

# **COMPARISON OF BASALT AND OLIVINE'S POTENTIAL AS CARBON SEQUESTRATION TOOLS**

FINAL PROJECT

NS111: Implications of Earth's Cycles

Minerva Schools at KGI

April 2021

<b>Introduction</b>	<b>2</b>
<b>Overview of Weathering Process</b>	<b>3</b>
<b>Olivine: Enhanced Weathering in Coastal Areas</b>	<b>4</b>
Enhanced weathering via olivine	4
Olivine mechanical activation study	5
Study limitations	6
<b>Basalt: Enhanced weathering on farmland</b>	<b>7</b>
<b>Comparison of Olivine &amp; Basalt's Potentials</b>	<b>8</b>
<b>HCS &amp; LOS APPENDIX</b>	<b>12</b>

**Word counts: 2189 words** (excluding figure captions & footnotes)

## INTRODUCTION

The planet's natural systems put  $\text{CO}_2$  into the atmosphere through respiration, water evaporation, and volcanic eruptions. Meanwhile,  $\text{CO}_2$  is absorbed through photosynthesis, weathering, and dissolution into the ocean. Within the overall carbon cycle (figure 1), weathering does not seem like a significant flux. However, over geologic time scales, this flux adds up and plays an important role in regulating atmospheric  $\text{CO}_2$ . In this paper, we will be exploring the current research on enhanced weathering as a means to increase  $\text{CO}_2$  removal from the atmosphere and storage at the bottom of the ocean in the form of sediment layers.

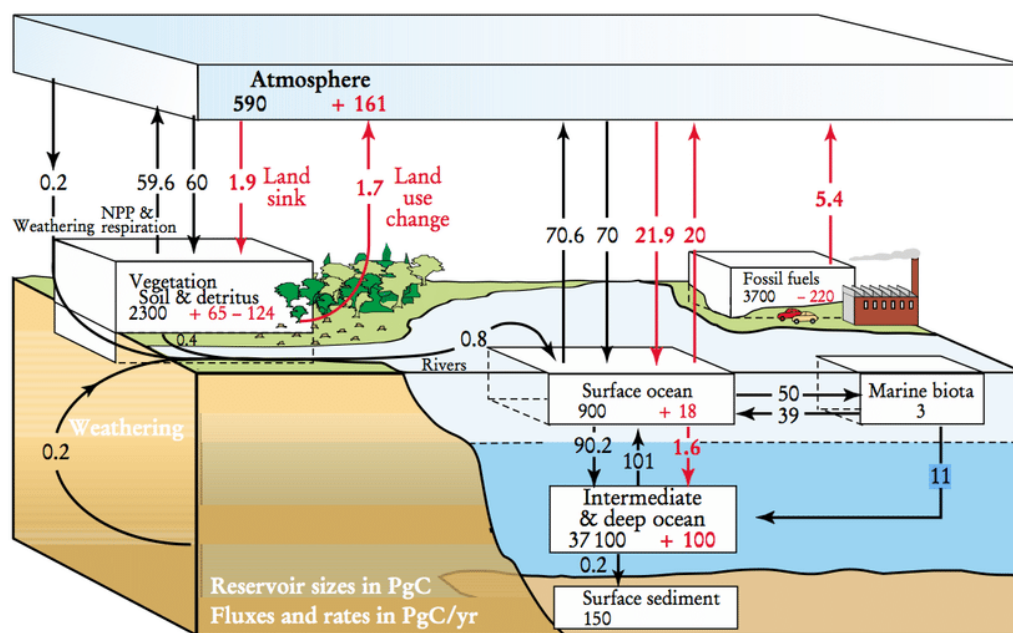


Figure 1: The Carbon Cycle (Hughlett, 2016)

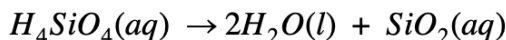
## OVERVIEW OF WEATHERING PROCESS

Weathering begins with the process of carbonation where rainwater reacts with the carbon dioxide in the atmosphere to produce carbonic acid. Once this reaches land, it washes over silicate rocks and breaks them apart (equation 1) into metal ions, bicarbonate, and silicic acid. These products are carried into nearby water systems and eventually end up in the ocean. The silicic acid breaks down into water and silicon dioxide (equation 2), while the remaining products react to form water, carbon dioxide, and calcium carbonate (equation 4). The chemical process is as follows:

