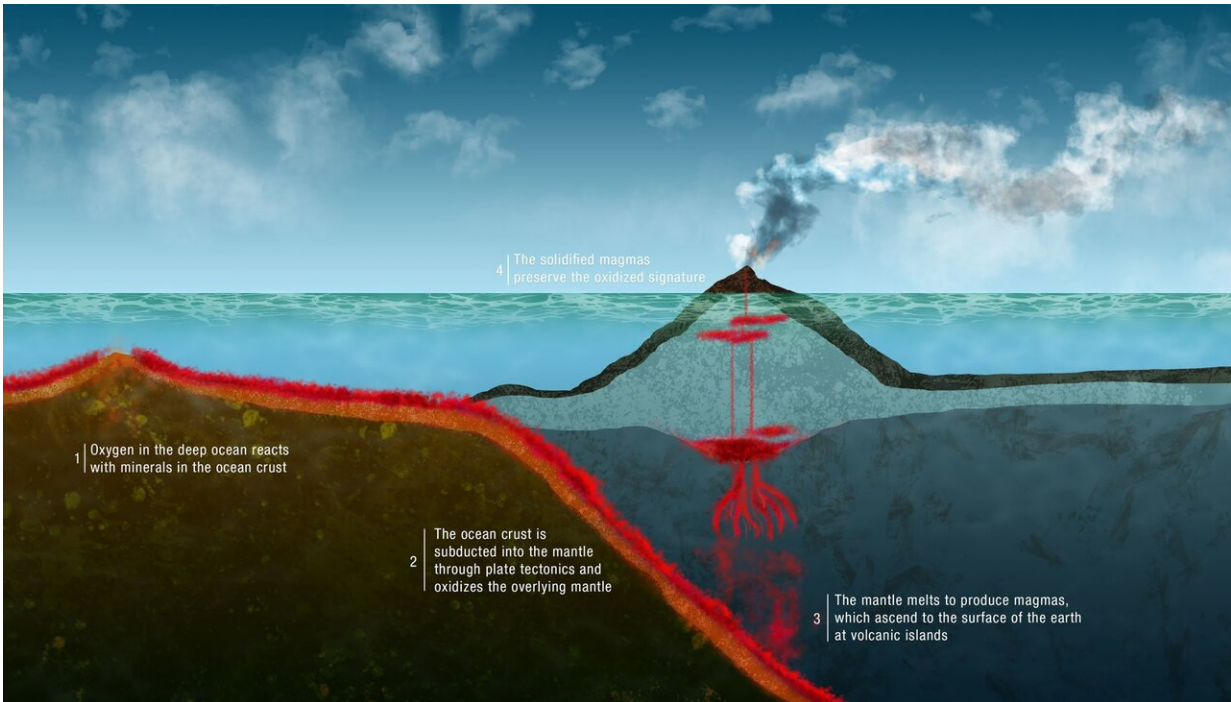


How life on Earth affected its inner workings

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Credit: California Institute of Technology

It is well known that life on Earth and the geology of the planet are intertwined, but a new study provides fresh evidence for just how deep—literally—that connection goes. Geoscientists at Caltech and UC Berkeley have identified a chemical signature in igneous rocks recording the onset of oxygenation of Earth's deep oceans—a signal that managed to survive the furnace of the mantle. This oxygenation is of great interest, as it ushered in the modern era of high atmospheric and oceanic

oxygen levels, and is believed to have allowed the diversification of life in the sea.

Their findings, which were published in *Proceedings of the National Academy of Science* on April 11, support a leading theory about the geochemistry of island arc magmas and offer a rare example of biological processes on the planet's surface affecting the inner Earth.

Island arcs are formed when one oceanic tectonic plate slides beneath another in a process called subduction. The subducting plate descends and releases water-rich fluids into the overlying mantle, causing it to melt and produce magmas that ultimately ascend to the surface of the earth. This process builds island arc volcanoes like those found today in the Japanese [islands](#) and elsewhere in the Pacific Ring of Fire. Eventually, through plate tectonics, island arcs collide with and are incorporated into continents, preserving them in the [rock record](#) over [geological time](#).

The most abundant magmatic, or igneous, rocks are basalts—dark-colored and fine-grained rocks commonly found in lava flows. Most basalts on the earth today do not form at island arcs but rather at mid-ocean ridges deep underwater. A well-known difference between the two is that island arc basalts are more oxidized than those found at mid-[ocean ridges](#).

