The Deep Earth Engine Driving Major Surface Events

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During Earth's 4.6 billion-year history, its surface has experienced environmental changes that drastically impacted habitability. The changes have been mostly attributed to near-surface processes or astronomical events with little consideration of Earth's deep interior. Recent progresses in high-pressure geochemistry and geophysics, however, indicate that deep Earth processes may have played a dominant role in the surface (Mao and Mao, 2020).

Systematic observations of the Earth's surface by the geoscience community around the world have collected a gigantic amount of data and deduced a series of major catastrophic events, that dictate the evolution in the biosphere throughout the Earth's history, including the great oxidation event (GOE), snowball Earth, five mass extinctions, large igneous provinces (LIP), converging and rifting of supercontinents, and starting of the plate tectonics. These events are closely correlated in their geological timeline, yet their proposed origins diverge widely among surficial effects, such as photosynthesis of cyanobacteria, environmental changes, ocean chemistry changes, sedimentary carbon sequestration, orogenic processes, volcanic activities, etc., and astronomical effects, such as asteroid impacts, Earth's spin axis wobbling, and gamma-ray burst (GRB). The most likely effects of the massive deep Earth interior, however, have been hardly considered due to the lack of information.

Our samplings of the deep Earth, including the deepest core drilling, volcanic eruptions, and diamond inclusions, are limited to less than ten percent of the Earth's radius. Most information of the depth comes from geophysical explorations, including seismic, gravitational, geomagnetic, and geothermal observations. These findings have limited variables. Moreover, they do not contain the time dimension; they only represent the present Earth, and that is difficult to record the Earth's past nor predict the future. Therefore the most powerful tool for studying the deep Earth is to use in-laboratory high pressure-temperature (*P*-*T*) experimentation to simulate the behaviour of minerals and rocks in the depth. Recent advances of the high *P*-*T* technology with diamond-anvil cell (DAC) (Mao et al., 2020) and multianvil device (MA) (Walker and Li, 2020), and the integration with analytical probes at synchrotron x-ray facilities (Hirao et al., 2020; Ji et al., 2020) have led to surprising and unexpected discoveries in chemistry (Yoo, 2020) and geochemistry (Zhang et al., 2014), and a unified theory based on deep internal engine-driven surface effects begins to emerge and consolidate (Fig. 1).

Oxygen as an essential bioelement is the most abundant element on Earth. Recent discoveries on the pressure-altered chemistry revealed that the oxygen cycles through Earth's deep interior could also be the origin of the mantle dynamics and that could cause the disruptive evolution of the life on surface. Subducting slab injects the oxidized crust down into the reduced deep lower mantle. H_2O severs as a strong oxidant and oxygen transporter (Katsura and Fei, 2020; Lin et al., 2020; Walter, 2020) to meet Fe at the core-mantle boundary (CMB), Fe can be oxidized to produce superoxide FeO_2 with the cubic pyrite structure (Hu et al., 2016). At the middle of the lower mantle, Hu et al. (2020) show that H_2O can also react with ferropericlase (Mg, Fe)O, a major lower-mantle mineral, to form pyrite-structured superoxide. At shallower depth, Liu et al. (2020) found that H_2O induced oxidation of ferropericlase to form $Fe_2O_{3+\delta}$ with a new hexagonal structure. The subducting process may compile substantial oxygen-rich materials to form oxygen reservoirs at the CMB. The basic form of reaction is:

$$\underset{\text{oxides}}{MO_n} + H_2O \leftrightarrows \underset{\text{oxygen-rich material}}{MO_{n+1}} + H_2 \quad (1)$$

where M stands for metal cation (Fe, Mg, Ca, Si…).

In addition to oxygen-rich materials, the Reaction (1)

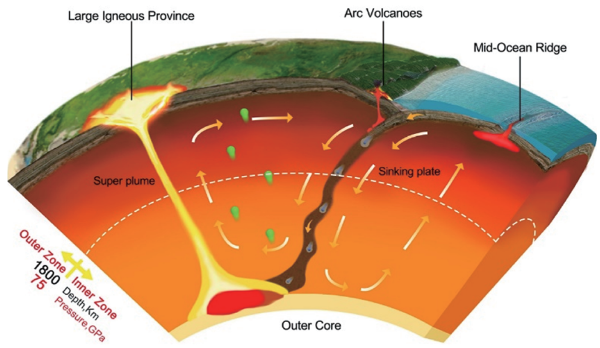

Fig. 1. Schematic diagram of the deep Earth engine.
The white dash curve at 1800 km depth (75 GPa) divides the high- and low-pressure zones governed by different physics and chemistry. The difference causes the separation of hydrogen and oxygen during the water cycling and drives the Earth's dynamics movement. Blue droplets represent hydrous minerals in the subducting plate; water oxidizes minerals in the deep lower mantle, release hydrogen (green uprising symbols), and accumulates oxygen-rich minerals at the CMB; stockpiling oxygen-rich materials beyond a critical amount leads to oxygen outburst and creates rising superplume (yellow); the oxygen-rich superplume reaches upper mantle and crust, causing LIP (Mao and Mao, 2020).

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produces hydrogen which arises through various paths and returns to the surface, completing the water (hydrogen) cycle. The uprising hydrogen can react with metallic elements to form metal hydrides, or with non-metallic elements to form hydrocarbon, nitrogen hydrides, hydrogen sulfides, hydrogen phosphates, etc., thus opening a large frontier of unexplored hydrogen chemistry under high pressures. Reaction (1) typically leaves a minor amount of hydrogen in the oxygen-rich material ($MO_{n+1}H_x$) (Hu et al., 2020; Liu et al., 2020). Under the extreme pressures of the deep lower mantle, the hydrogen atoms are no longer tied up in the O-H bond but become H^+ ion in the structure. At the high temperature of the deep lower mantle, the H^+ ions are further liberated to become superionic and move freely in and out of the crystal lattice, impacting the electrical, magnetic, thermal and hydrogen fugacity balance of the deep lower mantle (Hou et al., 2021).

Recognition of novel materials in deep Earth relies on seismological observations of their characteristic elastic signatures which must be determined in-situ at high pressure-temperature conditions of the deep interior. The oxygen and iron-rich piles are denser than the surrounding mantle materials and settle stably on top of the core (Liu et al., 2017). The CMB is a thermal boundary layer with a very steep temperature gradient controlled by heat transferred from the core that could cause the oxygen reservoirs to melt, lose Fe to the core, and leave lighter oxidized component trapped by the overlaying mantle. When a significant quantity of the trapped oxidized component bursts out and ascends, it forms superplume and provides a powerful driving force for chemical convection of the mantle. The oxygen outburst, therefore, could well crank-start the plate tectonics of the mantle and cause splitting and merging of supercontinent.

LIP is a process that a gigantic amount of magma ($\geq$ 100 km^3) intrudes in a relatively short period ($\sim 10^5$–10^6 years). Our unpublished experiments have showed that excess oxygen plays a dominant role in systematically lowering the melting point of rocks. An oxygen-rich superplume would be able to generate a huge quantity of magma chamber in the upper mantle and crust. LIP was often associated with oxygen rise including the GOE. Large igneous activities would certainly cause global environmental changes that would have catastrophic impacts on the atmosphere, hydrosphere, and biosphere. Overall, the oxygen activities in the deep interior could be the common thread for most major events, including supercontinent cycles, LIPs, atmospheric oxygen fluctuations, snowball Earth, and mass extinctions.

Key words: deep lower mantle, oxygen cycle, subducting water, great oxidation event

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