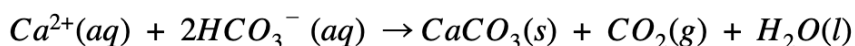
*Equation 1 (CaSiO<sub>3</sub> is used as an example of a silicate rock):*



*Equation 2:*



*Equation 3:*



A key aspect of this process can be seen by comparing equations 1 and 3: in equation 1, two moles of CO<sub>2</sub> were inputted but in equation 3, only one mole of CO<sub>2</sub> remains. Thus, there is a net decrease of one mole of CO<sub>2</sub>. Essentially, CO<sub>2</sub> gets swept into the ocean through weathering and becomes a stable dissolved inorganic alkaline (HCO<sub>3</sub><sup>-</sup>). Then, with the help of calcifying organisms such as coral or plankton, Ca<sup>2+</sup> is combined with HCO<sub>3</sub><sup>-</sup> to form calcium carbonate (Riebeek, 2011). After these organisms die, they sink to the sea floor carrying the CO<sub>3</sub> in their shells and eventually become layers of limestone (Riebeek, 2011). Even if the dissolved inorganic carbon remains in the ocean without forming CaCO<sub>3</sub>, the estimated timescale for

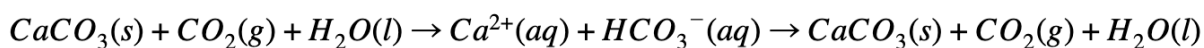
storage is around 100,000 - 1,000,000 years, making it essentially a permanent carbon storage reservoir on a human timescale (Renforth & Henderson, 2017). Additionally, the alkaline material that gets runoff to the ocean also mitigates the effects of ocean acidification if done on a large enough scale. Finally, some might be concerned that the additional bicarbonate would cause the ocean to be saturated, but Ciais et. al. (2013) has reported to the International Panel of Climate Change that oceans worldwide have a capacity of around 38,000 PgC (38 thousand billion metric tons CO<sub>2</sub>), which is around 45 times the current atmospheric CO<sub>2</sub>. Thus, it is unlikely that the ocean would be the limiting factor.

## **OLIVINE: ENHANCED WEATHERING IN COASTAL AREAS**

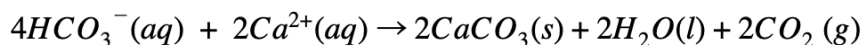
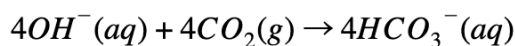
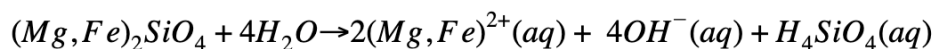
### **Enhanced weathering via olivine**

The most common method of enhanced weathering uses olivine, which weathers more rapidly than other silicate rocks. Olivine is considered the one of the most reactive minerals: theoretically, 1 mm sphere grain of olivine would dissolve in 2300 years, compared to 34 million years for 1mm grain of quartz (Hartmann et al., 2013). The only mineral that is more reactive is calcium carbonate which is not beneficial for climate mitigation as it leads to no net sink of CO<sub>2</sub> (see equation 5).

*Equation 5:*



The process of bringing atmospheric CO<sub>2</sub> down via olivine and storing them in reservoirs is essentially the same as the weathering process detailed in section 1:



### **Olivine mechanical activation study**

A popular method of using olivine for enhanced weathering is by spreading a thin layer of milled olivine across coastlines, where the energy from waves will cause mechanical activation (Schuiling & Tickell, 2009). The location is important because the rate of olivine weathering is limited by its surface activated complex (Schuiling & de Boer, 2011), and the breakdown of this complex is the rate-determining step of the reaction. Schuiling and de Boer hypothesized that removing the surface complexes would accelerate olivine weathering. In their pre-post study (Aggarwal & Ranganathan, 2019), they attempted to mimic the movement olivine grains would experience from tidal currents by putting grains in an open erlenmeyer flask filled with tap water. The underlying mechanism they were relying on was that the collision of the grains into each other would remove the silica coating that limited the reaction.

All the variables were kept constant except for the olivine grain sizes. Fine and coarse grain sizes (0.71–1.4 mm and 2–5 mm) were tested in the experiment with three flasks for each. All of the flasks were placed on a table top rotary shaker to induce collisions, and the open tops allowed for CO<sub>2</sub> exchange.

