The Green Cookery book:
Recipes against climate change and ocean acidification

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Introduction

CO_2 has always leaked out of the Earth, mainly from volcanoes. If all that CO_2 had remained in the Earth's atmosphere, its CO_2 pressure would now be about 100 bar (instead of the current value of 0.0004 bars), the surface temperature of the Earth would be close to 500^0C due to the greenhouse effect, and the oceans would be converted to steam.

Throughout geological history, the weathering of basic silicates has been the negative feedback mechanism by which CO_2 was removed. Without weathering, there could be no life on Earth. Weathering neutralizes carbonic acid ($H_2CO_3 \rightarrow CO_2 + H_2O$) to bicarbonate ($HCO_3^-$) solutions. These are then carried to the sea by rivers, where they are converted to carbonates by marine organisms (corals and shells), forming solid rocks (limestones and dolomites) in which the CO_2 is sustainably stored. Carbonate rocks contain 99.94% of all the CO_2 near the surface of the Earth. So rocks are the main reservoir for CO_2, much larger than the oceans, biosphere and atmosphere together. A generalized description of these processes can be found in Hartmann et al. (2013).

Humanity is now causing a spike in the CO_2 input by burning fossil fuels, and natural weathering cannot cope with this greatly increased rate. The olivine option provides a logical answer because it enhances the natural feedback mechanism to restore the balance. It can be applied in many sectors of society. Here you can find how and where people can use it. This cookery book contains the recipes for the most important applications of the

olivine option. The olivine option provides a multi-pronged attack to counteract climate change and ocean acidification

Thanks to this wide range of applications virtually **everybody** can assist in their own way to achieve climate stability. Many of the mentioned applications are devised in such a way that they profit from natural conditions and solve other problems at the same time, thereby reducing costs. Some will even be financially self-supporting, without recourse to subsidies or carbon credits.

The applications have been arranged by sectors. These are agriculture, forestry, roads, buildings, playgrounds, coastal protection, suppression of poisonous dinoflagellate and cyanobacteria blooms, diatom farms for biodiesel production, mining, mineral waters, olivine as a green fuel, olivine in environmental applications, natural emissions of CO_2 for carbon capture and miscellaneous.

For people who are not familiar with the olivine option, or with the volumes of olivine required, nor with the mining and milling costs involved, the following information is provided. Olivine, $(Fe,Mg)_2SiO_4$ is the most abundant mineral in the Earth, since the Earth's mantle consists mainly of olivine (and at great depth, its high pressure forms). If all that olivine had stayed in the mantle it would be difficult to mine because the continental crust has a thickness of 30 km. Fortunately large slabs of olivine rock have been pushed to the Earth's surface by plate tectonic movements, so in many countries in every continent huge massifs of olivine rocks are found close to the surface, where they can be mined in open pit mines. There are thousands of times more olivine available than we will ever need to counteract climate change and ocean acidification. To reach a new balance between the annual anthropogenic production of CO_2 of somewhat more than 30 Gt we need about 25 Gt of olivine through:

$Mg_2SiO_4 + 4H_2O + 4CO_2 \rightarrow 2Mg^{2+} + 4HCO_3^- + H_4SiO_4$

At a specific mass of 3400 kg/m^3, that is equivalent to the mining every year of an olivine volume of slightly over 7 km^3, large, but within the range of modern mining. The largest mine on Earth, the Bingham mine in Utah has an excavated volume of 25 km^3. It is evident that we should not start one single huge olivine mine, but a number of large new olivine mines strategically spread in order to reduce transport costs.

The costs of mining and milling bulk rock in open pit mines are well known in the mining sector. In large mines, mining bulk rock costs approximately 4 Euro/ton, and milling these rocks to a grain size of fine sand costs 2 Euro/ton (Steen and Borg, 2002). Four tons of olivine can sequester five tons of CO_2.

Dunites and peridotites (the major olivine rocks) are widespread over at least 1 million km^2 of the land surface. Several hundred million people live on these rocks for many generations, grow their crops on them, graze their animals on them, and drink the waters from these rocks without any harm. Weathering of olivine has been the main mechanism that has throughout geological time kept the CO_2 levels of the atmosphere within livable bounds, so it is highly unlikely that it would all of a sudden become an environmental danger when we use it to counteract climate change and ocean acidification.

Inventory of olivine applications

1 Agriculture

1.1 Wet grasses, like rice, sugar cane, bamboo and reed need silica. Three properties of olivine are important for agriculture: it remediates soil acidity, it supplies magnesium (essential for chlorophyll), and it provides silica, which is important for "wet" grasses like rice and sugar cane, which make silica deposits, or phytoliths, in their leaves. The normal weathering reaction (Schuiling and Praagman, 2011) is
$Mg_2SiO_4 + 4\ CO_2 + 4\ H_2O \rightarrow 2\ Mg^{2+} + 4\ HCO_3^- + H_4SiO_4$
Soil acidity is a very severe problem in the Mekong delta, which has many acid sulfate soils, which negatively affect rice production (van Breemen, 1976). The same holds for estuaries along the East coast of Australia that also suffer from acid sulfate soils, sometimes completely destroying the sugar cane plants. Spreading olivine sand can cure these problems, and increases the productivity.

