

Olivine against climate change and ocean acidification

R.D.Schuiling¹⁾ and Tickell, O.²⁾

¹⁾ Olivine Foundation for the reduction of CO₂. schuiling@geo.uu.nl

²⁾ Oxford Climate Associates / Kyoto2. oliver.tickell@kyoto2.org

Abstract

The weathering of calcium and magnesium silicates is the main natural mechanism limiting atmospheric CO₂ levels. The weathering process transforms CO₂ into bicarbonate, which washes down to the oceans where it ultimately precipitates as carbonate.

However weathering at its natural pace is unable to keep up with current and prospective anthropogenic CO₂ production. Thus we propose to mitigate excess CO₂ by increasing the rate of weathering: olivine, volcanic ash and similar silicate rocks should be mined, milled, and spread widely, mainly in the humid tropics where weathering rates are highest.

This may produce important additional benefits, reversing the acidification of soils, rivers and oceans, and enriching soils with mineral nutrients. Oceans would receive additional fluxes of orthosilicic acid, a limiting nutrient for marine diatoms: the consequent increase in diatom phytoproductivity could increase carbon fluxes to deep ocean, or support the production of biofuels in 'diatom farms'.

Carbon capture and storage (CCS) technology attached to power stations is currently being pursued as a solution to climate change. However CCS costs are estimated as \$50-\$100/t CO₂, while there are fears as to the long term security of reservoirs. Using accelerated rock weathering, by contrast, CO₂ could be securely and rapidly sequestered for about €10/t CO₂, while bringing benefits to agriculture and forestry, and restoring ocean alkalinity.

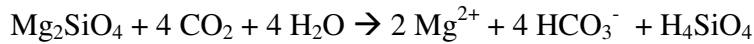
With key countries including India, China, Brazil, Indonesia and Canada rich in exploitable olivine deposits, international acceptance of CO₂ mitigation by accelerated weathering would advance the prospect of achieving an encompassing climate agreement.

Keywords: CO₂ capture, olivine, enhanced weathering, mycorrhizal fungi, diatoms, lugworm, nickel laterites, mineral nutrients, industrializing nations (Brazil, China, India)

Introduction

The world public is desperately looking for safe and cost-effective solutions to counteract climate change by reducing the CO₂ levels of the atmosphere. The solution proposed here is not new, but is literally as old as the world, namely to use olivine or similar rocks not in a technology, but in the way it works in nature. Weathering of calcium and / or magnesium silicate rock has kept the CO₂ content of the atmosphere within reasonable

bounds throughout geological history. Weathering is the neutralization of an acid (usually carbonic acid) by rocks, turning CO₂ into the innocuous bicarbonate ion in solution. For the abundantly available magnesium-silicate olivine, the reaction is as follows:



These bicarbonate solutions are carried by rivers to the sea, where they are ultimately deposited as limestones and dolomites. These carbonate sediments form the ultimate sink for CO₂. They contain 1,500 times more CO₂ than the amounts of CO₂ in biomass, atmosphere and dissolved CO₂ in the oceans combined (Table 1).

	Amount (x 10 ¹⁵ kg)	Relative amount (%)
Limestones (CaCO ₃)	35.000	46.6 %
Dolomites	25.000	33.3 %
Sedimentary carbon	15.000	20 %
Recoverable fossil fuels	4	0.005
Oceanic CO ₂	42	0.056
Atmospheric CO ₂	3	0.004
Biomass	0.056	0.0007
Anthropogenic emission	0.03 /year	
Input from Earth's interior	0.0025/year	

Table 1: Distribution of carbon on Earth. Modified after Dunsmore (1992)

It is proposed here to enhance the rate of weathering, and store the CO₂ as bicarbonates in solution. This will be a safe and cost-effective alternative to expensive and energy-intensive technologies. It can also deliver additional benefits to agriculture and forestry.

The approach

Mankind burns at considerable economic, social and environmental cost in a few hundred years the fossil fuels that have formed over hundreds of millions of years. Weathering cannot keep up with this greatly increased CO₂ production, and the atmosphere's CO₂ content is rapidly rising. Many of the most weatherable rocks are now covered by a thick weathering crust - called lateritic soils - which effectively prevents them from further contributing to CO₂ capture (Fig.1).

The preferred response to date has been to reduce the rate at which fossil fuels are burnt – in principle at least. However despite widespread agreement as to this objective, there has been little actual progress to this end (IPCC 2007, Prins & Rayner 2007). It therefore

makes sense to prepare to deploy 'geoengineering' solutions. As noted by the Royal Society (2009):

“The safest and most predictable method of moderating climate change is to take early and effective action to reduce emissions of greenhouse gases. No geoengineering method can provide an easy or readily acceptable alternative solution to the problem of climate change. Geoengineering methods could however potentially be useful in future to augment continuing efforts to mitigate climate change by reducing emissions, and so should be subject to more detailed research and analysis.”

Two broad families of geoengineering solutions have been proposed. First is to alter the Earth's thermal balance by reflecting more incident solar radiation out to space. Second is the direct removal of CO₂ from the atmosphere. Both approaches have their place but note that the first category does not address the serious issue of ocean acidification. Accordingly it would be unwise to rely on enhanced reflectivity alone.

Of the second category of geoengineering approaches, the most logical is to increase the rate of weathering (Schuiling & Krijgsman, 2006) since this is a natural process whose enhancement may be considered “benign in principle” (Royal Society 2009). This can be done by mining abundantly available and easily weatherable rocks, milling them and spreading the grains over the surface of the land or in shallow seas.

Another way of applying this approach is to inject CO₂ into peridotite rocks that are rich in the easily weatherable olivine (Schuiling, 2006b, Kelemen & Matter, 2008). The heat of reaction is considerable, and this may help to crack the rock thermally, and increase the rate of reaction. It has even been proposed (Schuiling, 2006b) to recover the heat of reaction from large and thermally well isolated olivine reactors at locations where a point source of CO₂ is available.

In order to capture CO₂ from such point sources, it has been widely proposed to construct 'Carbon Capture and Storage' facilities at power stations, cement factories and other concentrated sources of CO₂. These CCS facilities would chemically remove CO₂ from the exhaust gas stream and pump it into underground reservoirs such as depleted gas fields and saline aquifers. However there are concerns as to:

- the high cost of operating CCS;
- the additional fuel that needs to be burnt for a given electrical output;
- the security of these reservoirs in the long term.

