

# Olivine - The Alteration Rock Star

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## Abstract

Olivine is the main component of the Earth's upper mantle, on which our tectonic plates rest. As such, olivine has been studied since the dawn of geology and is regarded as the storyteller of the Earth's interior. Its physical and chemical properties provide insight into its creation in magmas and its voyage through the upper mantle. However, when olivine is exposed to aqueous fluids, it adopts a more rebellious, rock star-like disposition. Here, we show that the discord, or disequilibrium, between olivine, its reaction products, and fluids containing water and carbon dioxide is so significant that it has been instrumental in changing the Earth throughout the planet's history and will continue to do so well into the future.

## 1 INTRODUCTION

Olivine  $[(\text{Mg}, \text{Fe})_2\text{SiO}_4]$  is considered by many geoscientists to be a key mineral that motivates us to explore inaccessible environments, from the inside of volcanoes to the Earth's upper mantle. The products of olivine's reaction with fluids provide lubrication for subduction zones, create environments where life may have originated, and could ameliorate the current global climate crisis. This contribution focuses on the reactions between olivine and water as well as carbon dioxide, and the subsequent alteration of the reaction products, specifically serpentine minerals. These reactions have stimulated the interest of numerous multinational research projects, including ocean- and land-based drilling. Among these projects, we highlight the recently concluded Oman Drilling Project, which sheds new light on what is unquestionably one of the most essential fluid alteration processes on Earth and other terrestrial bodies.

## What is Alteration? How Does Olivine Get Involved?

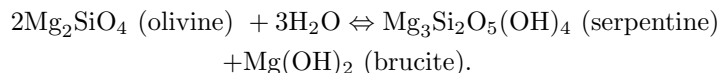
We refer to the term "alteration" as the mineralogical transformation of an original mineral into a new one, typically as a result of the addition of fluids that are out of equilibrium with the mineral. Generally speaking, alteration refers to low-temperature (low- $T$ ) processes near the Earth's surface. However, it is important to note that the term "hydrothermal alteration" refers to reactions between minerals and fluids over vast temperature ranges greater than 600°C. Although olivine is thermodynamically stable within the Earth's upper mantle, once the temperature drops below  $\sim 600^\circ\text{C}$ , the addition of fluids triggers a broad range of mineral reactions that result in the production of serpentine minerals  $[\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4]$ , brucite  $[\text{Mg}(\text{OH})_2]$ , magnesite  $[\text{MgCO}_3]$ , oxides (e.g., magnetite;  $\text{Fe}^{2+}\text{Fe}^{3+}_2\text{O}_4$ ), and other silicates (even quartz  $[\text{SiO}_2]$ ). The main serpentine group minerals are antigorite, lizardite, and chrysotile. Here, we use the general term "serpentine" to refer to lizardite and chrysotile as these are most widespread in low- $T$  and low-pressure (low- $P$ ) alteration processes, whereas antigorite is typically found at higher  $T$  exceeding 300°C. Additionally, serpentine and brucite can contain varying amounts of Fe.

Olivine is typically not the only mineral in the mantle. It forms ultramafic rocks that range from peridotites (>50 % olivine) to pyroxenites (<50 % olivine) when combined with pyroxene minerals (general formula  $M_1M_2T_2O_6$  with  $M_1 = \text{Mg, Fe, Mn}$ ;  $M_2 = \text{Mg, Fe, Mn, Ca}$ ; and  $T = \text{Si, Al}$ ). In addition to the minerals listed above, the alteration of these ultramafic rocks can result in the presence of calcite [ $\text{CaCO}_3$ ] and dolomite [ $\text{CaMg}(\text{CO}_3)_2$ ]. As such, the transformation of olivine and pyroxene across temperature gradients, from the Earth's surface to its interior, initiates numerous chemical and physical processes of global significance. Alteration of ultramafic rocks has been demonstrated to: (1) greatly weaken the lithosphere (e.g., Escartin et al. 2001), (2) generate unique geochemical environments that may have helped to kick-start life on Earth and feed the past and present deep biosphere (e.g., Schrenk et al. 2013), and (3) provide a vast potential for the permanent sequestration of carbon dioxide (Kelemen and Matter 2008). Figure 1 portrays the different occurrences of ultramafic rock alteration exposed on land, from the addition of  $\text{H}_2\text{O}$  to cause serpentinization - the formation of serpentine minerals - to the addition of carbon dioxide to form carbonate minerals and quartz.

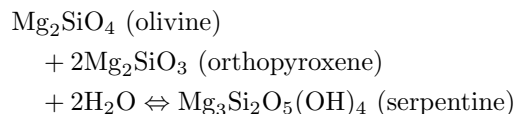
## 2 OLIVINE AND ITS “OPPONENTS”

### Just Add Water

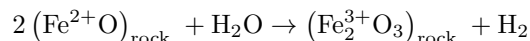
*Some geochemical consequences.* When olivine is exposed to water (hydration), reaction is not just possible, but inevitable. In its simplest form, considering magnesium endmembers, the reaction of olivine with  $\text{H}_2\text{O}$  can be written as:



Together with orthopyroxene, the hydration reaction may be written as:



In addition, as olivine and pyroxene typically contain iron, serpentinization involves oxidation and, in turn, the development of reducing fluids. This coupling is best portrayed by:



Ferric iron can be found in magnetite, Fe-rich brucite, or serpentine minerals. A study by Klein et al. (2014) found a correlation between the abundance of magnetite, the Fe content of brucite, and serpentinization temperature, demonstrating that serpentinites formed at higher temperatures (200–300 °C) have abundant magnetite and Fe-poor brucite, whereas serpentinites formed at lower temperatures (200 °C) have less magnetite and Fe-rich brucite.