A leading but debated hypothesis for this difference is that oceanic crust is oxidized by oxygen and sulfate in the deep ocean before it is subducted into the mantle, delivering oxidized material to the mantle source of island arcs above the subduction zone.

But Earth is not thought to have always had an oxygenated atmosphere and deep ocean. Rather, scientists believe, the emergence of oxygen—and with it the ability for the planet to sustain aerobic

life—occurred in two steps. The first event, which took place between about 2.3 and 2.4 billion years ago, resulted in a greater than 100,000-fold increase in atmospheric O₂ in the atmosphere, to about 1 percent of modern levels.

Although it was dramatically higher than it had previously been, the atmospheric O₂ concentration at this time still was too low to oxygenate the deep ocean, which is thought to have remained anoxic until around 400 to 800 million years ago. Around that time, atmospheric O₂ concentrations are thought to have increased to 10 to 50 percent of modern levels. That second jump has been proposed to have allowed oxygen to circulate into the deep ocean.

"If the reason why modern island arcs are fairly oxidized is due the presence of dissolved oxygen and sulfate in the deep ocean, then it sets up an interesting potential prediction," says Daniel Stolper (Caltech Ph.D. '14), one of the authors of the paper and an assistant professor of Earth and Planetary Science at UC Berkeley. "We know roughly when the deep oceans became oxygenated and thus, if this idea is right, one might see a change in how oxidized ancient island arc rocks were before versus after this oxygenation."

To search for the signal of this oxygenation event in island arc igneous rocks, Stolper teamed up with Caltech assistant professor of geology Claire Bucholz, who studies modern and ancient arc magmatic rocks. Stolper and Bucholz combed through published records of ancient island arcs and compiled geochemical measurements that revealed the oxidation state of arc rocks that erupted tens of millions to billions of years ago. Their idea was simple: if oxidized material from the surface is subducted and oxidizes the mantle regions that source island arc rocks, then ancient island arc rocks should be less oxidized (and thus more "reduced") than their modern counterparts.

"It's not as common anymore, but scientists used to routinely quantify the oxidation state of iron in their rock samples," Bucholz says. "So there was a wealth of data just waiting to be reexamined."

Their analysis revealed a distinct signature: a detectable increase in oxidized iron in bulk-[rock](#) samples between 800 and 400 million years ago, the same time interval that independent studies proposed the oxygenation of the deep ocean occurred. To be thorough, the researchers also explored other possible explanations for the signal. For example, it is commonly assumed that the oxidation state of iron in bulk rocks can be compromised by metamorphic processes—the heating and compaction of rocks—or by processes that alter them at or near the surface of the earth. Bucholz and Stolper constructed a variety of tests to determine whether such processes had affected the record. Some alteration almost certainly occurred, Bucholz says, but the changes are consistent everywhere that samples were taken. "The amount of oxidized iron in the samples may have been shifted after cooling and solidification, but it appears to have been shifted in a similar way across all samples," she says.

Stolper and Bucholz additionally compiled another proxy also thought to reflect the oxidation state of the mantle source of arc magmas. Reassuringly, this independent record yielded similar results to the iron-oxidation-state record. Based on this, the researchers propose that the oxygenation of the deep ocean impacted not only on the earth's surface and oceans but also changed the geochemistry of a major class of igneous rocks.

This work complements earlier research by Bucholz that examines changes in the oxidation signatures of minerals in igneous rocks associated with the first oxygenation event 2.3 billion years ago. She collected sedimentary-type, or S-type, granites, which are formed during the burial and heating of sediments during the collision of two

landmasses—for example, in the Himalayas, where the Indian subcontinent is colliding with Asia.

"The granites represent melted sediments that were deposited at the surface of Earth. I wanted to test the idea that sediments might still record the first rise of oxygen on Earth, despite having been heated up and melted to create granite," she says. "And indeed, it does."

Both studies speak to the strong connection between the geology of Earth and the life that flourishes on it, she says. "The evolution of the planet and of the life on it are intertwined. We can't understand one without understanding the other," says Bucholz.

The *PNAS* study is titled "Neoproterozoic to early Phanerozoic rise in island arc redox state due to [deep ocean](#) oxygenation and increased marine sulfate levels."

More information: Daniel A. Stolper et al. Neoproterozoic to early Phanerozoic rise in island arc redox state due to deep ocean oxygenation and increased marine sulfate levels, *Proceedings of the National Academy of Sciences* (2019). [DOI: 10.1073/pnas.1821847116](https://doi.org/10.1073/pnas.1821847116)

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