1.2 The problem of soil acidity, which is usually treated by adding limestone, can be solved better by using olivine sand. Olivine spreading is CO_2 negative, so it not only solves the problem of soil acidity but it also helps to counteract climate change. Liming works faster, but needs to be repeated more often, whereas olivine spreading can control soil acidity for a longer period.

1.3 On a more modest scale, many people's lawns are on acidic soils, and full of moss. Here again a dose of olivine sand can help to improve the quality of their lawn. Pot experiments carried out at the Wageningen Agricultural University with grass grown with different doses of olivine added have shown that olivine has a positive effect on the growth of the grass (ten Berge, 2012).

1.4 On the smallest scale, even pot plants in apartments can profit from potting soil enriched with olivine, which is available in garden centers in the Netherlands.

1.5 Another way to make farmland more productive is the combination of olivine spreading with biochar (pyrolized wood). This should be an ideal combination by which the pH of farmland is raised, its water retention is improved and CO_2 is captured, because this biochar is another way to capture CO_2.

1.6 The growing season in alpine regions and in high latitudes is short because snow remains on the fields till late Spring. Farmers can extend the growing season by covering the snow with a thin layer of olivine or serpentinized olivine grains. Snow reflects sunlight, whereas dark silicates absorb it. In serpentinized olivine rocks, tiny magnetite crystals are formed that give the rock a blackish color by which sunlight is absorbed even better.
The dark grains are heated by absorbing sunlight, causing the underlying snow to melt faster, and the growing season is extended. After the snow has disappeared, the olivine grains will mix with the topsoil and capture CO_2. In Switzerland this general approach to make the snow melt faster is already long established, only instead of olivine or serpentine a black shale powder is used, the so-called Bündner Schiefer. That way they miss the additional advantage of carbon capture.

1.7 A completely different agricultural application of olivine is in biodigesters. Organic wastes are digested, and produce a biogas that consists of roughly 2/3 CH_4 and 1/3 CO_2, with traces of H_2S. For commercial applications it would be an advantage if the CO_2 content could be lowered, and the H_2S removed. Test runs at the Wageningen Agricultural University and the Technical University of Delft have shown that both aims can be reached by adding some fine-grained olivine to the digesters. The digester doesn't smell any more, and part of the CO_2 gas has been converted to bicarbonate in the digestate. There is even some evidence that the absolute amount of methane increases, probably by the following reaction with the iron member of the olivine

$$6\ Fe_2SiO_4 + CO_2 + 14\ H_2O \rightarrow 4\ Fe_3O_4 + \mathbf{CH_4} + 6\ H_4SiO_4$$

This reaction is often observed to take place in nature. Notorious examples are the Yanartasi ("the rock that always burns") in Turkey, and los Fuegos eternos ("the eternal fires") in the Philppines.

The Yanartasi (the rock that always burns)

Using part of the CO_2 to produce methane serves two purposes. The absolute amount of produced methane in the digester increases, and the amount of CO2 in the biogas decreases, so both the quality and the quantity of the methane are improved. The tiny magnetite crystals formed by the reaction catalyze the formation of methane.

2 Forestry

2.1 The first application of olivine is similar to the spreading of olivine over farmland to reduce soil acidity, because many forest soils also suffer from soil acidity. Spreading, however, is difficult in a standing forest, so it is best to wait until the trees are felled, and then to spread olivine when the grounds is prepared for the new tree planting. Governments could use the fact that they decide on concessions for forest exploitation to impose on the concessionary the condition to prepare the soil with olivine, both as a means to capture CO_2, and to preserve soil fertility. This last aspect may be strengthened by adding other types of rock meal to the olivine sand before spreading.

2.2 The parts of the trees that have no commercial value (bark, branches, sawdust) should be converted to biochar, which can either be used on the spot, or transported to arable land to improve its soil structure and water retention. By mixing the biochar with olivine an even better result can be obtained.

3 Roads, biking and walking paths

3.1 The green highway. Although highways are evidently great producers of CO_2 by traffic, they can also serve to capture CO_2. Their top layer is often composed of a mixture of bitumen and sand, which makes braking more effective. This layer is slowly worn down by the traffic, the sand grains are pulverized, and the tiny slivers are blown away by the wind. Quartz and olivine have closely the same hardness, making it easy to replace the quartz sand by olivine sand. Here again, the layer is worn down by the traffic, the tiny slivers are blown away, but contrary to quartz slivers they weather fast and neutralize CO_2.