The production of hydrogen ( $\text{H}_2$ ) during serpentinization is of critical importance as it may not only provide a feedstock for a deep-seated biosphere but may also react with  $\text{CO}_2$  to form methane ( $\text{CH}_4$ ) and longer-chained hydrocarbons (e.g., Schrenk et al. 2013, Preiner et al. 2020, Nan et al. 2021). Furthermore, these compounds are thought to have been the building blocks for the origin of life in serpentinite-hosted hydrothermal vent systems (Schrenk et al. 2013 and references therein). Although the formation of abiotic hydrocarbons, particularly  $\text{CH}_4$ , is thermodynamically favored and proceeds very slowly under most serpentinization conditions, catalytically active minerals help to overcome a significant kinetic barrier, speeding up hydrocarbon production. Some potential minerals, such as magnetite ( $\text{Fe}_3\text{O}_4$ ), awaruite ( $\text{Ni}_3\text{Fe}$ ), chromite ( $\text{FeCr}_2\text{O}_4$ ), Fe–Ni sulfides, and saponite [ $\text{Ca}_{0.25}(\text{Mg,Fe})_3((\text{Si,Al})_4\text{O}_{10})(\text{OH})_2 \cdot n(\text{H}_2\text{O})$ ] are found in serpentinites, but their catalytic activity under hydrothermal conditions remains debated. Nevertheless, numerous experimental studies suggest that these minerals aid the abiotic synthesis of organics (e.g., Preiner et al. 2020), whereas recent network analysis indicates that these minerals play a minor role (e.g., Barbier et al. 2020).

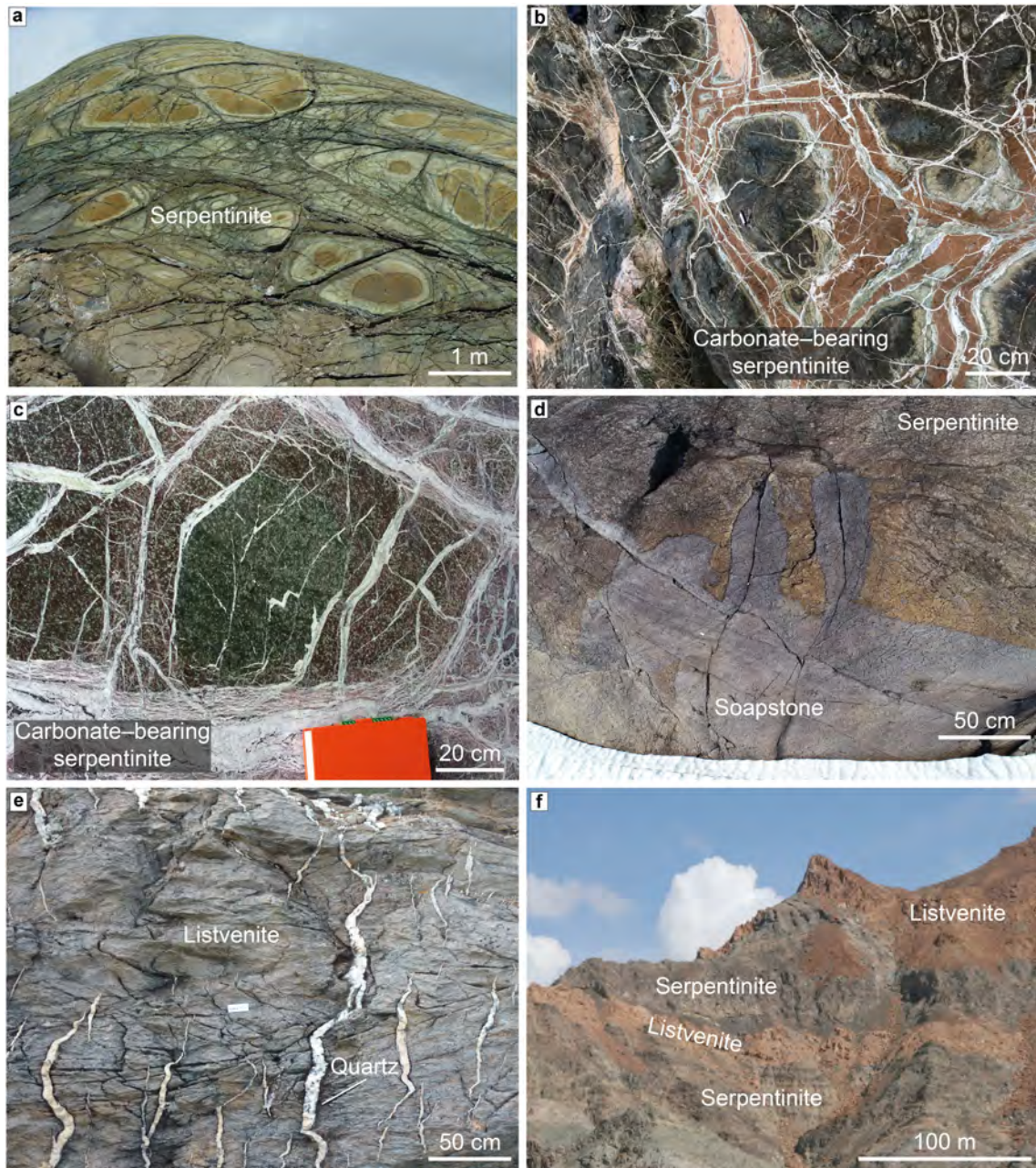
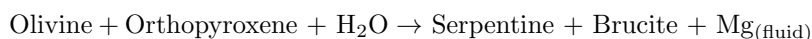


Figure 1: (a) Serpentinite with a prominent kernel pattern from Linnajavri, Norway (Beinlich et al. 2012). Photo: O. Plümper. (b) Carbonate (white) veins in oxidized serpentinite from Oman. Photo: J.C. de Obseso. (c) Carbonate (white) veins in carbonated serpentinite from the Ligurian Alps, Italy. Photo: L. Eberhard. (d) CO<sub>2</sub> reaction front between serpentinite and soapstone (talc + magnesite) and (e) listvenites (quartz + magnesite) with quartz veins from Linnajavri. Photo: O. Plümper. (f) The base of the Oman ophiolite shows bands of listvenite (rusty orange) parallel to contacts of serpentinized ultramafic rocks (Kelemen et al. 2020).