After 24 hours, the flasks with the finer grain olivine became cloudy while those with a coarser grain were milky white and opaque, indicating that more CO<sub>2</sub> was sequestered in the flasks with coarser grains. One of the flasks with fine grains rose to a pH of 8.91, while a flask

with coarse grains rose to 9.02 (both started off at 8.22, the pH of the tap water). After 12 days, the pH values increased to 9.41 and 9.22 respectively. A shortcoming of their data is that it does not include measurements from all six flasks (they only reported results from one of each), so although their study design included aspects of replicability, they did not follow through with it. Thus, their results were not as reliable as they could have been. From the data they did collect, they inferred that the greater mass of the coarse grains likely led to heavier mutual impacts, which would be more effective at removing the surface complex through mechanical activation (Méndez-Rojas & de la Rosa, 2018). The result indicates that crushing olivine to an appropriate size can increase the rate of  $\text{CO}_2$  removal to a rate that is significant to human timescales.

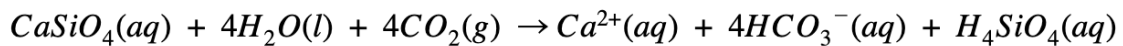
### **Study limitations**

The experiment was conducted in a lab where the water was not changed in 9 days. Thus, as the products accumulated, the reaction likely slowed down or may even have stopped, but this is not reflective of a coastline environment where waves would continually remove the products. Although the study results point to coarse (2–5 mm) grains being more effective at increasing pH (caused by the increased production of bicarbonate, which points to more  $\text{CO}_2$  being stored), its efficacy on a larger scale and beyond a lab environment cannot be known. However, existing literature has suggested that the actual rate in the environment is 10 - 100 times faster than under laboratory conditions as there exists mycorrhizal fungi which has a symbiosis with plants around olivine (Schuiling & Tickell, 2017). The fungi secretes an acid and chelating agent which releases the essential plant minerals in olivine. After the plants take up these minerals, they provide the sugar necessary for the fungi to survive and reproduce, which causes further breaking down of minerals and so on is a positive feedback loop. Compared to existing

weathering rates where olivines are not crushed, the weathering rate is 4,000 times faster (Schuiling & Tickell, 2017).<sup>1</sup>

### **BASALT: ENHANCED WEATHERING ON FARMLAND**

Another enhanced weathering method that is taken into consideration is the removal of CO<sub>2</sub> by crushing basalt onto soil. This practice has existed on small scale farms, especially prominent in tropical areas including Brazil, Malaysia and Mauritius (Beerling et. al, 2018). Basalt contains roughly 40 - 52% silicate. This silicate, mainly in the form of  $CaSiO_4$  and  $MgSiO_4$ , draws down CO<sub>2</sub> from the air or respiration of organisms in the soil and reacts with water to form  $H_4SiO_4$ ,  $Ca^{2+}$  or  $Mg^{2+}$ , and  $HCO_3^-$ .



Besides acting as a carbon sink, crushed silicates improve agricultural productivity, which has a secondary effect of more sequestration of CO<sub>2</sub> from increase in photosynthesis. The alkaline products from weathering reduces soil acidification common in agricultural areas that overuse ammonium and sulfur fertilizers. It also reduces metal toxicity and increases phosphorus availability, primarily in the form of calcium phosphate, which add plant-essential nutrients (Gillman 1980). Additionally, while silicon is not considered an essential nutrient in soil, it can increase productivity by making soil more resilient to abiotic stress such as drought, salinity and

---

<sup>1</sup> #interventionalstudy: We interpreted an pre-post interventional study, first outlining the experiment design (and the mechanism it relied on), then their results, before discussing the conclusions they drew. We also pointed out flaws in their experiment (data collection) and laid out the limitations of their study.

heat which are all becoming increasingly common with climate change (Jian, 2003). An application of crushed basalt and NPK fertilizer in Mauritius led to a 30% increase in yield compared to the control trial with fertilizer but no basalt (de Villiers, 1961). Experiments in Florida, Louisiana and New Jersey also reported an increased yield for many types of crops, including oats, cabbage and corns (Tubana et. al, 2016).