3.2 Olivine can also be used in sound walls. It sounds strange to use olivine, meant to weather as fast as possible as a construction material, but there are two reasons to do so. When dunite (dunite is the rock-type that consists for >90% of olivine) is quarried, the operation will automatically produce some fine materials that will weather fast, either on location or blown elsewhere with the wind. After the useful life of the construction has come to an end, it will be demolished, and usually reduced to powder that will weather fast (Renforth et al., 2009).

3.3 The banks of roads and wadis can be covered with a layer of olivine that will react with the rainwater that drains from the road or land. They may also have another unexpected application (see section below on mining).

3.4 Biking and foot paths. These can be covered with olivine sand that will give them an attractive greenish color, fitting better in the landscape than road surfaces of bitumen or slabs of concrete.

3.5 Inspection paths along railways. The first tests have been successfully completed by the Dutch railway system. The olivine sand on the inspection path did in fact capture CO_2 during every rainfall.

3.6 Driveways. It is a nice view to have one's driveway covered with green olivine grit, and it shows that the owner has an environmental conscience. In the section on coastal protection a way is described to produce nicely rounded olivine grit in the most environmentally friendly way.

3.7 Parking lots. Parking lots should be constructed on a layer of olivine sand, through which the rainwater can percolate. Measures should be taken to make sure that the rainwater drains through the top layer.

3.8 A recurrent problem is hazardous road conditions in winter, due to snow or ice. Spreading salt is an effective way to solve the problem, but has environmental disadvantages. On secondary roads one can avoid these by spreading olivine sand over the snow or ice layer, to provide more grip for cars.

4 Buildings (including roofs)

4.1 Many offices and schools suffer from the sick building syndrome. When people come in in the morning, the internal atmosphere has a CO_2 concentration of around 400 ppm, but at the end of the day that has gone up to 1500 or 1600 ppm. People get drowsy, they lose concentration and their productivity goes down. A simple solution, to open all doors and windows, is usually out of the question for reasons of energy loss, noise and dust. The best solution is to install a system for internal air circulation, by which the internal atmosphere is passed through a CATO reactor (CATO stands for **C**lean **A**ir **T**hrough **O**livine). This is a trough filled with a suspension of fine olivine grains in water. Along the bottom runs a pipe with many tiny holes open to the trough. The air is circulated through that pipe under a slight overpressure. Bubbles pass through the suspension and give off not only their CO_2, but also traps pollen and allergenic dust particles. In order to prevent scaling by silica or magnesium carbonates, the water from the reactor must regularly be pumped in an outside large reservoir (a pond), and the reactor refilled with new water. In the pond, silica will be used by diatoms. Diatoms are a favorite fish food.

4.2 The total roof surface of towns is large and constantly increasing. Large roofs need ballast to prevent the roof being blown off in a storm, and pieces of olivine (specific mass of olivine is around 3.4 gm/cm^3, considerably higher than most rocks) can serve well as ballast. For carbon capture, one can additionally cover the roofs with olivine sand and making it into a roof garden by planting some sedum on it. Under vegetation olivine weathers faster. Due to the higher pH imposed by the olivine on the percolating rainwater, metals like copper, lead and zinc are immobilized, saving expensive remediation measures in urban sewage treatment plants. Many roofs in Amsterdam have already been covered by olivine.

4.3 Serpentinite is a very common rock-type. One can consider it as a kind of clay mineral, and it can be used as such. It is known that calcined serpentine reacts very fast (faster even than olivine) with CO_2 and water, contrary to other baked clays. It is suggested here to test if serpentine can be used as a raw material to make roofing tiles. These roofing tiles will already contribute to carbon capture during their time on the roof, but when crushed after they are broken or after the house is torn down they will very quickly react with CO_2 and water, thus making a contribution to CO_2 removal from the atmosphere.

5 Playgrounds

5.1 Gravel on tennis courts can be replaced by olivine gravel. It serves the purpose of capturing CO_2 even better than on other open spaces, because in very dry times the tennis courts are kept wet by sprinkling. This increases the time during which reaction between olivine CO_2 and water can take place. Although the total contribution of green tennis courts to carbon capture is limited, their frequent exposure on television during tennis matches will help the introduction of olivine options.

5.2 Golf courts. A double possibility, the greens can be covered with a thin layer of olivine sand which will improve the quality of the grass, and the paths for golf carts can be covered with olivine sand.

5.3 Astroturf playing fields. During their installation a mixture of sand and rubber shreds or pieces of cork is added to the mats. After 10 to 12 years these are replaced, and the old mats are thrown away. The following variation is in line with the cradle-to-cradle principle. Instead of normal sand, olivine sand is used, so the Astroturf fulfills an environmental role right from the beginning. When it must be replaced, the mats are not thrown away, but used for roof covering. The heavy sand holds the mats down, and the "grass" protects the sand from being blown away. This serves as an insulating layer for the house, keeping heat out in summer, and conserving heat in winter.

5.4 Sand-boxes. At nursery schools or gardens, sandboxes with olivine sand can be installed (the first ones have been installed in schools in the Netherlands). Olivine sand gives a good feel. If necessary the grains can first be tumbled, or collected from olivine beaches, where they are rounded by tumbling and abrasion by the surf. Sand sculpturing with olivine sand can produce spectacular results.