Investigations of natural serpentinites, however, show that condensed organic matter is frequently associated with these minerals (e.g., Nan et al. 2021), with no direct evidence of past or present biological activity. This association suggests that either (1) the thermodynamic conditions during the alteration of olivine-bearing rocks favor the formation of organics and heterogeneous mineral surface catalysis is active in nature, or (2) metal-bearing minerals in serpentinites act as traps for externally derived organic matter due to high surface energies and proton donation capacity, or (3) many of the organics observed in these rocks are contamination introduced during sample collection and preparation. The latter is addressed carefully in most recent studies, but future investigations will need to combine experiments, natural observations, and simulations to further constrain the potential pathways for abiotic synthesis of organics during serpentinization and associated alteration processes.

*Some mechanical consequences.* The hydration of olivine-bearing rocks may also result in self-induced deformation. Alternatively, fluid infiltration may initially be facilitated by tectonic forces, cooling-induced fracturing, and grain boundary diffusion, and the significant positive solid volume change during serpentinization can deform the rock. It has long been debated whether serpentinization occurs at a constant solid volume or results in a substantial volume increase. Combining reactions (1) and (2) to a general reaction such as



we can construct a diagram (Fig. 2A) that portrays how the removal of magnesium from the system and addition of orthopyroxene could counterbalance an overall positive solid volume change. It becomes apparent that even a substantial loss of magnesium results in a positive solid volume change during serpentinization. This is supported by a plethora of natural, theoretical, and experimental studies demonstrating that serpentinization does not lead to the loss of magnesium during the precipitation of secondary minerals (e.g., Klein and Le Roux 2020). Hence, the associated volume changes must be accompanied by tectonic movements that provide "space" for the reacting rock, or considerable differential stresses will arise. Macdonald and Fyfe (1985) were some of the first to propose that increasing stresses due to the solid volume expansion may result in fracturing, which in turn increases or maintains permeability, i.e., the ability of a rock to transmit fluids. The microstructures of partially serpentinized olivine grains are consistent with what has been termed "hierarchical fracturing" (Fig. 2B; e.g., Plümper et al. 2012), where olivine is progressively fragmented into smaller and smaller pieces, indicative of internally generated forces rather than far-field tectonic stresses. Based on natural observations and thermodynamic constraints, Kelemen and Hirth (2012) suggested that reaction-induced differential stresses may exceed 300 MPa at temperatures  $>200^\circ\text{C}$ . These considerations indicate that olivine alteration may be able to fracture rocks located  $>10$  km depth within the Earth's interior. Plümper et al. (2012) investigated the micro-physical mechanism of reaction-induced fracturing and concluded that cracking is driven by stress generated from serpentine growth in reaction-interface perturbations that originate from the anisotropic dissolution of olivine. Recent in situ synchrotron X-ray tomography experiments of an analog system to serpentinization, the hydration of MgO to form  $\text{Mg}(\text{OH})_2$ , suggest, however, that reaction-induced stresses during mineral hydration at laboratory timescales may be limited to several tens of megapascals due to the reduction of fluid film thickness at the reaction interface (Zheng et al. 2018). Regardless of a positive or negative feedback loop between olivine dissolution, serpentine growth, and fracturing, serpentinization can most often go to completion. Even in the absence of renewed reaction-induced fracturing, a potential mechanism that may sustain fluid pathways to the reaction interface is the inherent nanoscale porosity within serpentinite. Tutolo et al. (2016) used neutron scattering to show that serpentinites have a significant porosity of up to 4 %, of which the majority is less than 10 nm. Indeed, these nanopores are not only abundant in pure serpentinites (Fig. 2C) but are also found in carbonated serpentinites (Beinlich et al. 2020a), where they may play an essential role in controlling the carbonation process. Recent investigations by Malvoisin et al. (2021) further highlight the presence of nanoscale porosity that appears to be connected to the olivine reaction interface. The size of these pores may not favor fluid transport driven by fluid pressure gradients but rather by electrokinetic transport mechanisms (e.g., Plümper et al. 2017).



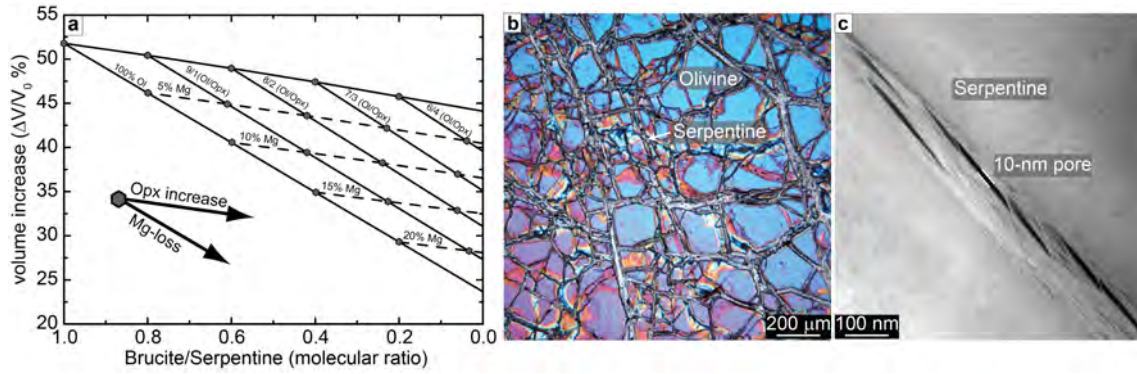
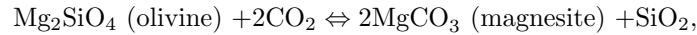


