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Earth in five reactions: Grappling with meaning and value in science

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Abstract

The Earth in Five Reactions Workshop posed two significant challenges: (1) the formulation of a conceptual definition of "reaction" and (2) the identification and ranking of the "most important reactions" in the context of planetary evolution. Attempted answers to those challenges, collated in this collection of articles, reflect both the opportunities and hurdles when scientists deal with questions of meaning and value.

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Introduction

The objective of the "Earth in Five Reactions" project was to identify the five "most important reactions" that influence planetary history (Li et al. 2019). A diverse team of 50 scientists tackled this task during a workshop at the Carnegie Institution for Science in Washington, D.C., March 22–23, 2018. The event was conceived both as a forum to promote discussions among scientists with diverse backgrounds in geology, chemistry, biology, and space science, and to start conversations that might provide opportunities to engage a broader community of non-professional science enthusiasts.

On the surface, the task seemed straightforward. Each participating scientist was asked to formulate an opinion regarding the "most important reaction" that has influenced Earth's origin and evolution and then advocate that position to the larger group. At the Workshop's conclusion the proposed reactions were tabulated, everyone voted, and the top five reactions "won." Each of the top five reactions, as well as several "runners-up" promoted by minorities of passionate advocates, were given the chance to contribute articles to this special section of *American Mineralogist*.

In reality, this task proved exceptionally challenging for two reasons that only emerged through lively, and sometimes confused, conversations. The first challenge related to meaning: general agreement was lacking on what constitutes a "reaction" in the context of planets and their evolution. The second challenge focused on value: it was unclear by what metrics we should evaluate the "most important" reactions. Both points of discussion—meaning and value—have a character that provoked intense and enjoyable debates, but neither question is amenable to unambiguous resolution by the scientific method. This contribution is an attempt to characterize the Workshop's gestalt, and to draw lessons from the exercise that might inform similar efforts in the future.

What do we mean by "reaction"?

The first hurdle facing the Earth in Five Reactions Workshop was lack of a collective agreement on the definition, or rather broad range of meanings, of "reaction." All participants accepted a general conceptual definition involving a transformation by rearrangement of atoms in one or more materials, but several types of uncertainty in meaning complicated the discussions.

One aspect of this uncertainty related to the degree to which a reaction can be idealized. For some participants with a more chemical background, a reaction is a specific rearrangement of atoms and their electrons, such as the oxidation of iron:

$$4Fe + 3O_2 \leftrightarrow 2Fe_2O_3. \quad (1)$$

To many chemists, this form of reaction equation represents real atoms of iron reacting with real molecules of oxygen. A similar aqueous reaction, "hydrogenation," represents a useful model in the context of natural Earth systems:

$$2FeO + H_2O \leftrightarrow Fe_2O_3 + H_2. \quad (2)$$

Others argued for a more general definition of reaction that recognized classes of related chemical reorganizations, for example, "serpentinization," which can be represented by a number of different reactions of Mg- and Fe^{2+}-bearing basalt minerals via aqueous alteration (Schrenk et al. 2013). On the one hand, serpentinization can be defined in terms of the reaction of anhydrous magnesian olivine and water to form the hydrous minerals serpentine and brucite (also known as a "hydration" reaction):

$$2Mg_2SiO_4 + 3H_2O \leftrightarrow Mg_3Si_2O_5(OH)_4 + Mg(OH)_2. \quad (3)$$

However, serpentinization's role in supporting microbial communities may be more closely linked to the oxidation of iron-bearing olivine to produce magnetite, silica, and hydrogen:

$$3Fe_2SiO_4 + 2H_2O \leftrightarrow 2Fe_3O_4 + 3SiO_2 + 2H_2. \quad (4)$$

In another respect, the essence of all of these reactions from the perspective of biological energy flow is the oxidation of Fe^{2+} and release of hydrogen—a process that can be idealized as:

$$3FeO + H_2O \leftrightarrow Fe_3O_4 + H_2. \quad (5)$$

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Scientists who considered reactions from the perspective of biology and the origins of life also emphasized the role of serpentinization in producing organic molecules—a process epitomized by the unbalanced schematic reaction:

$$(Fe,Mg)_2SiO_4 + H_2O + CO_2 \leftrightarrow Mg_3Si_2O_5(OH)_4 + Fe_3O_4 + CH_4. \quad (6)$$