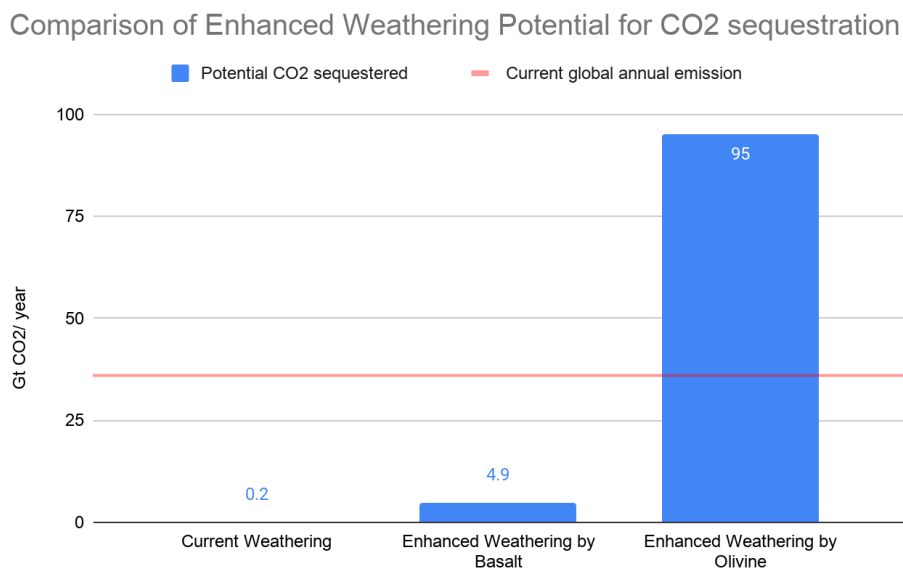
This is where basalt delivers a much higher potential than olivine. While olivine is the fastest weathering silicate mineral (especially at pH levels of less than 6) and has the highest potential for CO<sub>2</sub> drawdown, olivine-rich rocks also contain high concentrations of nickel, chromium or both. This causes a suppression of calcium intake, an essential nutrient for plants, while bioaccumulation of these harmful metals leads to increased concentration higher up in the food chain (ten Berge et. al, 2012). Meanwhile, basalt has a lower concentration of both nickel and chromium. Further, weathering basalt releases P, K, Ca, Mg and Fe, all of which are essential nutrients for plant growth (Hinsinger et. al, 2001). Lastly, soil pH (around 4) is significantly lower than ocean pH (around 8), and at a pH of 4 the weathering rate of basalt is roughly equivalent to olivine dissolution at a pH of 8 (roughly  $10^{-10}$  mol/ m<sup>2</sup>/ s) (Brantley et. al 2008).

### **COMPARISON OF OLIVINE AND BASALT'S POTENTIALS**

Olivine and basalt both have great potentials as large-scale, scalable carbon capture and storage methods. Olivine-rich rocks such as dunites are capable of sequestering more CO<sub>2</sub> due to having higher concentration of silicate in the rocks. Dunite is expected to sequester 1.1 ton of CO<sub>2</sub>/ ton of dunite, while basalt only sequesters 0.3 ton CO<sub>2</sub> /ton basalt (Strefler et al. 2018). According to Strefler et. al (2018), the theoretical limit for carbon removal for dunite is 95 Gt CO<sub>2</sub> annually. Schuiling and de Boer (2011) estimated that to remove the annual anthropogenic



emission of CO<sub>2</sub> using olivine (~36 Gt/ year), only 2% of tropical shelf seas are needed, which is 0.12% of Earth's surface. In comparison, the basalt method is estimated to have a drawdown potential ranging from 0.5 - 4.9 Gt/ year (Beerling et al., 2018; Strefler et al., 2018), or 1 - 13% of global annual emission. This is more limited primarily to croplands for reasons stated above, and most estimates argue that it would require at least  $\frac{2}{3}$  of the lands to be covered in basalts (Beerling et al., 2018) to get this amount of CO<sub>2</sub> sequestered - a much higher requirement. Thus, olivine has a lot more potential as a carbon sequestration tool, because it requires fewer land resources and sequesters carbon at a higher rate. Regardless, both of them still speed up CO<sub>2</sub> sequestration by a magnitude of 4000 times compared to natural weathering, and with large scale implementation they can be powerful carbon sequestration tools.