Sand sculpture of the Nativity, from 48 tons of olivine sand.

The Hague, Christmas 2012

6 Coastal protection

6.1 Longshore currents can erode coasts. A curved olivine dam can be constructed on rapidly eroding coastal sections. Such a dam should be built with fairly coarse olivine blocks, making it permeable. When the main current along the coast is from South to North, the general direction of the dam should be North-West, curving in a northerly direction. This way the current is gently deflected away from the coast, and loses part of its strength, because the water in the current that passes through the olivine blocks in the dam will lose momentum. When a dam is placed perpendicular to the coast, and at right angles to a longshore current, sand accumulates on its front side, and on the backside sand is eroded. As the flow of water on the backside will be partially pushed back by the water that forced its way through the permeable dam, it is expected that erosion will be less in this set-up.

6.2 A second way to reduce erosion is the following. The seafloor of the part behind such a dam should be covered with olivine sand. Olivine is significantly heavier than quartz (3400 kg/m^3 vs 2650 kg/m^3), so it offers a larger resistance to erosion. It will react with seawater, capturing CO_2 and readjusting the pH of the local water. Such a sector on the leeside of the olivine dam may even serve as a refuge for marine fauna suffering from ocean acidification.

6.3 Covers of dikes should preferably be made of blocks of olivine rocks. Admittedly, the amount of olivine from coarse blocks that will react with seawater will be minimal, but mining of olivine rock itself is carbon-negative, because the dust produced during olivine mining will weather fast, whereas mining granite or basalt carries a CO_2 penalty. Basalts and granites weather also, but their total concentration of calcium and magnesium is considerably lower than that of dunites (olivine rocks) and their rate of weathering is much slower.

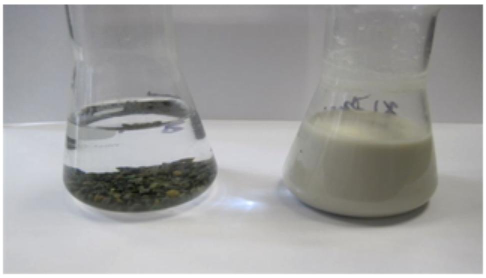
6.4 One can construct olivine reefs at places where these can serve best to keep currents and waves away from the shore in order to reduce erosion. The pH of the pore waters inside these reefs will rise as a consequence of their reaction with olivine, and this will probably lead to calcite precipitation, cementing the reefs and making them better erosion resistant. Very likely, such olivine reefs will become attractive places for marine organisms to settle, and for fish to serve for hiding and hatching. If these reefs attract an abundance of marine life forms, they may become an interesting target for tourists, and of course, as holds also for the other proposed measures, they help to protect coasts against erosion, they will capture CO_2 and help to restore the pH of the sea**.**

6.5 Deposit olivine grit on a rough part of the coast. In the surf zone angular pieces will become quickly rounded and polished by repeated collisions.

What happens to olivine on the beach? Before shaking, the grains are rough and angular

After 10 days of shaking, the grains are rounded and smooth

The water becomes opaque from all the micron-sized olivine slivers



During this abrasion process they lose small slivers of olivine that rapidly weather and add alkalinity to the sea (Schuiling and de Boer, 2011).

The surf is the largest ball-mill on Earth and is free of charge!

Tourists are free to collect some nicely polished olivine marbles as a memory of this new way of coastal protection. People who want roundish olivine grit on their driveways can use the surf to obtain nicely rounded grit. Another application of this tumbled olivine grit might be for chicken farms, to provide grit to the chicken. Sharp angular pieces can damage the chicken stomach, and a short round of cost-free rounding on the beach can avoid this risk.

7 Suppression of dinoflagellate and cyanobacteria blooms

7.1 Toxic dinoflagellate blooms, the feared red tides, occur more and more frequently in coastal waters. A similar problem is faced in fresh waters that are often threatened by cyanobacteria that make them unsuitable for swimming. Dogs die when they swim in such waters. Both marine and freshwater diatoms (siliceous algae) are very common, they grow very fast, and make up 20 to 25% of the marine biomass. They are a favorite fish food. Their existence is dependent on availability of dissolved silica in the water, which they need to make their silica skeletons. As long as silica is available, they grow so fast that they can outcompete dinoflagellates and cyanobacteria. In the coastal sea off China, the following sequence of events unrolls every year. In spring there is a diatom bloom. As the reservoir of silica that was built up during winter comes to an end, the diatoms die, and a toxic dinoflagellate bloom takes over.