Figure 2: (a) Serpentinization of olivine typically results in a substantial solid volume increase. The diagram depicts this volume increase as a function of the original mineralogical composition (i.e., olivine (Ol) versus orthopyroxene (Opx) ratio), the resultant brucite/serpentine ratios, and progressive magnesium loss from the system (based on Hostetler et al. 1966). (b) Reaction-induced fracturing during serpentinization results in a mesh-texture vein network where (c) shows that the inherent serpentine porosity is nanometer-sized.

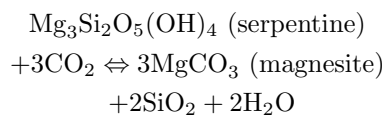
## Just add Carbon Dioxide

In its simplest form, the reaction of olivine with carbon dioxide (mineral carbonation) can be written as



where  $\text{SiO}_2$  can be quartz or opal. In this idealized reaction, all of the magnesium contained in olivine is converted into magnesite. This reaction has been observed in experiments where fine-grained olivine may readily react with  $\text{CO}_2$  (Miller et al. 2019 and references therein). Flow-through experiments on rock cores (e.g., Hövelmann et al. 2012), however, suggest that although olivine may react to magnesite, the formation of amorphous silica as a precursor to, e.g., quartz can passivate the olivine surface, hindering reaction progress if reaction-induced fracturing does not occur to generate new surface area.

In nature, the direct replacement of olivine by carbonates is less frequently observed, and numerous studies show that it is the carbonation of serpentine that appears to be dominant (e.g., Beinlich et al. 2020a), which can be written as



where  $\text{SiO}_2$  can be quartz or opal. These observations suggest that carbonation in ultramafic rocks occurs either in tandem with or is preceded by serpentinization. However, the absolute time relationships between carbonation and hydration reactions remain largely unknown. Moreover, although reactions (5) and (6) show the maximum carbonation potential, the resultant amount of Mg-carbonate is dependent on the  $\text{CO}_2$  concentration within the alteration fluid. Figure 3 depicts the mineralogical evolution and carbon uptake potential with increasing  $\text{CO}_2$  content, here portrayed as the ratio between  $\text{CO}_2$  and  $\text{H}_2\text{O}$  ( $X_{\text{CO}_2} = \text{CO}_2/(\text{CO}_2 + \text{H}_2\text{O})$ ). Carbonated ultramafic rocks with 0.1-30 wt. % magnesite are typically referred to as carbonated serpentinites. The term "ophicarbonate" is used frequently, but it generally refers to brecciated ultramafic rocks cemented primarily by Ca-carbonate. Ultramafic rocks with 30-40 wt.% magnesite are termed soapstones (dominated by talc  $[\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2]$  and magnesite), and listvenites (quartz and magnesite, see Fig. 1E-F) represent the maximum carbonation potential, with 40-60 wt.% magnesite. Figure 3 shows the carbonation potential of ultramafic rocks at Linnajavri, Norway (Fig. 1A, 1D, and 1E)

and in Oman (Fig. 1F). Generally, carbonation can occur across a broad range of  $T$  and  $P$  and produce a variety of alteration products, but the overall dependence on  $X_{\text{CO}_2}$  remains.

Although these carbonation reactions show a great carbon storage potential, their feasibility for geoengineered carbon sequestration schemes remains to be fully explored. Fieldscale experiments within ultramafic rocks are just starting. Excitingly, multi-element advection-diffusion-reaction transport modeling does suggest that natural serpentinite carbonation to form soapstone may be instantaneous, at least on a geological timescale (Beinlich et al. 2020b).

## Natural and Enhanced Weathering of Olivine and its Alteration Products

Mineral alteration at the Earth's surface, or "weathering," is a key carbon sink. Because olivine is the most reactive mineral on the Earth's surface, its weathering has attracted considerable attention over the past two decades. Numerous authors have considered geoengineered olivine weathering to sequester  $\text{CO}_2$  to counteract global warming (e.g., Köhler et al. 2010). This method would entail spreading large amounts of finely ground olivine powder within, for example, river catchments, along coastlines above the wave base, or as roof-top covers. However, numerous studies (e.g., Hangx and Spiers 2009) suggest that olivine dissolution rates at ambient conditions are too slow and require materials that pose significant economic and infrastructural challenges. Nevertheless, Earth's surface carbonation of waste products from ultramafic mining, particularly the carbonation of brucite, has been shown to occur rapidly and may be a local means for carbon sequestration (e.g., Harrison et al. 2013). Additionally, as we will further see below, the production of high-alkalinity water during ultramafic rock alteration, and the high-alkalinity water springs at the Earth's surface can rapidly extract  $\text{CO}_2$  from the atmosphere.

### 3 A LOOK AT NATURE

As shown in the preceding section, ultramafic rock alteration does not cease with the disintegration of olivine, but rather continues in a spectrum of possibilities with the continued alteration of olivine's products. These alteration processes have been extensively studied both on land (Fig. 1) and in oceanic expeditions (e.g., Früh-Green et al. 2017). Here, we focus on the recently completed Oman Drilling Project to highlight the efforts of a multinational research project dedicated to advancing our understanding of the alteration of olivine and serpentine.