Sequestration of CO₂ as oceanic bicarbonate and carbonate rock is far more dependable and can be achieved, our calculations suggest, at considerably lower cost

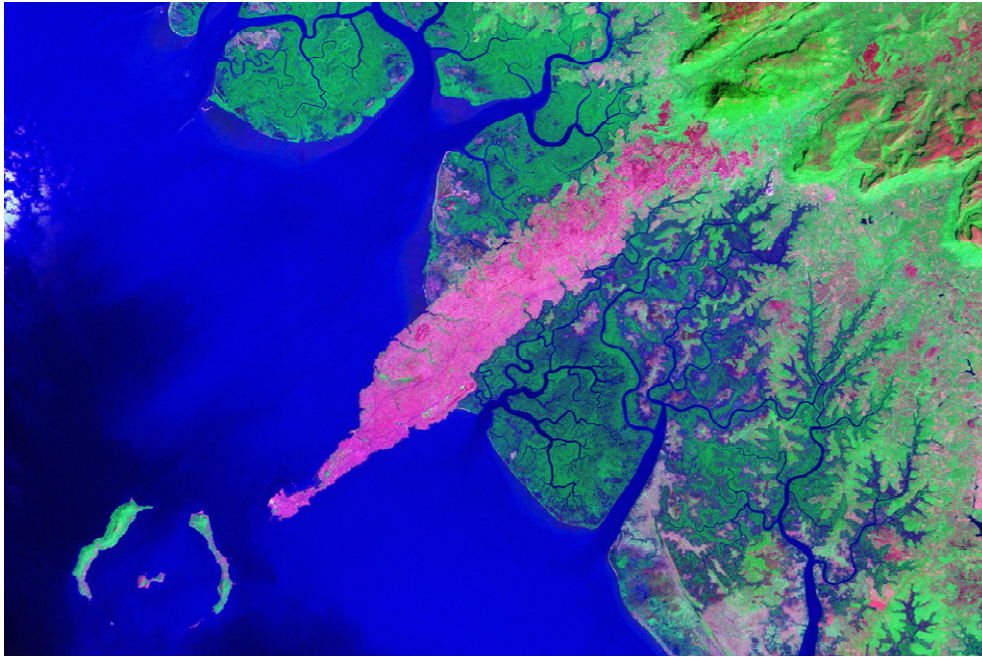


Figure 1: The dunite at Conakry, Guinea, is covered by a thick laterite crust.

	Fe %	Cr ₂ O ₃ %	NiO %	P ₂ O ₅ %	SiO ₂ %	Al ₂ O ₃ %	MgO %
A layer	53 (49.6)	1.7 (1.0)	0.15 (0.06)	0.2 (0.7)	1.5 (3.8)	9.0 (11.2)	nil (0.18)
C layer	57 (49.8)	0.4 (1.5)	0.4 to 0.5 (0.7)	0.05 (0.05)	2 (3.9)	3 to 4 (7.7)	nil (0.36)
Conakry Olivine	12.5	0	0.3	n.a.	39.2	n.a.	43.9

Table 2: Chemical composition of the Conakry laterites. Results of 2 samples taken in 2008 by the author near Mount Kakoulima added in parentheses. Olivine analysis by microprobe at the Institute of Geosciences, Utrecht.

The example of the dunite body at Conakry, Guinea is illustrative. It stands out in pink color on the satellite image (Fig.1) as an elongated body of 50 by 5 km extending from the tip of the peninsula in a northeast direction. The laterite cover is between 30 and 100 meters thick (Golightly, 1981). The underlying dunite consists for 80 to 85 % of MgO and SiO₂, but these elements are virtually absent in the laterite. (Table 2, Percival, 1965 and own analyses)

This means that 1 meter of the weathering residue is at least equivalent to 10 meters of source rock. This ratio will be even larger if there has been some erosion, or if some of the iron has also been removed in solution, along with magnesium and silica.

Percival (1965) presents convincing evidence that some erosion has indeed taken place, and that iron was fairly mobile and was partly leached out. The dunite intrusion is dated at 195 million years before present (Deckart et al., 1997). This permits us to calculate a *minimum* rate of weathering. 50 Meters of laterite are equivalent to 500 meters of dunite. Five hundred meters equals 500 million microns, divided by 195 million years is 2.5 micron/year.

This is already considerably faster than indicated by laboratory data from abiotic chemical-only experiments, which show rates of weathering of a few tenths of a micron. The real rate of outdoor weathering must have been considerably higher, for the following reasons:

- 195 million years is the age of the *intrusion*, so even if the rock was intruded at a shallow depth of 3 km, it must have taken a hundred million years before erosion had completely exposed the dunite at the Earth's surface, assuming an average erosion rate of 3 cm/1000 years for the African continent. This number is corroborated by data for the sum of dissolved and suspended loads transported by rivers from the continent, and the rate of sedimentation in the ocean basins. Only after denudation could it begin to weather.
- The dunite is now covered by a laterite crust of ~50 meter, which effectively shields it from virtually any interaction with CO₂ and water, so the average rate of weathering must have been much higher earlier in its history.

A conservative estimate is that the rate of weathering must have been at least 10 microns / year. This, however, is for a solid rock, with a 2-dimensional front of attack for weathering. In the case of loose mineral grains, which are attacked by soil solutions from all sides, we must double the rate of weathering to 20 microns/year.

A similar result is reached for the dunite in the Jacupiranga complex in Brazil (Oliveira et al., 1988). The dunite intrusion is overlain by a lateritic caprock of over 40 meter thickness. The age of the intrusion is 130 million years. Here again some of the major elements from the dunite have been completely leached out during weathering. Assuming again that 1 meter of laterite represents at least 10 meters of fresh rock, the minimum weathering rate for the solid rock should have been 3.1 micron/year, but again, this number should be increased for the same reasons as the preceding example from Guinea, namely that at the time of its formation the intrusion was not yet exposed to weathering, and that under its present cover of > 40 meters, weathering must have come to a virtual standstill. This indicates that weathering of loose olivine grains in a tropical soil proceeds at least at a rate of 20 microns / year.