The feared red tide

Some species of dinoflagellates produce a strong neurotoxin, killing fish and making the waters unfit for touristic uses. All these planktonic species are dependent on the availability of sufficient macronutrients, mainly phosphate and nitrogen, which are brought in from land, derived from fertilizers and untreated wastewaters. As long as there are plenty of diatoms, there will be neither dinoflagellate blooms in the marine realm, nor cyanobacteria blooms in freshwater lakes or canals. The most sustainable way by which large volumes of CO_2 can be captured is by weathering of olivine sand on beaches, or in drains through which fresh water lakes are fed. This will continue to deliver silica to the water, in summer even more than in winter, because the rate of weathering of the olivine is dependent on the ambient temperature.

8 Diatom farms for biodiesel production

8.1 A very different way of using diatoms is the following. About 50% of their body weight is lipids (fatty acids), which makes them attractive as a raw material for biodiesel production.

Diatoms have beautiful silica skeletons

In order to make this commercially attractive, ways must be found to farm them and harvest them. The technology to make biodiesel out of algae already exists. One can set up a diatom farm with silica supply as follows. Make an artificial lagoon in front of a beach, by damming off a section of coastal water. Cover the beach with a deposit of olivine sand (~0.5 m thick) between the high tide level and the ebb level. Make a U-tube through the dam, permitting water to flow into the lagoon at high tide, and flow out at ebb tide. This will cause a diurnal wetting and draining of the beach, and deliver the products of olivine weathering to the lagoon. Magnesium, of course, is not an issue, because it is already a major component of seawater. Silica is the determining factor, but the bicarbonate will also be used by the diatoms for photosynthesis. Other deficient nutrients must be added to the water, maybe in the form of digestate from anaerobic digesters, or as struvite ($NH_4MgPO_4.6H2O$) produced from such digestates by the struvite process (Schuiling and Andrade, 1999, Andrade and Schuiling, 2001). The lagoon side of the U-tube is covered by a perforated metal disk, which acts as a support for a plankton net that serves to catch diatoms that otherwise might be carried out of the lagoon with the ebb stream. These are collected on the plankton net. Hopefully a more direct way to catch the diatoms is as follows. Make one section of the lagoon deeper than the rest. Dead diatoms will sink in this pit. Their siliceous skeleton makes them fairly heavy. From time to time a slurry of dead diatoms is sucked up from this hole, and serves as raw material for biofuel production. Biofuel production on land from corn, sugar cane or oil palms is getting a bad reputation. It uses large areas of land that were meant for food production, it uses large quantities of scarce irrigation water, and it consumes large amounts of fertilizer. Biofuel from marine algae carries none of these negative properties.

9 Mining

9.1 For all these activities large volumes of olivine must be mined, or recovered from olivine-rich mine tailings. Olivine rocks host a number of other commodities, like chromite, magnesite, PGE (platinum group elements), sometimes diamonds, and, of course gemstone quality olivine crystals (peridot). When reworking the tailings to recover the olivine, it may be worthwhile to go for a second harvest of the materials that were mined.

9.2 Olivine rocks may also host economical concentrations of other minerals. In this respect chromite is the main candidate. If the deposit is mined for olivine, and the rock is crushed to produce olivine sand, it may be worthwhile to recover the chromite as well, as the technology using washing tables is simple and effective to separate chromite from olivine. This will improve the olivine grade of the product, and bring some extra cash from the chromite by-product.

9.3 Although somewhat speculative at this moment, the recovery of another metal from olivine rocks may become economically far more important. All olivine rocks, and the serpentinites derived from these rocks contain between 0.25 and 0.3% nickel, which replaces some of the magnesium ions in their crystal lattices. Such concentrations are far below ore grade. Baker and Brooks (1989) found that there are a number of plants (presently there are about 400 species known) that very efficiently extract nickel from such rocks, and from the soils on such rocks.

A nickel hyperaccumulator plant on serpentinite soil

The ash of these so-called nickel hyper-accumulating plants may contain over 10% of nickel, far more than the richest nickel ore. Moreover, it is easier, less polluting and less energy-intensive to recover the nickel metal from these plant ashes than from regular nickel ores. In simple laboratory tests small nickel ingots were produced from the plant ashes. Sowing these plants on appropriate soils and harvesting them at the end of the growing season makes for an environmentally friendly way of recovering nickel. Because these plants extract nickel from the olivine lattice, for every ton of nickel in the plants 330 tons of olivine must weather, equivalent to a capture of 400 tons of CO_2. Weathering proceeds faster under vegetation. The introduction of this method (Schuiling, 2013) could revolutionize the nickel mining industry. It is also possible that once this method of farming nickel becomes established, governments will require nickel mining companies to realize part of their nickel production in this way, to save the environment, and extend the life of their nickel reserves. These countries can claim such measures as their share in global CO_2 sequestration. Soils on olivine rocks are usually poor soils, so switching to this technology will not harm world food production. On the contrary, it may provide income for poor farmers that will permit them to buy some fertilizer and thus increase their food production.