## Oman: A Natural Field Laboratory

The Samail ophiolite in the Sultanate of Oman and the United Arab Emirates is one of the most complete and well-studied oceanic lithosphere sections (Fig. 4). Since the 1960s, the ophiolite has served as a crucial laboratory for numerous geoscientists. Not only have scientific studies on the Samail ophiolite improved our understanding of the origin and evolution of the oceanic lithosphere, but they have also played a significant role in determining the alteration processes and mechanisms of olivine-bearing rocks across a wide range of spatial scales and environmental conditions.

*The Oman Drilling Project.* Recently, the Samail ophiolite has been the International Continental Scientific Drilling Program (ICDP)'s drilling target, which initiated the "Oman Drilling Project (OmanDP)." In this project, a crosssection was drilled through the ophiolite from 2016-2019 (15 boreholes with a total of 5400 m drilled, and 3220 m of core collected) to (1) improve our understanding of the processes that create and modify the oceanic lithosphere and (2) quantify processes of mass and energy transfer between the mantle, crust, hydrosphere, atmosphere, and biosphere. The latter focuses on processes that occur over a temperature range of  $\sim 1350$  to  $20^\circ\text{C}$ , depths of 20 km below the paleo-seafloor to the surface, and tectonic settings spanning from spreading ridges and subduction zones to modern subaerial hydrology and surface weathering.

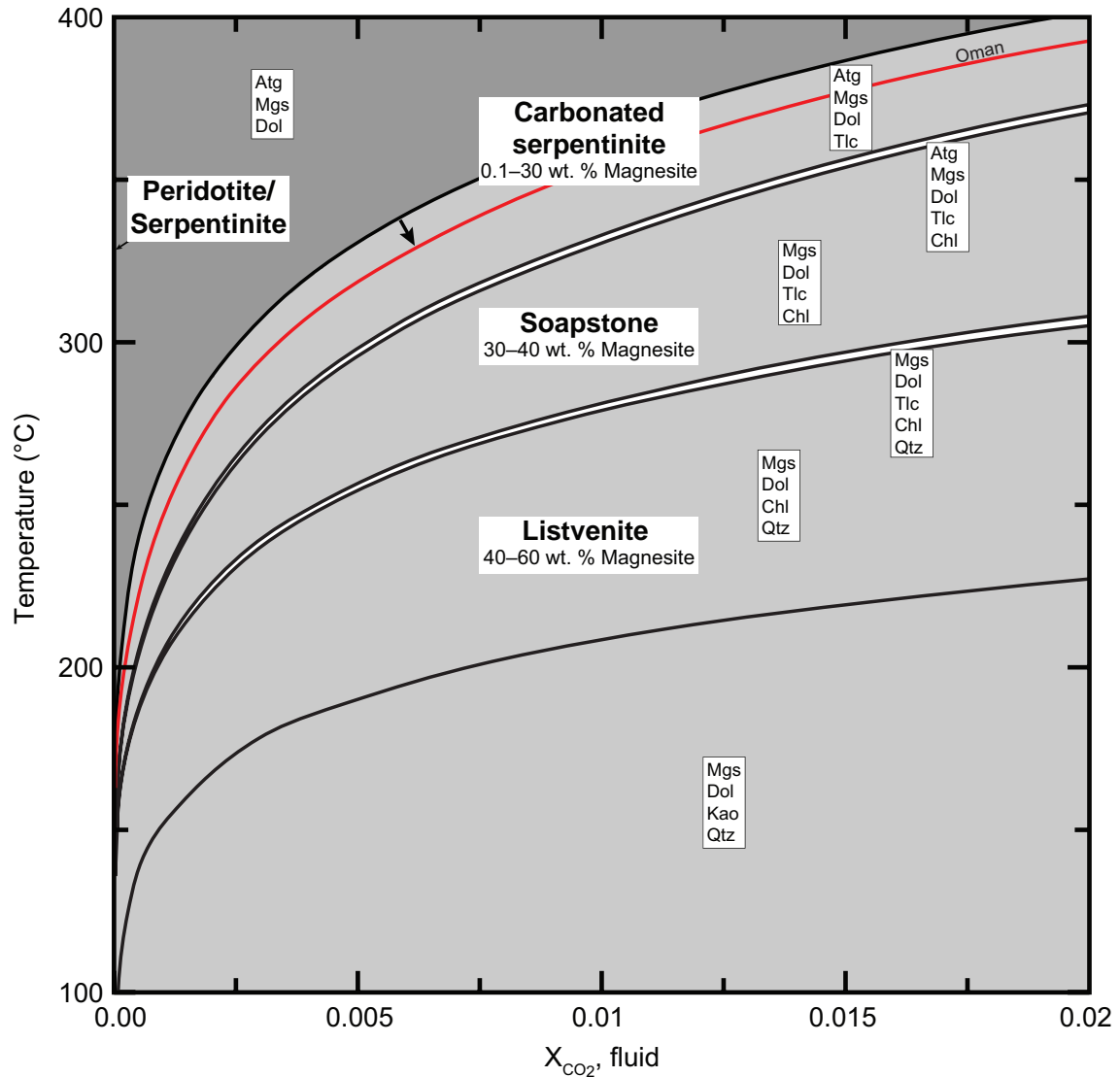


Figure 3: Isobaric  $T - X_{\text{CO}_2}$  pseudosection for ultramafic rock carbonation calculated using PerpleX (<https://www.perplex.ethz.ch/>) for the bulk-rock compositions of the Linnaajavri serpentinites (Fig. 1A; composition Lin\_31 in Beinlich et al. (2012) and Oman harzburgite (Kelemen et al. 2021) at 3 kbar). The  $\text{SiO}_2$  content of silicate phases and carbonate abundance increases with  $X_{\text{CO}_2}$  content of the alteration fluid. All univariant curves are nearly identical between Linnaajavri and Oman except for the predicted onset of talc formation (red curve). Abbreviations: antigorite (Atg), magnesite (Mgs), dolomite (Dol), talc (Tlc), chlorite (Chl), quartz (Qtz), and kaolinite (Kao).