Another astonishing example of rapid and massive weathering comes from olivine-rich mining wastes in Canada (Wilson et al., 2009). They find that the tailings of some

ultramafic-hosted chrysotile mines weather fast, producing a host of newly formed magnesium carbonate minerals. One of the mine dumps has captured at least 82,000 tons of CO₂ in less than 20 years. This amount is exclusive of the magnesium bicarbonate solutions that have been emitted by the dumps. Evidence for this is the abundant growth of diatoms in the pit lake at one of the localities, caused by the silica-rich waters that are formed during olivine or serpentine weathering. The lead author (Wilson, pers.comm., 2009) confirmed that both tailing dumps showed evidence of seepage through the tailings of water with a high pH. Wilson et al. conclude that the annual sequestration of CO₂ at a large mine hosted in olivine-rich rocks can easily exceed its annual emissions of greenhouse gases. A similar observation was made by one of us (RDS) on the tailing dumps of the abandoned asbestos mine at Amianthos/Cyprus. Water, passing through the tailings, had a pH value of 9.04, and a bicarbonate content of 392 mg HCO₃⁻/liter. At an estimated outflow of 500 liter/minute, this means that this small brook, draining less than 1 km² captures annually 75 tons of CO₂, without requiring any human intervention.

What causes this discrepancy between weathering rates as measured under abiotic conditions in the laboratory as compared to the real world, where the weathering rates are 10 to 100 times faster? Laboratories are (hopefully) free of fungi, but fungi and lichens play an important role in the dissolution of minerals. Higher plants live in symbiosis with mycorrhizal fungi. These secrete an acid and chelating agent that rapidly attacks mineral grains. The mineral nutrients that are liberated by the fungi are taken up by the plants that 'reward' the fungi by providing them with sugars.

This is a major reason why laboratory measurements of dissolution rates of minerals are irrelevant to obtain rates of weathering of minerals in tropical soils. Fig.2 shows fungi in the process of digesting a mineral grain (van Schöll et al., 2008)

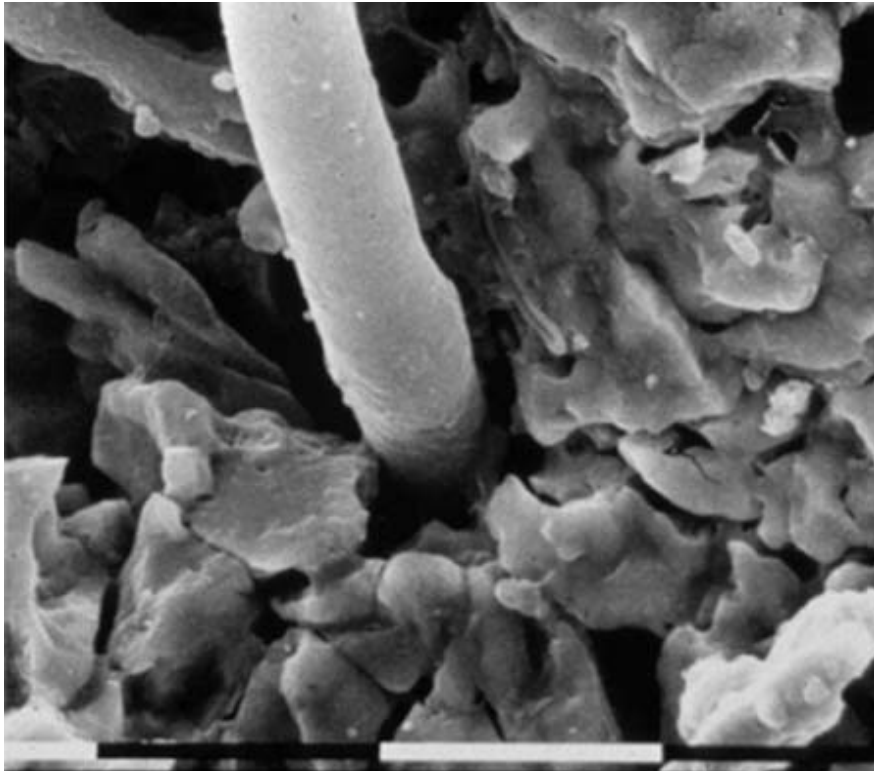


Figure 2: Scanning electron micrograph showing a fungal hypha penetrating a mineral grain (bar size, 10 μm). With thanks to van Schöll et al., 2008.

Lichens are also able to attack rock surfaces, by secreting oxalic acid (Wilson et al., 1981). Initial products are Mg-oxalates and a gel-like silica substance.

Weathering and climate

It has been claimed by Raymo & Ruddiman (1992) that the rapid exposure of large volumes of fresh rock in Eocene times in the Himalayas and the Tibet plateau has caused an enhanced weathering coupled to decreasing CO_2 levels of the atmosphere. According to these authors, this has led to a gradual global cooling, and ultimately to the onset of the current Quaternary Glaciation, approximately 2.5 million years ago.

A very similar conclusion was reached by Saltzman and Young (2005) who explain the late Ordovician glaciation by the uplift of the Appalachians, which increased the area of fresh exposed rocks, and the resulting decrease in atmospheric CO_2 levels. In a later paper (Young et al. 2009) the authors discuss the role of increased volcanism. Briefly summarized, while during the most active period of volcanism CO_2 emission levels and increased weathering of volcanic rocks more or less balanced, after the end of the period of active volcanism the huge volumes of fresh volcanic rock captured huge volumes of CO_2 , lowering its atmospheric level and causing a new glaciation period.

In a small way we can do the same by exposing large volumes of fresh rock to the elements, but the advantage is that we are in the position to select the most suitable rock types, and the most favorable climates for weathering. Olivine-rich rock types like dunites that occur in large massifs in a great number of countries, are the most suitable.

A world map (Fig.3) shows the distribution of dunite massifs. By removing their lateritic overburden, mining the underlying dunite (a rock that consists of > 90% olivine), grinding the rock and finally spreading the olivine grains in a thin layer over the surface of the surrounding land, large volumes of CO₂ gas can be captured as bicarbonate in solution.

When the olivine grains are plowed under, the weathering rate is further enhanced, because the soil atmosphere is on average hundred times richer in CO₂ than air (Schachtschabel et al. 1982, Sumner, 2000). This is due to the fact that plant material is decaying, and soil fauna is breathing, both increasing the local CO₂ content. As the CO₂ level of the atmosphere has been rising, it is likely that the pace of weathering has already increased in recent years.