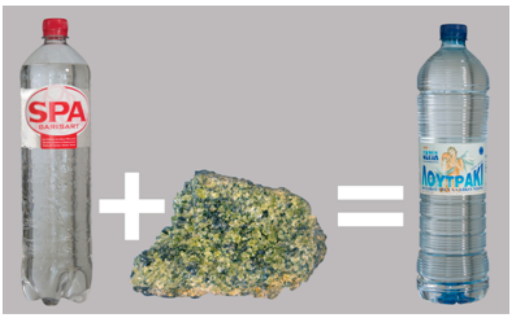
9.4 Interest is growing in use unproductive soils in the same way even if they have no relation with olivine rocks. One can classify as unproductive soils the cover of waste deposits, sites of urban sewage treatment plants, but also road banks. Before the financial crisis many municipalities had bought agricultural land to convert it into industrial sites, or use it for housing projects. Due to the financial crisis many of these projects were halted, but the municipalities still have to pay the interest on their loans. If covered by a layer of olivine mixed with topsoil, and planted with nickel hyper-accumulator plants they can bring a modest income to the managers of such sites.

9.5 A major problem in the mining industry is Acid Mine Drainage (AMD). Sulfide minerals exposed to the atmosphere are altered very fast and produce sulfuric acid. This will damage, and often completely destroy the vegetation, and it makes waters unsuitable for irrigation. If olivine- or serpentine-rich rocks are found in the neighborhood, these can serve very well to neutralize the acid waters, and once neutralized, these waters can serve for irrigation and can sequester some CO_2.

10 Mineral waters

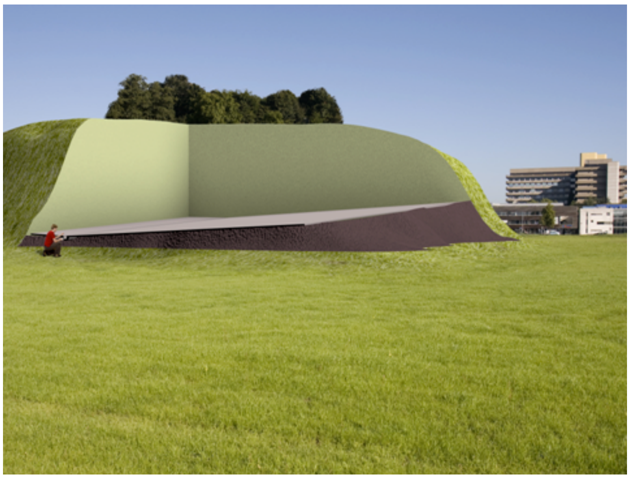
10.1 As said before, the weathering of olivine (and serpentine) produces magnesium bicarbonate waters, and several well-known mineral waters, like the Greek mineral water Loutraki, issue from springs in olivine rocks. In a FAO handbook from 2002, the effects of different chemical species on human health are described, and for magnesium-rich waters the verdict is very positive. Such waters are effective against cardiovascular diseases and a too low intake of magnesium causes premature aging. A simple experiment, visualized above, can demonstrate the origin of magnesium bicarbonate mineral waters. When Spa Red, a Belgian table water bottled under high CO_2 pressure with a pH of 3.9, is reacted with olivine sand the pH rises. After 1 month it had reached 8.3, and the chemistry of this water had become almost identical to that of Loutraki, the best-known Greek mineral water. Not surprisingly, the Loutraki spring issues from an olivine-rich rock-type near Corinth (Schuiling et al., 2012).

This is the origin of magnesium bicarbonate waters



10.2 This public health aspect is almost an invitation to produce more of these waters to improve public health, also in countries where there are no olivine rocks. This can be done with the help of olivine hills. Such hills can be constructed and operated in the following way. First install an impermeable bottom in the shape of a very flat slightly inclined gutter. Cover this with several meters of olivine sand.

The grain size of the olivine must be selected in such a way that water entering the olivine hill from above should take at least one day to reach the bottom. This will provide sufficient time for the water to react with the olivine. The olivine must be covered by a layer of topsoil, which will be planted with shrubs and grass. This serves a double purpose, a vegetation cover will prevent the erosion of the hill during heavy rainfall, and the vegetation causes high CO_2 concentrations in the soil atmosphere. The decay of dead plant material in the soil and respiration of soil fauna both produce CO_2. Rainwater will first pass through this soil and take up CO_2. Then it will pass through the olivine and is converted to magnesium bicarbonate water. After this water has reached the impermeable bottom, it will slowly migrate to a tap at the low end of the gutter, where it can be collected.



A board placed next to the tap should offer an explanation of the olivine option, and how this particular water forms, and what the favorable effects of this mineral water are on public health.

10.3 In countries with a poor quality drinking water, like Bangladesh where much of the drinking water contains high concentrations of arsenic that has led to widespread illness and death, olivine hills constructed near villages will provide healthy water to the population. In times of inundations, such hills can serve as a refuge for the population.

10.4 People who want to serve their own brand of mineral water to their guests can build a small replica in their garden. Although the CO_2 capture of such a small olivine hill is modest, it will make more people aware of the possibilities of the olivine option against climate change and ocean acidification, and provides a modest improvement to public health.
Olivine hills can even be planted with nickel hyperaccumulator plants, and the owner can proudly produce his own "nickels".