Numerous drillholes were established to investigate past and active alteration processes (Fig. 4). The past alteration processes include listvenite bands within carbonated serpentinites (Figs. 1F and 4C-E), which record complete carbonation via reaction with  $\text{CO}_2$ -rich fluids at  $\leq 200^\circ\text{C}$  (Beinlich et al. 2020a). In the following section, we focus on active, low-  $T$  alteration processes, emphasizing the processes that drive carbonation of ultramafic rocks.

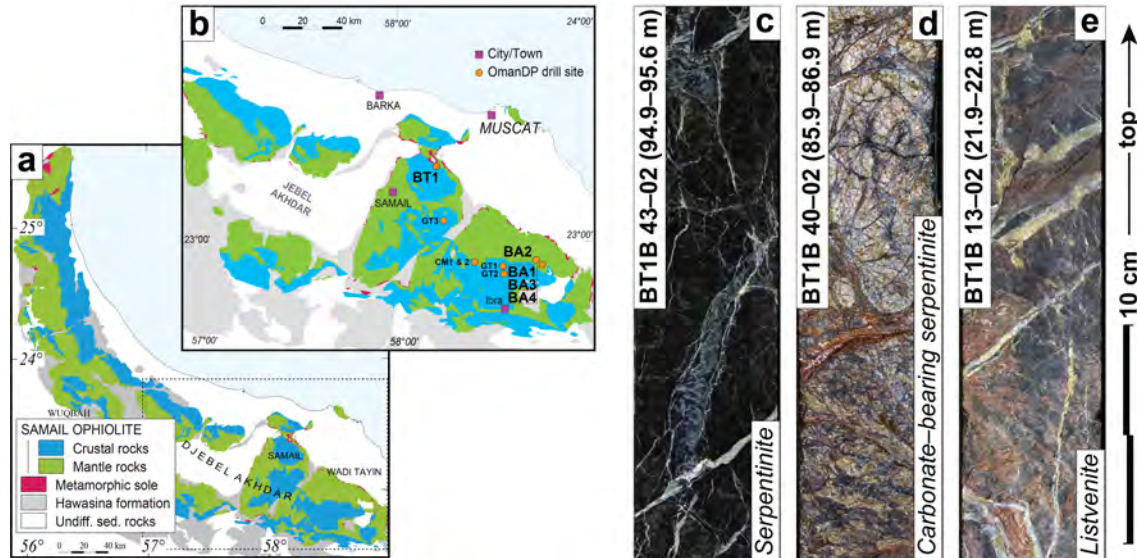


Figure 4: (a) Geological overview map and (b) map of the southeastern Samail ophiolite massif showing the drill site locations. Modified from Kelemen et al. (2020). Drill sites related to ultramafic rock alteration and discussed here are highlighted with larger font size. (c-e) Drill cores from BT1B show various alteration stages (Kelemen et al. 2020): (c) serpentinite, (d) carbonate-bearing serpentinite, and (e) fully carbonated ultramafic rock (listvenite).

*Active alteration.* To decipher ongoing alteration processes within the Samail ophiolite, The Multi-Borehole Observatory (MBO) was established. The MBO boreholes have two major sequences: fully serpentinitized dunite with gabbro and 85 % - 100 % serpentinitized harzburgite with gabbro (Kelemen et al. 2020). Surface weathering dominates the upper 30 m of all MBO cores, causing yellowish to brownish orange oxidation. Groundwater appears to hydrate and carbonate serpentinitized harzburgite and dunite at the MBO site, creating two types of fluids (Type I: near-surface, oxidized,  $\text{Mg} - \text{HCO}_3$ ,  $\text{pH} \sim 8$  fluids; Type II:  $\text{CH}_4$ -bearing  $\text{Ca} - \text{OH}$ -rich,  $\text{pH} > 11$  fluids). This low- $T$  alteration uses fluid pathways from centimeter-scale fracture networks to rock matrix nanopores, but the interconnectivity of these pathways remains poorly understood. Previous studies mainly described a conceptual hydrogeological model (Dewandel et al. 2005) with an intensively fractured, permeable zone of about 50 m below the surface and a deeper, less permeable zone, dominated by discrete fractures.

OmanDP's new borehole wireline and shipboard core logs corroborate the conceptual hydrogeological model. The upper serpentinitized dunite sequence has higher porosity, higher crack density, and lower electrical resistivity than the serpentinitized harzburgite sequence (Fig. 5). These parameters also correlate with a higher degree of alteration at shallow depth. Borehole flowmeter logs and crossborehole multi-level hydraulic experiments show that complex vertical and horizontal structural heterogeneities determine the hydrodynamic response (Lods et al. 2020). Highly conductive fractures channel groundwater flow in the upper 75 m, but at greater depths ( $< 150$  m), horizontal and vertical flows around and far from the pumped boreholes determine the hydraulic response. Calculated hole-to-hole permeabilities, the rock's ability to transmit fluids, range from  $\sim 10^{-12} \text{ m}^2$  near the surface ( $< 50$  m) to  $\sim 10^{-14} \text{ m}^2$  down to 150 m in the serpentinitized dunite and  $< 10^{-17} \text{ m}^2$  in the serpentinitized harzburgite (Lods et al. 2020). Decreasing permeability with increasing depth correlates with decreasing crack/vein density and a decreasing degree of alteration.