*Figure 2: The bar graph shows the maximum sequestration potential for both the enhanced weathering methods discussed in this paper, as well as the current weathering rate. The current global annual emission is added for comparison. Source: Beerling et al., 2018; Huglett, 2016; Strefler et. al (2018).<sup>2</sup>*

<sup>2</sup> #dataviz: We created a bar graph based on data regarding the maximum sequestration potential for enhanced weather via olivine and basalt. We also added a line for our current global emissions to put the numbers into context. Having visual representation of the numbers we discussed in our comparison section makes them easier to

The higher rate of CO<sub>2</sub> capture also means that olivine is more economically viable and is more likely to achieve economy of scale. Cost of sequestering a ton of CO<sub>2</sub> is estimated to be as low as US\$14/ tCO<sub>2</sub> (Schuiling & de Boer, 2011), roughly 10 times cheaper than current CCS technology, but more realistic estimates put it as US\$60/ tCO<sub>2</sub> (Strefler et al., 2018). Meanwhile, costs of basalt application is between US\$52 - 380/ tCO<sub>2</sub> (Beerling et al., 2018; Strefler et al., 2018) which is significantly more expensive. This, however, has not taken into account the potential increase in carbon sequestration by crops due to increase in soil productivity.

Further, basalt's main advantage over olivine is its secondary effects on crop productivity, which means given enough education, theoretically, farmers can naturally start to adopt this method without government incentives. Meanwhile, spreading of olivine does not have any secondary effect that gives rise to direct monetary benefits, which means its adoption will be dependent on a vibrant carbon market which currently does not exist. This means that although olivine has more potential, it is dependent on government legislation, which can come at a much slower pace, leading to slower adoption.

Nonetheless, both are still areas under active research and may have hidden long-term effects on human health or biodiversity when applied on a large scale. This is where we need to be more rational: while the risk associated with new technology, especially on a global scale, is unavoidable, the current risk of letting current emission go unchanged is even larger. As both individuals and institutions tend to overly discount future outcomes, and climate change is one that will be most acutely felt in future years, it is easy to dismiss these solutions due to insufficient research and favour short-term ones with more immediate economic benefits.

---

conceptualize. The visualization is clearly labeled, all data are well presented in a scale that is appropriate to visualize the magnitude of these solutions.

However, the more rational thing to do would be to increase funding for active research and start trial implementations on a large scale, such as one being done by non-profits like Project Vesta, in order to mitigate the risks as much as possible while maximizing potentials for future gains.<sup>3</sup>

---

<sup>3</sup> #expectedutility: We point out the uncertainty with regards to enhanced weathering and how while the outcomes are unknown, the presence risks are too high for us to not take actions. We also point out common biases by both people and institutions (overtly discounting future values, disproportionately discounting losses) and what is the appropriate course of action (continue exploring while mitigating the risks as much as possible).

## HCs & LOs Appendix

### **#elementstominerals**

We detailed the process of how silicate rocks break down into ions and other compounds through weathering, and the precise chemical equations of how they react to form  $\text{CaCO}_3$  (among other products). We then discussed how a property of this mineral creation is its ability to store carbon at the bottom of the ocean, contributing to the negative feedback loop of atmospheric  $\text{CO}_2$  removal (both on the geological and human scale).

### **#scale**

We have determined the appropriate scale of comparison for both olivine and basalt applications both temporally (rate of  $\text{CO}_2$  sequestration) and spatially (through comparing the amount of land needed for drawdown the amount of  $\text{CO}_2$  expected). We then use these scales of comparison to judge their effectiveness as a carbon capture and storage tools to come to the conclusion that while one (olivine) is more efficient than the other (basalt), both have huge potentials when it comes to climate regulations on a global scale.

### **#climateregulation**

We explain how weathering contributes to the carbon cycle and in doing so, regulates climate temperature in our introduction. We then go in more detail with olivine and basalt application and how each of them will ensure enhanced weathering and drawdown of carbon emission, points out to existing research on the limiting factor and capacity of  $\text{CO}_2$  sequestration by the ocean, while also being cautious that without large scale experiments, it is unlikely for us to be sure of the effects on climate regulation in the long run.

**#systemsthinking**

Throughout our paper, we took an interdisciplinary, system thinking approach - we consider not only the weathering aspects to draw down the CO<sub>2</sub> necessary, but also its impacts on land and oceans, its impacts on the economy and so on with clear details and evidence to support our findings. For instance, we discuss the application of basalts in the soil instead of olivine despite olivine being the more potent CO<sub>2</sub> sequestration tool in the laboratory, because basalts is less likely to have harmful effects on the plants and may actually perform better given the pH conditions of acidic soil.