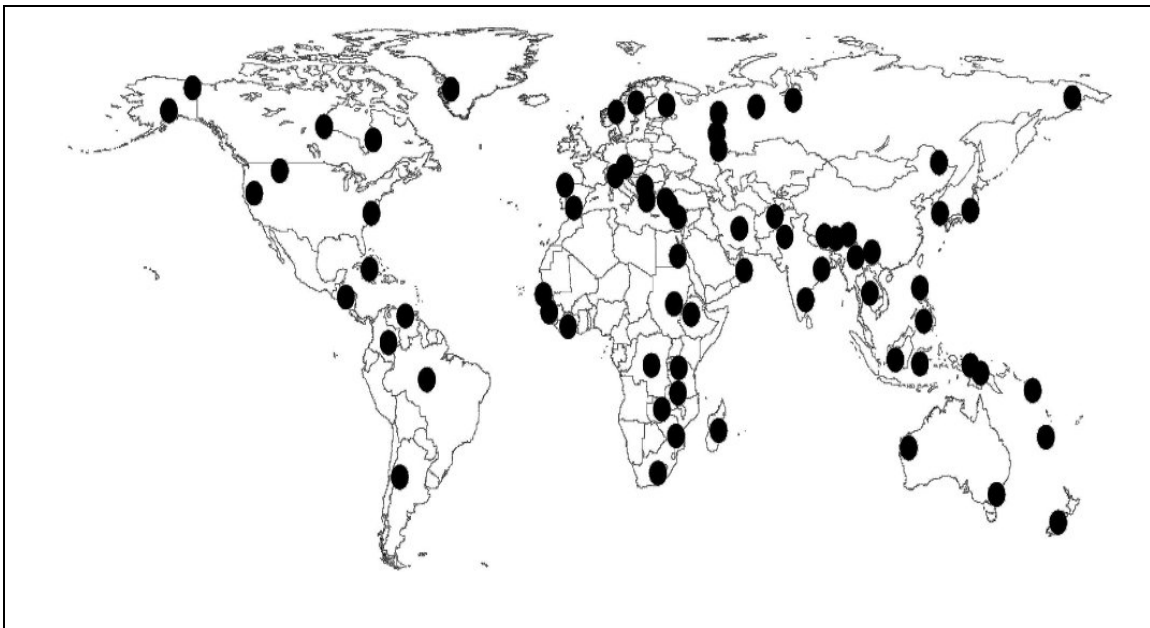


Figure.3: Distribution of dunites in the world. One dot often represents several dunites.

Because most tropical soils are very poor in mineral nutrients, including magnesium, the addition of fine magnesium-silicate grains will be a bonus to the local population who lack money to buy fertilizers.

There will also be a case for the use of other rocks beside olivine, based on local considerations, even where they are less efficient CO₂ captors on a per ton basis. Factors influencing the use of such rocks would include:

- the local availability of rock, reducing transport costs and energy inputs, while also creating local employment;
- the consistency of rock – friable rocks or deposits already in powder form (such as volcanic ash deposits) would reduce or eliminate the need for milling, reducing costs and energy input;
- the presence of other mineral nutrients in rock – where local soils would be improved by the addition of those nutrients.

Considering the last point, the presence of other mineral nutrients besides magnesium, it is worthwhile to make maximum use of the pulverized host-rock of diamonds, a rock called kimberlite. In addition to olivine, kimberlites contain the mineral phlogopite, which carries potassium as a main component. Unfortunately, diamond mines are considerably less abundant than normal dunite rocks. It has been shown that nesquehonite forms in the tailings of the Diavik diamond mine (Wilson, 2010). Its carbonate has been dated by ^{14}C and turns out to be recent, meaning that it is derived from atmospheric CO_2 .

In addition to mineral nutrients, it is also advisable to add biochar (Lehmann, 2007, Reinders, 2009) particularly on plantations. This pyrolyzed product, a form of charcoal, can store carbon over medium long times, and adds considerably to the fertility and water- retaining capacity of the soil. However note that Reinders and others have voiced doubts about the net greenhouse gas emissions associated with the biochar life cycle.

In order to make this macro-engineering approach work, a number of large open pit olivine mines must be started in different countries, and principally in the tropics. This has the following advantages:

- Weathering is most rapid in humid tropical climates.
- To reduce transport costs, distances from the mine to the point of use should be limited to < 300 km.
- Large mines (> 100 million tons/year) profit from the economy of scale
- Wages in developing countries are low, so mining is relatively cheap.
- It will bring employment for millions, and boost the economies of developing countries.
- Some dunites contain sub-economical contents of chromite, nickel or platinum minerals. By mining them for olivine, it may become economical to recover these by-products as well. This holds also for kimberlites, the host rock of diamonds, where marginal diamond grades may become economical, if the rock is mined and crushed to spread kimberlite.

Many of the lateritic cap rocks of dunites are rich in nickel, and these nickel laterites are mined in a number of countries (e.g. New Caledonia, Philippines, Indonesia, Cuba, Brazil). Nickel laterite mines are favorable locations to mine the underlying dunites as well. It will minimize the ecological damage because it will not be necessary to clear forest to start a new mine, and the infrastructure required for mining is already in place.

Maximum use should also be made of the tailing dumps of existing or abandoned mines in olivine-rich rocks. Such mines include nickel, chromite, PGE-elements, magnesite, asbestos and diamond mines. All these commodities are hosted in olivine-rich rocks, which makes these mine dumps attractive targets for cheap CO₂ removal.

Collateral benefits

If farmers, foresters or fishermen experience direct benefits from olivine spreading, they will be more prone to collaborate. In the preceding section we have mentioned already a few possibilities, like spreading a mineral dust with a broader compositional range than only olivine, in order to provide a balanced mix of mineral nutrients. This would be similar to the effect of volcanic dust. As Buttram (1914) said:

“It is a well known fact that volcanic dust is an excellent fertilizer. Wherever this dust has spread over an area with an average rainfall there is a very abundant and prolific vegetation. Along certain parts of the Rocky Mountain plains and over scattered areas of the Great Basin the country in places is literally covered with volcanic dust, and wherever this volcanic soil is subject to irrigation no better or more fertile soil can be found. The very beauty of Java, the 'garden spot of the world' is due to the rich, fertile soil formed largely from volcanic dust and other eruptive matter that have fallen over the island at different periods in former volcanic eruptions.”