Ca - and Mg-carbonates occur in veins or replace serpentine mesh textures in MBO cores. Carbonate veins become scarce below 150 m (Kelemen et al. 2021). This decrease correlates with increasing borehole fluid pH and the proposed reaction path of infiltrating surface water or shallow groundwater descending through the porous upper aquifer, progressively interacting with the ultramafic rocks (e.g., Paukert et al. 2012). Most vein carbonates and inorganic and noncarbonate carbon from whole rock samples contain  $^{14}\text{C}$  and reveal  $^{14}\text{C}$  ages between 50,464 and  $20,300 \pm 100$  y for vein carbonates and from 29,750 to 293 y for the dispersed carbon in the matrix (Kelemen et al. 2021; Ternieten et al. 2021).

Stable carbon isotopes and clumped isotope measurements reveal a mixture of atmospheric  $\text{CO}_2$ , organic soil carbon, and possible bicarbonate from limestone dissolution as the dominant carbon source, and precipitation temperatures between  $\sim 20$  and  $\sim 40$  °C (Ternieten et al. 2021). Vein carbonates decrease with depth, which also correlates with permeability, crack density, and alteration degree, indicating that meteoric water flows along fractures and microcracks. Dispersed carbonates in the matrix, which are not depth-limited, are likely the result of more diffusive fluid flow along grain boundaries and interconnected porosity in the serpentine mesh network (Ternieten et al. 2021).

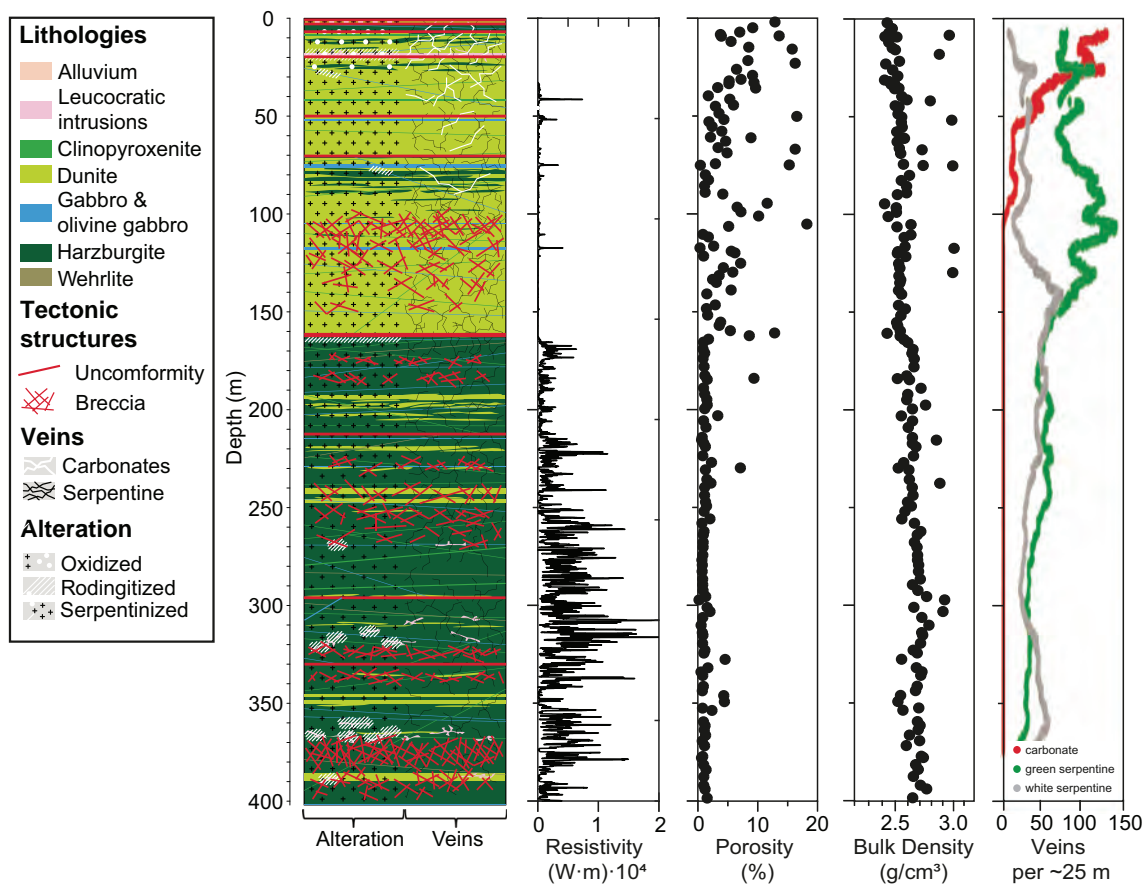


Figure 5: Borehole BA1B lithostratigraphy summary log borehole wireline resistivity log, and down-hole plots of discrete sample measurements of porosity, bulk density, and specific vein types (25-m average). Modified from Kelemen et al. (2020).

*Carbon mineralization.* Present-day alteration seems to be a "top-down" process driven by weathering, indicating that the deeper subsurface of ultramafic rocks has a great carbon uptake potential that could be utilized for engineered carbon sequestration. As discussed above, ultramafic rocks have both olivine, which may react with atmospheric  $\text{CO}_2$  or dissolved  $\text{CO}_2$  in fluids, and its alteration products, serpentine and brucite, which can undergo extensive reactions with  $\text{CO}_2$ -bearing fluids to form carbonate minerals.