Therefore, while many of us agreed that "serpentinization" is one of the most important chemical reactions on wet terrestrial worlds, multiple facets of serpentinization exist. Consequently, the representation of that reaction by an equation remains somewhat ambiguous. Bioscientists provided another perspective on the definition of "reaction," epitomized by the globally important process of oxygenic photosynthesis, but more generally described as "carboxylation," idealized as:

$$6H_2O + 6CO_2 \leftrightarrow C_6H_{12}O_6 + 6O_2. \quad (7)$$

However, this equation for the oxygenic photosynthetic reaction is a simplified representation of an intricate reaction cascade involving 10 or more individual enzyme-induced steps, driven by the energy gathered in two different photon-capturing complexes, called Photosystem I and Photosystem II (e.g., Cox 2017). In this instance, the simplified reaction of Equation 7 is a proxy for several complex reaction networks, each a sequence of biochemical steps.

The biological case is also striking in that some scientists argued that the reverse reaction, "respiration" as employed by many animals (including us), is equally important:

$$C_6H_{12}O_6 + 6O_2 \leftrightarrow 6H_2O + 6CO_2. \quad (8)$$

Indeed, all of the proposed reactions may be written with arrows pointing in either direction; consequently, some participants asked whether bi-directional arrows should be used. Of special note in this regard are carbonation/decarbonation reactions, which are critical to Earth's deep carbon cycle (e.g., Dasgupta 2013; Kelemen and Manning 2015). These reactions can be written in idealized form as:

$$CaSiO_3 + CO_2 \leftrightarrow CaCO_3 + SiO_2. \quad (10)$$

The reaction from left to right plays an important role in silicate weathering and carbon sequestration, whereas the reaction from right to left occurs both in nature (charnockitization) and in human industry (e.g., a net, long-term effect of the curing of Portland cement). Interestingly, hydrocarbon burning, the class of oxidation reactions most implicated in Earth's recent anthropogenic increases in atmospheric carbon dioxide (and arguably the single most prominent chemical reaction informing the news and policy today), was not included in the final Workshop list:

$$2[C_nH_{2n+2}] + (3n + 1)O_2 \leftrightarrow 2nCO_2 + (2n + 2)]H_2O. \quad (11)$$

Geophysicists presented yet another discipline-informed perspective on the nature of a "reaction." For example, planetary-scale differentiation and core formation, which is fundamental to planetary evolution, can be represented as the chemical separation of immiscible silicate- and iron-rich liquids from a homogeneous fluid and the subsequent physical process of gravitational segregation:

$$[Fe,Si,O](fl) \leftrightarrow [Si,O](fl) + Fe(fl). \quad (12)$$

In a similar vein, Papineau et al. (2017) propose that a class of chemically oscillating reactions, by which phase separation leads to complex concentric patterning and self-organization in many natural and synthetic chemical environments, represents a central organizing principle in both living and nonliving systems.

A part of the debate centered on whether changes in state and phase transformations should be included as "reactions." For example, some participants suggested that the transformation of carbon dioxide in an aqueous fluid to a gas phase should be numbered among Earth's most important reactions:

$$CO_2(aq) \leftrightarrow CO_2(g). \quad (13)$$

Finally, at one point the discussion led to consideration of stellar nucleosynthesis, by which a range of new chemical elements form through cascades of nuclear reactions. Such reactions are confined to stellar processes and are beyond the scope of Earth and other terrestrial bodies, but they were instrumental in the formation of all planets and moons. Similarly, nuclear reaction associated with radioactive decay, though fundamentally important to planetary heat production, were not considered by the Workshop participants.

By the end of the Workshop, all participants developed a more nuanced understanding of the breadth and depth of the question, "What is a reaction?" Ultimately, the majority agreed that "reaction" refers to a constellation of processes, all of which can be expressed by an equation, some more fictive than others, but all involving the rearrangement of atoms and their electrons and all serving as representations of planetary events that shaped the evolution of Earth.

What are Earth's "most important" reactions?

The second and arguably more difficult challenge to the Earth in Five Reactions Workshop was the ranking of reactions as most important. "Most important" implies value, but scientists are not typically schooled in assigning a value to natural objects or phenomena. Indeed, the epistemology of science, rooted as it is in independently reproducible and verifiable observations, would seem antithetical to assigning relative values to natural processes. And so Workshop attendees grappled with competing perceptions of importance.

A revealing aspect of the Workshop was the initial general mood that some agreement might be reached regarding a "correct" answer that could be identified by focused presentations, conversations, and debate. Only gradually did the subjective challenge of the task of identifying the "most important reactions" dawn on workshop participants. None of us was trained in the epistemology of assigning value to natural processes. Faced with the task of ranking "reactions," we were stymied. Nevertheless, we tried and, as the Workshop progressed, participants became bolder (and in a sense more exuberantly playful) in their advocacy of one subjective "truth" vs. another.