11 Olivine as a green fuel

11.1 Supergreen energy. The weathering reaction of olivine is exothermal. It releases a lot of heat, known as supergreen energy, because it is heat that is produced while at the same time CO_2 is sequestered, whereas green energy is energy that is produced without CO_2 emission. Unfortunately the heat is produced at such a slow rate that it is normally impossible to recover it, unless one uses large and very well isolated volumes of olivine. If the reaction is

$$2\ Mg_2SiO_4 + CO_2 + H_2O \rightarrow MgCO_3 + Mg_3Si_2O_5(OH)_4$$

a stochiometric mixture of the reactants would heat itself to ~700^0C if perfectly isolated. If one relates this to the energy produced by burning coal normalized to the same amount of CO_2, it turns out that the total energy produced by burning coal could be increased by 50%! Moreover, it would offer the possibility to store the CO_2 produced in the coal fired power plant in a safe and sustainable way.

11.2 With such high stakes it is tempting to look for ways to implement this idea. Rocks are excellent thermal insulators. It would be an advantage to have underground cavities that are no longer in use, and even may have a negative value. One can think of cavities produced by solution mining of salt. For safety reasons, to prevent subsidence or even caving in, these cavities must remain filled with saturated brine and indefinitely pressurized. Filling them with fine-grained olivine will push out an equivalent volume of brine, which would otherwise be lost. This additional volume of brine recovered is the first financial advantage. Hot CO_2 will then be injected into the mixture of olivine grains with interstitial brine. Laboratory tests have shown that olivine reacts faster in a brine than in fresh water. Because the volume of serpentine + magnesite is larger than the volume of the olivine, the pore space between the olivine grains begins to be gradually closed, and the solid reaction product can support the cavity, obviating the need for further pressurizing and monitoring. Once the reaction is underway, the produced heat can be tapped by exchanging it from the solid rock to water circulating in pipes installed in the system. The warm water can be used for space heating or for the heating of swimming pools.
11.3 It would be even better to recover the heat as high-enthalpy steam to run turbines. This may become practical if a thermal power plant is located close to a dunite massif, like near Orhaneli, NW Turkey, where a

lignite-powered plant is located near a dunite body that is already used for small-scale olivine mining. The following suggestions are speculative. If one excavates a large room inside this dunite body, constructs a set of perforated pipes in this room, and fills it with olivine rubble obtained from roof caving and connects the piping system to a well isolated pipe through which the hot flue gases from the power plant are brought in, one can set the reaction in motion. The room must first be closed to the outside. As rocks are good thermal insulators, the reaction will go faster and faster as the temperature goes up. The high temperature steam may eventually be used for power production, while at the same time CO_2 is captured.

11.4 Lignite mines in Germany. A system that allows better control is the following. The area between Aachen and Köln in Germany is underlain by thick lignite coal seams, at depths around 500 meters. These seams are mined in deep opencast mines, and as the seams are excavated at the front side, the mined-out opposite side is filled again with the original overburden, and the area is rehabilitated.

This way the mine moves slowly through the landscape. Instead of filling the entire cavity with the original overburden, one can fill the lower 250 meters with olivine sand, and cover it up with the remainder of the overburden. Before doing this, a set of perforated pipes should be installed in the olivine layer that permits injection of CO_2/water mixes. After the olivine and the overburden have been emplaced, the system is thermally well isolated. Again, as the system heats up by the ongoing reaction, the steam pressure will go up also, but the overburden will provide a containing pressure of more than 60 bars, equivalent to a steam temperature of 275^{o}C. The tapping of this high enthalpy steam makes it possible to run a steam turbine.

12 Olivine in environmental applications

12.1 Sulfide mines suffer from acid mine drainage (AMD). Remaining sulfides in the mine tailings or in the mine itself oxidize fairly rapidly in contact with the air, producing sulfuric acid. It is one of the major environmental problems of mining. Some mine locations have the good luck that their mine is situated in a limestone area, which neutralizes the acid (making gypsum), but in many cases AMD remains a problem. Olivine may act as a useful neutralizing agent. It is abundantly available, and when applied in sufficiently high doses it may impose a pH at which many toxic heavy metals become immobilized, and are no longer bio-available.