As shown by the MBO core data, natural carbon mineralization is ongoing at a rate of  $\sim 1,000 \text{ tCO}_2 \text{ km}^{-3} \text{ y}^{-1}$ . The injection of  $\text{CO}_2$ -rich fluids into the ultramafic rocks of the Samail ophiolite could enable in situ mineralization, potentially sequestering a total of  $10^5$  to  $10^8 \text{ GtCO}_2$  (Kelemen and Matter 2008). The current anthropogenic  $\text{CO}_2$  emission is  $\sim 40 \text{ GtCO}_2/\text{y}$ . As noted above, the hydration of ultramafic rocks results in the formation of alkaline, Ca-rich fluids along the subsurface reaction path. When these fluids emerge on the surface as springs, they react with atmospheric  $\text{CO}_2$  to form calcite-travertine deposits (Fig. 6B). These alkaline fluids can provide another option for  $\text{CO}_2$  removal from the atmosphere and solid storage by either accelerating the production of these alkaline waters or by  $\text{CO}_2$  injection into the alkaline peridotite-hosted aquifers, where carbonate precipitation would occur. As shown by the newly acquired MBO site data, permeability is limited in the deeper subsurface, and engineered carbon mineralization in ultramafic rocks will most likely require permeability enhancement via hydraulic fracturing. As discussed above, alteration could result in positive feedback. The reaction-induced volume change causes an increase in differential stress in the rock and the generation of fractures that increase the rock's permeability and expose reactive surfaces. Alternatively, carbon mineralization may result in a permeability reduction due to mineral growth in pore spaces passivating reactive surfaces. Experiments at different length scales, from individual mineral grains to field-scale approaches, are needed, and are, in fact, on their way. These experiments will further constrain the feedback mechanisms during ultramafic rock alteration. Despite this, innovative research-to-application initiatives like Carbfix ([www.carbfix.com](http://www.carbfix.com)) in Iceland have demonstrated the feasibility of extensive in situ mineral carbonation in basaltic rock formations. Similarly, Oman is also taking promising strides toward translating ultramafic rock carbonation research into practical solutions ([www.4401.earth](http://www.4401.earth)).

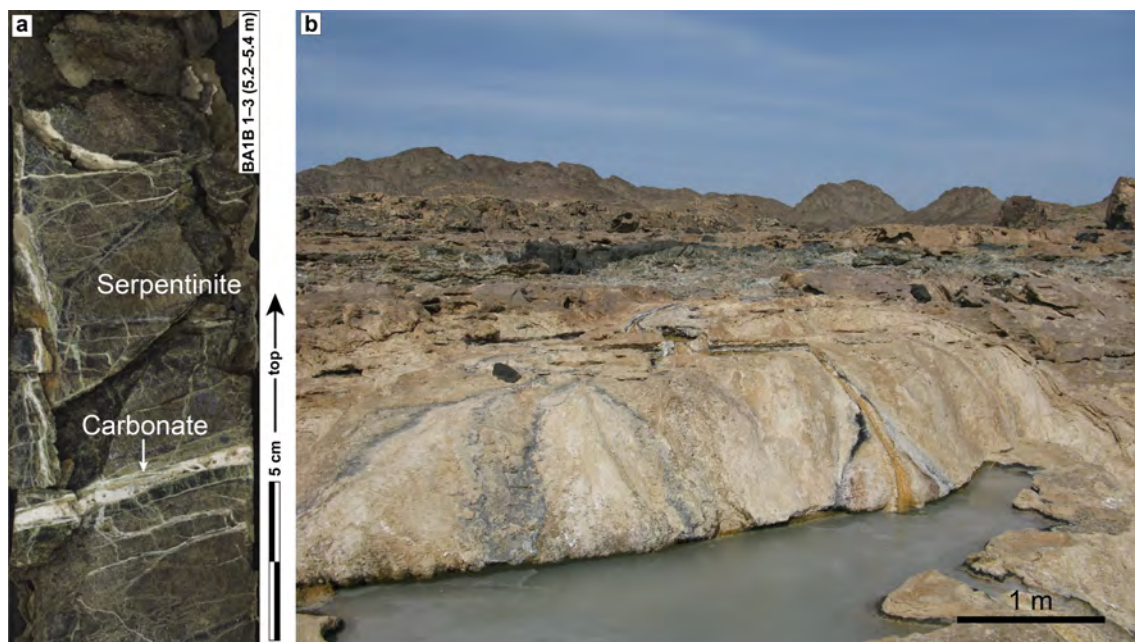


Figure 6: Active alteration within the Samail ophiolite. (a) Carbonate veins within serpentinite within the MBO drill hole (Kelemen et al. 2020) and (b) carbonate travertine deposits on the Earth's surface near the village of Falajj, Oman ( $22.846^\circ\text{N}$ ,  $58.056^\circ\text{E}$ ).

## 4 CLOSING THOUGHTS

Perhaps no other duet between a mineral and a liquid holds the answer to so many vital issues, ranging from the potential origin of life to the mitigation of global climate change. Olivine alteration is the first of a cascade of alteration processes in which its reaction products appear to be of equal

importance, particularly during carbonation processes. A first comparison of distinct rock sequences from Norway, Oman, and Italy (Fig. 1) shows that alteration patterns appear similar at first glance but may differ substantially upon closer inspection. The key to further constraining the processes controlling ultramafic rock alteration may lie in the structural and chemical analysis of these patterns across scales.

It remains to be seen if new nanoanalytical approaches coupled with experiments and natural observations can fully decipher the reaction paths for synthesizing organic molecules during serpentinization-type alteration processes. Furthermore, can coupled lab- and field-scale experiments unravel the positive feedback mechanisms and magnitudes of stress generation during carbonation and hydration of ultramafic rocks? If so, could we add the sequestration of carbon dioxide via the carbonation of ultramafic rocks into our portfolio to mitigate climate change? And finally, critically for most of the above, when do alteration processes take place on an absolute timescale coupled to the geological evolution of the oceanic lithosphere? Are rock transformation processes really that slow, or only in the absence of fluids? If not, should we view them as instantaneous, at least on a geological timescale? Only time will tell.

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