On a joint expedition in Kenya, Dutch soil scientists told the first author that they had observed a similar positive response of soils and crops to volcanic ash falls in East Africa.

There is thus a role for Ca/Mg/Na/K aluminosilicates to be used for combined CO₂ drawdown and soil improvement on farmland, forests and plantations as they will provide a richer mix of mineral nutrients. Suitable rocks include anorthosites, basalts, zeolitized tuffs, volcanic ash and kimberlites, the choice depending on their local availability. Chalk is also often mentioned, but after the calcium reprecipitates, the net CO₂ effect is zero. Zeolites or zeolitized tuffs are particularly useful because they can be loaded with ammonium, which will be slowly released, and they improve the water retention capacity of the soil. Soils over kimberlite pipes are also fertile. As noted by Alexander and Shrivastava (1984) “The entire tree layer over the pipe area is characterized by a more healthy growth of several species than over the country rock”.

Olivine can also help to buffer the pH in acid sulfate soils as found in the Mekong delta, or in estuarine inlets in Eastern Australia. This will boost their rice and sugar production. At the same time the ambient acidity will, in general, cause the more rapid weathering of the mineral particles.

This approach can be extended to forest soils that are often acid and poor. Many boreal and temperate forests are suffering from tree dieback associated with acidification and

demineralization (Klinger 1996, Klinger & Zingaro 2006). Olivine dust, mixed with aluminium-silicates, may be spread over the standing forest. The process will be most easily carried out in planting new forests or in replanting logged areas. The result will be to enhance forest growth, raise wood production and improve the health of trees. Note that faster tree growth also creates benefits in the drawdown of atmospheric CO₂.

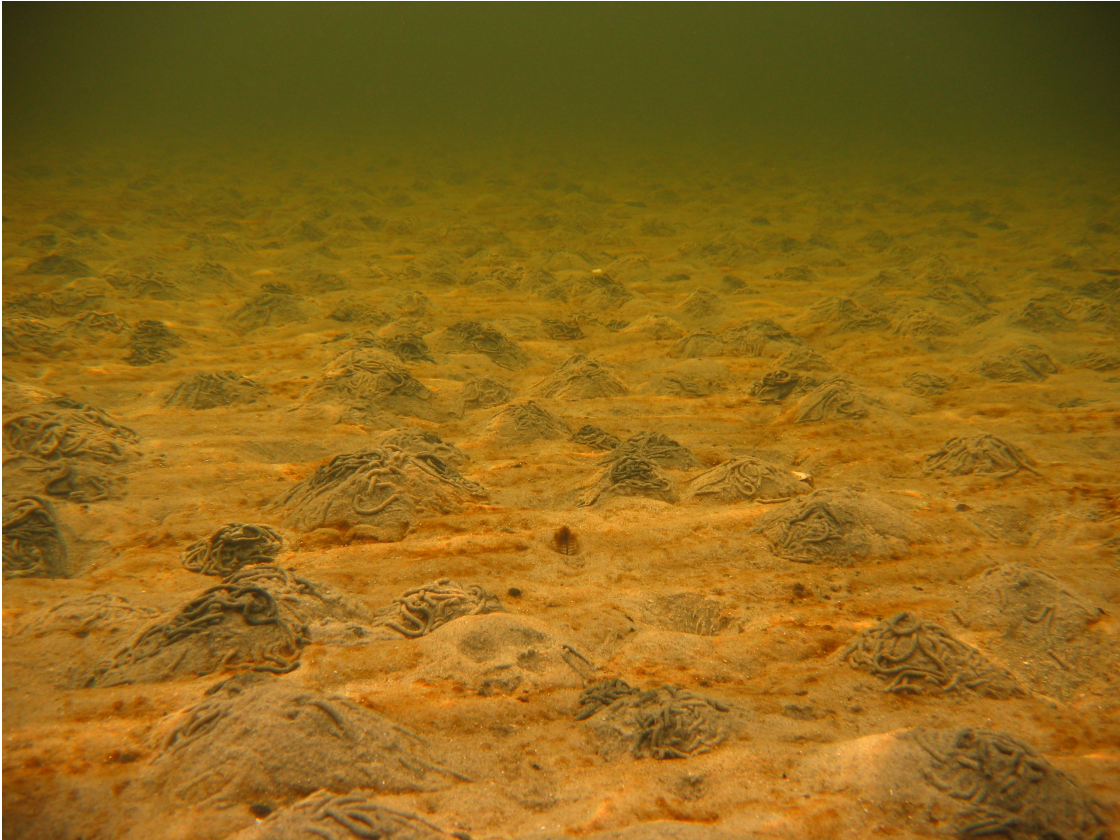


Figure 4: Underwater picture of a lugworm field. The upper few centimeters of the mud pass the guts of the lugworm on average three times a year.

Along coasts the use of olivine dust can have great advantages. It was found that the top few cm of tidal flats pass each year around 3 times through the guts of the lugworm (*Arenicola marina*, Fig.3). Mineral grains weather up to 1,000 times faster during the digestion by lugworms (Needham et al. 2006, Worden et al. 2006). When we spread a thin layer of olivine dust over tidal flats, this may become a significant contribution to carbon capture, not only directly, but also by increasing the living biomass

The solutions that are produced by the digestion of olivine grains are rich in silica, which is a limiting nutrient for diatoms – which have a silica skeleton (Fig.5). When silica becomes available in larger quantities, the diatom population will increase, providing food for fishes and birds further up the food chain.

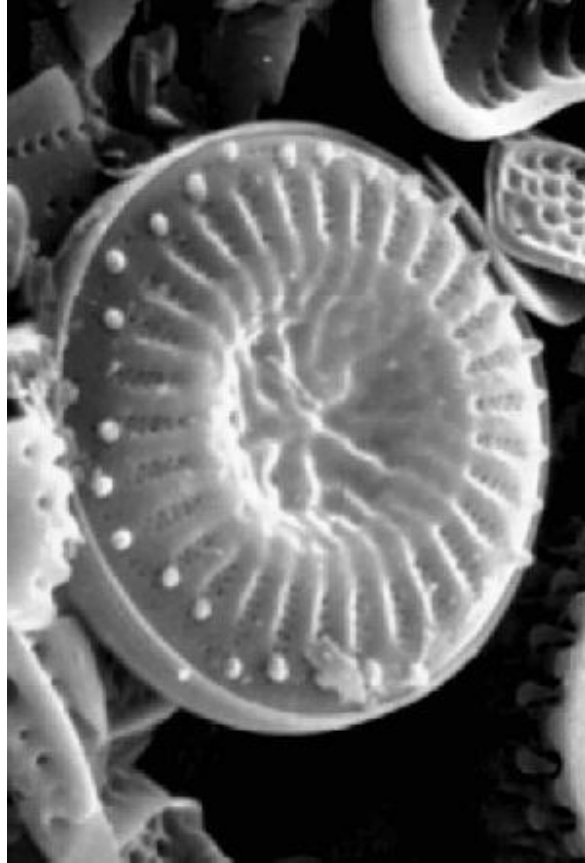


Figure 5: Diatoms have a silica cell, and are rich in lipids.