Some scientists attempted to rank reactions by calculating quantitative consequences: which reactions transfer the greatest planetary mass, affect the largest planetary volume, or sustain the largest near-surface redox gradients. Others favored reactions that most dramatically altered planetary-scale structures, mechanisms that synthesized molecules of life, or processes that created habitable planetary environments. Almost invariably, choices were biased by one's scientific specialty. Biologists favored biological reactions such as biomolecular synthesis, metabolic pathways, and photosynthesis, while geophysicists pointed to the global-scale processes of planetary differentiation, core formation, and the establishment of a magnetodynamo. In addition, significant sponsorship by the Deep Carbon Observatory, whose 10 yr mission is to understand the physical, chemical, and biological roles of carbon in Earth and other planets (see https://deepcarbon.net; accessed October 30, 2018), significantly swayed Workshop attendees to pay special notice to carbon-bearing reactions.

The centrality of several chemical reactions to the origins and evolution of life rose to the top of many scientists' lists. Oxygenic photosynthesis (and the reverse reaction, respiration), was a leading candidate. Some planetary scientists' focus included questions of habitability and the possibility of life's origins on other worlds; hence they advocated the Urey reaction, by which primitive atmospheric molecules reacted to form amino acids and other key biomolecular building blocks when exposed energetic electric discharges, UV radiation, or other ionization events (Miller and Urey 1959).

Comparative planetology added a layer of complexity to the question of value. While some participants focused exclusively on Earth and reactions specifically in the context of Earth's evolving geosphere and biosphere, other scientists considered reactions in the broader context of any terrestrial planet or moon. Thus, serpentinization may have "beaten out" oxygenic photosynthesis in the rankings because the former is likely to be a dominant near-surface process on any wet, rocky world, whereas the latter requires an evolutionary pathway thus far unique to Earth.

Given the diversity of scientific backgrounds, it quickly became apparent that participants embraced different conclusions regarding Earth's most important reactions—conclusions that are reflected in the diversity of articles in this special section. Perhaps the most intriguing shift in attitudes to occur during the Workshop was the general realization that ranking of the "most important reactions" inevitably is subjective; consequently, the participants became free to advocate for one position or another based on more qualitative and subjective arguments than are common in scientific discourse.

Implications

Participants in the Earth in Five Reactions Workshop came away with several insights beyond the details of planetary reaction mechanisms. One key lesson was the value of interdisciplinary conversations. Each participant left the meeting with a broader perspective of the natural world, thanks to the open and thoughtful interactions among individuals with diverse geo-, bio-, and planetary science backgrounds. Planetary evolution involves complex connections among, physical, chemical, and (in the case of Earth) biological processes. The only way to understand terrestrial worlds is to document interactions from varied perspectives, at many scales, from crust to core, and over immense spans of time.

A key meta-message of the Workshop—one still being processed by many who attended—is the importance of recognizing, perhaps embracing, the subjective role of "value" in science. Though we are trained as scientists to be objective in our collection and analysis of data, and we are not generally schooled in the philosophy of ranking, we are nevertheless faced with subjective choices every day of our careers. We make judgment calls about what topics we should spend our time studying. We provide prose on the "Broader Impacts" of our research to National Science Foundation proposals, while we evaluate and rank the proposals and manuscripts of other scientists. We write "Implications" sections as conclusions to our articles in *American Mineralogist*. Each of these activities and many others carries the responsibility of evaluating and ranking ideas and opportunities.

In that context, it is inspiring the extent to which one common theme emerged from our consideration of Earth's most important reactions. To those scholars who devote their lives to understanding Earth, our planetary home is unique, fascinating, and valued beyond all other worlds. The most important reactions are those that contribute to Earth's unique geosphere and biosphere. We value reactions that created a habitable world—a protective magnetosphere, a dynamic hydrosphere, and a benign atmosphere. We value reactions that led to life's origins and evolution—the prolific synthesis of essential biomolecules, the release of redox energy through serpentinization, and the self-organization of chemical systems. And we embrace reactions, notably oxygenic photosynthesis, that ultimately led to multi-cellularity, to the terrestrial biosphere, and to Earth's unmatched mineral diversity, as well. In that sense, the joyous task of identifying Earth's most important reactions became a celebration of the beautiful home that we cherish.

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