**#emotionaliq**

Context: When we started discussing this project, Anais mentioned that she had four finals due on week 15 so we anticipated that stress would arise. Due to this, we decided to start quite early and scheduled meetings into our Google Calendars according to the timeline we had chosen (as a nudge to have us stay on schedule). As well, since it was a dense topic, we knew that confusion could arise and was conscious that it could lead to frustration later on in the writing process. To prevent it from reaching this point, we did some preliminary reading before splitting our parts to ensure that we had sections we completely understood. Then we scheduled an office hour with the professor to ensure that we were also clear how to frame our LOs and HCs to prevent any frustration with each other at the end for not writing it the way the other thought we would. During the final writing process, stress still arose despite our mitigation efforts and Anais felt a bit of confusion about some of the content, leading to frustration with the assignment. To mitigate this, Ha forwarded some sources and we traded pieces of our sections leading to a smooth wrapping up of the writing process.

Application: We identified the emotions that were likely to arise and the secondary (and harder to deal with) emotion that stress and confusion would lead to. Thus, we implemented mitigation efforts and communicated clearly, allowing problems to be resolved quickly and eliminating the impact of these emotions on our paper.

### References

- Aggarwal, R., & Ranganathan, P. (2019). Study designs: Part 4—interventional studies. *Perspectives in clinical research*, 10(3), 137.
- Beerling, D.J., Leake, J.R., Long, S.P. et al. Farming with crops and rocks to address global climate, food and soil security. *Nature Plants* 4, 138–147 (2018).  
<https://doi.org/10.1038/s41477-018-0108-y>
- Brantley, S. L., Kubicki, J. D. & White, A. F. *Kinetics of Water-Rock Interaction* (Springer, New York, 2008)
- de Villiers, O. D. Soil rejuvenation with crushed basalt in Mauritius. Part I – consistent results of world-wide interest. *Int. Sugar J.* 63, 363–364 (1961)
- Gillman, G.P. (1980), The Effect of Crushed Basalt Scoria on the Cation Exchange Properties of a Highly Weathered Soil. *Soil Science Society of America Journal*, 44: 465-468.  
<https://doi.org/10.2136/sssaj1980.03615995004400030005x>
- Hartmann, J., & Kempe, S. (2008). What is the maximum potential for CO<sub>2</sub> sequestration by “stimulated” weathering on the global scale?. *Naturwissenschaften*, 95(12), 1159-1164.
- Hinsinger P, Barros ONF, Benedetti MF, Noack Y, Callot G (2001) Plant-induced weathering of a basaltic rock: experimental evidence, *Geochimica et Cosmochimica Acta*, Volume 65, Issue 1 Pages 137-152, ISSN 0016-7037.  
[https://doi.org/10.1016/S0016-7037\(00\)00524-X](https://doi.org/10.1016/S0016-7037(00)00524-X).

Hughlett, T. M. (2016). Sensitivity of the Younger Dryas climate to changes in freshwater, orbital, and greenhouse gas forcing in comprehensive climate models. Ph. D. Thesis.

Jian Feng Ma (2004) Role of silicon in enhancing the resistance of plants to biotic and abiotic stresses, *Soil Science and Plant Nutrition*, 50:1, 11-18,  
<https://doi.org/10.1080/00380768.2004.10408447>

Méndez-Rojas, M. A., & de la Rosa, L. A. G. (2018). Educational and Historical Aspects of Direct Synthesis of Metal Complexes. In *Direct Synthesis of Metal Complexes* (pp. 3-24). Elsevier.

Riebeek, H. (2011). The Carbon Cycle. Retrieved September 14, 2016 from: Retrieved from  
<http://earthobservatory.nasa.gov/Features/CarbonCycle/>.

Strefler, J., Amann, T., Bauer, T., Kriegler, E., & Hartmann, J. (2018). Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters*, 13, 3.

Schuling, R. D., & De Boer, P. L. (2011). Rolling stones; fast weathering of olivine in shallow seas for cost-effective CO<sub>2</sub> capture and mitigation of global warming and ocean acidification. *Earth System Dynamics Discussions*, 2, 551-568.

Schuling, Roelof. (2017). Olivine Weathering against Climate Change. *Natural Science*. 09. 21-26. <https://doi.org/10.4236/ns.2017.91002>.

Schuling, R. D., & Tickell, O. (2009). Olivine against climate change and ocean acidification.



ten Berge HFM, van der Meer HG, Steenhuizen JW, Goedhart PW, Knops P, et al. (2012) Olivine Weathering in Soil, and Its Effects on Growth and Nutrient Uptake in Ryegrass (*Lolium perenne* L.): A Pot Experiment. PLoS ONE 7(8): e42098.  
doi:10.1371/journal.pone.0042098