It has also been reported (Smetacek, 1985) that the large scale sinking of oceanic diatom blooms is responsible for the transfer of considerable volumes of geological and biological material into deep ocean – a possibly important mechanism of carbon sequestration. The enhancement of oceanic silicate may create an additional synergistic benefit in reducing atmospheric CO₂. This is a potentially important effect but has not, as yet, been adequately characterized.

This could also be used for the industrial production of diatoms in 'diatom farms' – artificial lagoons separated from the sea by a bar of olivine sand. We can introduce silica-rich solutions derived from the weathering of olivine on one side of the lagoon. These solutions could be from a CO₂ capture technology. It is also possible to deposit a thick

layer of olivine grains on the beach along the lagoon, and let sea water infiltrate into that layer during high tide, and be drained during ebb tide.

If we were to make a U-shaped tube through the sand bar on the other side, connecting the lagoon with the sea, we could operate such diatom farms as follows. When the nutrient limitation for diatoms is eliminated by providing silica-rich solutions, the diatoms will have a competitive advantage over other organisms and their population will rapidly increase. If a plankton net is mounted in the U-tube on a perforated metal support, during ebb the diatoms will be carried outward to sea, but will be retained on the plankton net, and can be harvested mechanically. During the following high tide, seawater will surge into the human-controlled lagoon, and bring a small but sufficient supply of other required nutrients.

Diatoms are rich in lipids, and the technology to convert these to biofuels is well known (Bozarth et al. 2009, Dismukes et al. 2008, Hu et al. 2008). It is claimed that diatoms produce more lipids when they are nitrogen-starved, or more generally when they are in stressful conditions.

Contrary to land-based biofuel crops, the production of biofuels from marine diatoms does not compete with human or animal food production, nor does it require large quantities of irrigation water. Indeed the phenomenon of diatom fertilization by silica enrichment could stimulate marine fish productivity and help maintain supplies of this important and nutritious foodstuff.

Spreading: it is an ill wind that blows nobody any good

A major part of the olivine operation will involve cost-effective, low-impact transport and spreading of olivine over land or shallow sea. This is the reason why a maximum distance of 300 km from the mine site to the point of use is recommended.

Classically one would think of trucks transporting the olivine inland, where it will be distributed either as grains by machinery that also spreads fertilizer, or as slurries mixed with pesticides. However transport by truck will significantly contribute to the cost, so one should also make good use of location-specific opportunities. In cases like Guinea, rail transport inland offers a good possibility, as two railroads for bauxite transport from the interior pass close by the likely location for a future olivine mine. The empty trains can carry loads of olivine inland on their return from the port at the tip of the peninsula. (Fig.1)

Most of the new olivine mines will be in the wet tropics. This means that they will often be situated in an area rich in rivers and creeks. It may be possible, then, to load barge-type boats with olivine, mount a pump on each boat and spray the passing river banks with an olivine slurry. The boats could also be used to transport loads of olivine more cost-effectively than by truck. If olivine is transported by barge-boats, transport distances are less critical than with trucks.

For olivine mines situated inland well above sea level, one can await a time in the wet season that the rivers are swollen and have burst their banks after heavy monsoon rains. The rivers carry heavy silt loads, up to $7 \text{ kg} / \text{m}^3$ in the rainy season, and this is the perfect time to release large volumes of olivine particles in the river. When the peak flow reaches the low lands, the olivine grains will spread and mingle with the other overbank sediments at no further costs.

Mindful of the saying “It's an ill wind that blows nobody any good”, we can also think of the following unusual use of climatic conditions. Over a large part of sub-Saharan West Africa, the harmattan blows in the period November till mid-March. The harmattan is a hot sandstorm originating in the Sahara, and carrying large volumes of mineral dust, sometimes limiting visibility to less than 45 meters. At the olivine mine sites, or on top of hills nearby, one could mount large vertical tubes and blow olivine powder into the air during sandstorms.

Each sand storm transports several million tonnes of dust, so an addition of olivine grains on the order of 1 % of the total dust load will make no difference for dust content and visibility. This will be a very cheap way of olivine spreading by which one can save around 1,500 truck transports during a single sand storm. In North Africa one can profit similarly from the haboobs, severe sandstorms that may last a few days and throw up a wall of dust (Oliver 2005).

A further approach to spreading olivine is to incorporate it into animal feeds, and fertilizers or soil improvers intended for use on acid soils. The olivine would then be spread to the land during fertilizer application and ‘muck-spreading’. Such methods could be widely employed where farmers perceived benefits in the health and productivity of their crops and animals.

Volumes and costs

In order to compensate the complete anthropogenic emission of CO_2 by olivine, 7 km^3 of olivine must be spread each year on appropriate regions of the Earth's tropics and oceans. Distributed over 10 million km^2 , this is equivalent to a layer of 0.7 mm. The rate of weathering of olivine in tropical climates is around 10 to 20 microns per year, so olivine grains with a diameter of 100 micron will dissolve in around five years.

For logistical reasons it will be more favorable to spread a layer of 3.5 mm in the first year over 2 million km^2 , then move to the next 2 million km^2 , and so on, and come back to the first 2 million km^2 after a lapse of only five years. One can even think of adding a thicker layer of 1 cm to an area of 700.000 km^2 , if this brings considerable savings. Considering the fact that weathering rates of more than 4.000 times average weathering rates were found on mine tailings of olivine rocks in Canada (Wilson et al., 2009), one could also construct piles of olivine, similar to mine dumps over much more restricted areas, preferably in conjunction with phytomining their elevated nickel content.

In this scenario for geoengineering the climate, olivine must change from a minor commodity into the third largest sector of mining, after construction materials and coal.

The proposed scale of olivine mining is large but within the range of modern mining operations. The largest open pit mine (the famous copper mine at Bingham, Utah in the USA, opened in 1904) for example has an excavated volume of 25 km³.

As well as spreading on land, olivine grains can also be applied in the tidal zone along seacoasts. As the olivine grains are abraded in the surf, they will rapidly capture CO₂, also contributing to the restoration of the pH in the oceans while adding bicarbonate to the sea water – required for the healthy, normal growth of corals such as Australia's Great Barrier Reef.

Crushed olivine in bulk from a small mine in Greenland costs 23 € / ton in the port of Rotterdam. It is expected that the cost of olivine will drop below 15 € / ton for large mines in low-wage countries and limited transport distances. The cost per ton of CO₂ will then be around 10 €/ton, as one metric ton of olivine captures 1.25 tons of CO₂. This compares very favorably with the cost of CO₂ capture by CCS, which is 60 to 90 € / ton according to a recent report by McKinsey & Company (2008).

The total CO₂ expenditure of the whole olivine operation (mining, milling and transport) has been calculated to be 4% of the amount of CO₂ that is captured by that olivine (Koorneef & Nieuwlaar, in prep.). The cost of mining, milling and grinding of 1 ton of rock in large scale mining is estimated by Steen and Borg (2002) to be about 6 Euro/ton. If average transport costs can be limited to a similar amount, the price per ton of CO₂ will drop to 10 Euro or slightly less.

Intermezzo

It is widely supposed that one has to capture the CO₂ from the flue gases of coal-fired power plants, cement factories or oil refineries. This is misconception. All molecules of CO₂ are identical, so one should aim for the most economical way to capture as much CO₂ as possible *anywhere* in the world, independent of location or origin. The atmosphere is a well mixed reservoir, so capture of CO₂ around a dunite mine in a tropical country reduces the CO₂ level of the entire atmosphere of Earth just as much as capturing the same amount of CO₂ from the flue gases of a power plant in Western Europe.

Implications for climate policy

Many nations, like China, India and Brazil, are reluctant to join international efforts to limit CO₂ emissions. As these nations have large reserves of olivine rocks on their territories, their resistance to join is likely to diminish, as the cost of joining will be considerably less than with CCS, and they can more easily participate to solve their emission problems by using their own resources and manpower.

It may also be possible to seek the inclusion of CO₂ abatements arising from accelerated weathering in the flexibility mechanisms of the Kyoto Protocol or a successor climate agreement, to offset emissions from Annex 1 industrialized countries. For example, countries, landowners or other parties could create carbon credits such as Certified Emissions Reductions (CERs) under the Clean Development Mechanism in this way.

This approach would need to be backed by a robust methodology backed by appropriate experimentally derived scientific evidence. However there is little difference in principle between this and the capture of CO₂ in growing trees, which is already acceptable under the CDM. Indeed the main difference is that the ultimate geological deposition as carbonate of the CO₂ captured by olivine weathering is far more secure than the storage of carbon in trees.

There are already several olivine mines operating in China. Brazil has a number of lateritic nickel mines in the weathering crust above large deposits of olivine rock. So for Brazil, mining is a matter of continuing to mine the underlying olivine rock after the nickel laterite crust is mined out: the mining infrastructure already in place; no new mining sites need to be cleared; and employment is extended for people who may depend on a working mine site for their livelihoods.

India can likewise profit from the fact that their chromite mines in Orissa are hosted by olivine rocks: they can use the huge volumes of already crushed olivine rocks lying on their mine dumps and tailings. India has many dunite deposits, among others in the Kolar and Chittadurga greenstone belts in South India (Devleena Mani et al, 2008), and in the Chalk Hills near Salem.

The choice

Contrary to general supposition, solving the anthropogenic climate crisis does not automatically require the development and use of new technologies. Moreover even the rapid and effective deployment of new technologies in, for example, renewable energy production, energy efficiency and CCS may not lead to sufficiently deep or rapid reductions in atmospheric CO₂ to prevent serious adverse impacts on climate, sea level and ocean acidity.

We may therefore make use of Nature's own technology which has been in operation since the dawn of time and which has always played the major role in the sustainable capture of CO₂. This concept has first been proposed under the title "Let the Earth help us to save the Earth" to the Virgin Earth Challenge (Schuiling, 2007). It makes use of the process of chemical weathering of calcium and magnesium silicates.

Even when researchers have considered olivine or similar rock-types, they have typically coupled it to a technology (Huygens & Comans, 2005). These include technologies to activate the olivine surface by thermal or chemical treatment, or to subject the olivine grains to high temperatures and pressures in industrial autoclaves with chemicals added,

or to calcine serpentine. However such operations add to the costs, are energy-intensive and make these solutions unsuitable to solve a global problem.

Kelemen & Matters' idea (2008) of using the olivine rock *in situ* to inject CO₂ comes close to a natural solution. The idea was first published by Schuiling (2006 b), who had also calculated the heat of hydration of olivine (Schuiling, 1964). A large heat of reaction is important, because it will enhance the rate of reaction. However our considered view is that such operations are relatively expensive, energy-intensive, and unsuitable to solve a global problem, although they may be feasible where a large coal-fired power plant is situated at close distance from a dunite massif, like near Orhaneli, NW Turkey.

The olivine mining and spreading option is a simple idea, but its implementation is certainly not simple or inconsequential. It will:

- require a global and evenly distributed system of 30 to 50 new olivine mines in the wet tropics, from New Caledonia to Brazil.
- cause a dramatic shift in the mining sector, moving olivine from a minor commodity into third place behind construction materials and coal.
- involve the spreading of olivine grains over large areas for a number of years, as well as the monitoring of these operations.

Technology-based options to solve the climate crisis and associated problems are likely to cost of the order of US \$1,000 billion per year (Tickell, 2008). However even rapid reductions of CO₂ emissions may nonetheless leave the climate on a trajectory of increasing warming. It is prudent to explore geoengineering options to deal with this possibility, however existing approaches may have deleterious side effects, and few if any collateral benefits. In particular geoengineering proposals that rely on raising the solar albedo, causing the increased reflection of solar radiation, do not address the problem of rising soil and ocean acidity.

We are therefore well advised to include the olivine option among our responses to climate change. On the basis that the entire excess of anthropogenic CO₂ in the atmosphere could be neutralized via the olivine option for US \$250 billion annually this is a low cost approach to solving the climate crisis, while also bringing significant collateral benefits to soils, forests, agriculture and ocean ecology. The resulting diatom fertilization with silica can also be expected to increase the benefit, by an as yet unknown factor.

Constraining factors

The principal constraint on the scale of accelerated weathering that could be put into effect is environmental. The widespread distribution of olivine powder will have impacts on terrestrial, riverine / lacustrine, and marine environments. Practiced with good sense and discrimination, the impacts will generally be positive. However we need to characterize the impacts in specific areas before proceeding to large scale deployment, and to be sensitive to the environmental limitations which apply.

Biodiversity must be a principal consideration. Some important ecosystems are adapted to acid conditions, and if the acidity is reduced acid-adapted communities will suffer. Olivine should not be applied on important examples of acid-adapted ecosystems in any region in order to conserve their biodiversity. Similar considerations apply to rivers and lakes where reduced acidity will also affect the ecosystem balance. However we note that the problem that is currently widely experienced is acidification and accompanying nutrient depletion. Application of olivine powder will counter this serious existing environmental assault.

Another impact highlighted by Lee Klinger (pers.comm 2009) is that conservation of biological carbon in peatlands depends in part on their acidity. The spreading of basic silicate rock powder on peatlands would therefore be expected to induce the breakdown of the peat and cause potentially large scale release of CO₂ and methane. Application of olivine in peatlands should therefore be avoided.

There are also limits to how much bicarbonate rivers and lakes can accommodate. As a general guide, we consider that the pH of river waters should be limited to <9. But at this pH, can the rivers of the world carry the required bicarbonate load? In a paper to be submitted soon (Köhler et al., 2010), it is concluded that the maximum carrying capacity of the world rivers will be exceeded if all the human emissions of CO₂ are compensated by enhanced weathering.

This can be deduced from the consideration of the compositions of natural waters issuing from olivine rocks (Fig. 6). This graph represents a number of water analyses of springs in dunites (olivine-rich rocks) (Schuiling and Praagman, in press). It can be seen that the CO₂ contents can rise to over 500 ppm, whereas the pH of all these waters was between 7.6 and 8.6. If we accept 500 mg / liter as an upper limit, the world's rivers, discharging 3.6×10^{16} liters annually, could transport 18 billion tons of CO₂ as bicarbonate, whereas they would need to transport almost 30 billion tons if enhanced weathering were to compensate the totality of human CO₂ emissions.

The large volume of additional magnesium-bicarbonate reaching the oceans will also have an impact. This impact appears likely to be benign, given that ocean waters are currently suffering from acidification, and that anticipated future CO₂ emissions are expected to raise the acidity of oceans to dangerous levels with severe implications for coral reefs and a multitude of organisms that build carbonate shells. Under the (unlikely) assumption that over the next 100 years all anthropogenic CO₂ emissions will be compensated by olivine weathering, and that all the resulting solutions will reach the oceans, the Mg-concentration will change from 1296 to 1296.8 ppm and the bicarbonate content from 42 to 45 ppm. Both changes are within the normal range of ocean water compositions. As for the silicic acid that is also formed by the weathering reaction, one anticipated result is to extend the lifetime of diatom blooms, at the expense of dinoflagellate blooms. Such a biotic shift would probably be benign from a climatic point of view, causing an increased drawdown of atmospheric CO₂ and diminishing the risk of red tides. The wider implications of such a shift in ocean chemistry and biology need to be carefully considered.

We therefore need to consider how we can put into practice a large scale program of enhanced weathering of olivine, while operating within environmental constraints. Thus:

- Olivine powder should also be spread on tidal flats, beaches and in the high-energy environment of coasts. In this way the weathering products will reach the sea immediately, without requiring rivers as an intermediate storage.
- Although spreading in the humid tropics is optimal for maximal weathering, we will also need to spread olivine in temperate zones and in areas of lower rainfall where the sequestration of atmospheric CO₂ will take place more slowly.
- Part of the weathering, particularly in dry climates, should end with the formation of solid carbonate minerals (such as magnesite, nesquehonite and lansfordite), as observed in mine dumps of former asbestos mines in Canada (Wilson et al, 2009).
- It may be useful to construct vast artificial “mine dumps” (flat hills of crushed olivine, mixed with broken nickel laterite, occupying small areas) which will absorb large volumes of CO₂ while at the same time serving as sites for phytomining of nickel.
- CO₂ may be directly injected into dunitic or basaltic formations.

If we adopt such measures, enhanced weathering in its different forms would be able to solve the problem of anthropogenic climate change, particularly if combined with the spreading of biochar. This should be seen, however, as an ultimate solution, but it is better to diminish our dependence on fossil fuels, thereby reducing emissions. The development of green energy, or at least energy production without CO₂ emission should be prioritized, in combination with a large array of measures to make the transition to a less wasteful way of living. These developments will be largely the responsibility of the industrialized nations, whereas industrializing nations should benefit longer from the advantages of cheap energy from coal. As the most populous nations of this group (China, India and Brazil) also possess huge reserves of olivine, it will be more attractive for them to compensate their emissions by using their olivine reserves than to cut their emissions, thereby curbing their economic development. No less important is the reduction of land-based emissions from deforestation, land clearance, peatland degradation and the oxidation of carbon in soils, and the enhancement of terrestrial carbon sinks by ecosystem restoration and improved agricultural practice.

Conclusions

Enhanced weathering holds a great promise to solve the climate change problem, and it will restore the carbonate cycle in the oceans, threatened by the lowering of the pH, which may damage ocean life, in particular the healthy growth of coral reefs. The use of olivine, or similar weatherable basic rocks has a number of collateral benefits for farmers, foresters and fishermen. The cost of enhanced weathering as a mitigation technology is in the order of 10% of the costs for a number of other proposed mitigation technologies. Even so, it will require an operation on a global scale that will bring olivine mining from a minor commodity to the world's third largest mining sector, with correspondingly large employment opportunities to people in developing countries. But even if its full potential within reasonable environmental constraints is exploited, accelerated weathering may not be able to sequester all the CO₂ that is emitted by the burning of fossil fuels. It will

therefore be better used alongside other measures to ameliorate climate change and its impacts.

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