12.2 A completely different environmental application, this time of serpentine, which is very commonly formed by a reaction of olivine with (hot) fluids, is its use in fighting forest fires. Serpentine can be considered as a kind of clay mineral, and baking clay for brickmaking requires a lot of heat. Normally that is an unfavorable property, but there are cases where one tries to remove as much heat as possible from a fire, namely in forest fires. To check the efficiency of using serpentine powders to extinguish fires, a set of test fires were subjected to spraying with serpentine slurry, and the effect compared to spraying with water. It turned out that spraying with serpentine slurries was a very effective and rapid way to quench the fire. In just a few seconds of spraying with a modest dose of serpentine slurry, the fire was quenched permanently. With the spraying of water it took much longer before the fire was quenched, and after the spraying was stopped the fire started again. Heat withdrawal from the fire, however, is probably not the major positive effect. When the fire is sprayed with a serpentine suspension, the baked serpentine forms a thin layer on the burning material, preventing oxygen from reaching the burning material, and preventing inflammable gases from escaping from the burning material.
After the fire, the calcined serpentine reacts very rapidly with water and CO_2. So, at the first rain shower, part of the CO_2 that was produced by the fire is already compensated. Forest fires are the world's second biggest emitter of CO_2, after the burning of fossil fuels (van der Werf et al., 2009). Even in the USA, with its many cars and trucks, forest fires are responsible for as much CO_2 emissions as all the traffic.

13 Using natural emissions of CO_2 for carbon capture

13.1 Although anthropogenic CO_2 emissions far outweigh natural CO_2 emissions, these form an easy prey for carbon capture. It is self-evident that for the climate it makes no difference whether man-made or naturally

emitted CO_2 is sequestered. The atmosphere is a well-mixed reservoir on the scale of a few months, so it makes no difference where the CO_2 is sequestered.
The first example is in the shallow sea near the Greek island of Milos, where each year 2.2 million tons of CO_2 bubble out of the seafloor. The CO_2 is very hot just before it reaches the surface (the bubbles themselves have the same temperature as the sea water). If one would create an olivine island over a location with active bubbling of CO_2, the temperature of the olivine would start to rise. This would set a convection system in motion. Warm water is lighter than cold water, so it rises to the top of the island, and will be compensated by a sideways inflow of cold seawater. When a depression is made in the top of the island, this will fill with warm water, making it a touristic attraction. Tourists, even in winter, can take a warm bath while looking over a cold blue Aegean Sea. The exothermal heat released by the olivine reaction with water and CO_2 adds to the heating effect.

13.2 This heat of reaction plays a major role in the following application. In NE Greece there are a number of geothermal wells that are used for the heating of greenhouses. The geothermal fluid contains high concentrations of CO_2. When a hill of olivine sand is set up over the well, the amount of available energy is increased by the heat of reaction, and CO_2 is captured.

13.3 A location where natural CO_2 emissions have caused a major catastrophe is Lake Nyos in Cameroon, where in 1986 a dense cloud of CO_2 was emitted from the lake. It rolled down the mountain, and killed 1800 people by asphyxiation. To prevent a future disaster, a kind of geyser system was installed to prevent the accumulation of CO_2 at the bottom of the lake. This is an expensive operation, and it is doubtful whether future funding will remain available. A more permanent solution, requiring no daily supervision and maintenance would be to spread a layer of fine olivine sand on the bottom of the lake (Schuiling, 2011). This will react with the bubbles of CO_2 and transform them into an innocuous bicarbonate solution, thus avoiding the danger of a build-up of CO_2 pressure. As the lake serves as a source of drinking water for the population, they can benefit from the advantages of healthy magnesium bicarbonate waters.

13.4 Mofettes. In many places mofettes are found, places where CO_2 escapes from the ground. These are harmful, and animals, but occasionally humans as well can die from asphyxiation when inhaling the concentrated CO_2. The author had a very unpleasant experience, when he sniffed just a little bit of concentrated CO_2 from a mofette in Belgium. Understandably, in several countries the mofettes are fenced off to prevent accidents. If the mofette area would be dug out somewhat, and the hole filled with olivine sand, the risk of accidents could be reduced, provided that the hole is deep enough to keep the olivine sand in a wet condition. Apart from risk reduction, it is also a small contribution to carbon capture.

14 Miscellaneous

14.1 Olivine grains can be spread on the bottom of sewage pipes. Temperatures in sewage pipes are usually above average, and CO_2 is plentiful thanks to the decay of labile organic substances. This will speed up the reaction rate of the olivine. It is expected that olivine, as it raises the pH, will slow down the corrosion of the concrete. Replacement of sewage pipes is a matter of millions of euro even for an average sized city, so extending the lifetime of the pipes even by just a few years can save a lot of money.

14.2 Slowing down lava flows with serpentinite blocks
Lava flows may destroy villages or even small towns downstream, so it is understandable that attempts are made to stop them. In an earlier paper it was calculated that throwing blocks of limestone in the lava flow has a much larger cooling effect than throwing in blocks of concrete (Schuiling, 2008).

A lava flow from Etna; can it be stopped?

This is caused by the endothermic reaction of the dissociation of the limestone.
A similar argument is presented here on the effect of serpentinite blocks, in which the dehydration of the serpentine withdraws more heat from the lava than unreactive rocks of the same weight. It will depend on the availability of limestones or serpentinites near the volcano and their distance from the flow whether one or the other is more convenient to use. Both are

common rock types. Serpentine ($Mg_3Si_2O_5(OH)_4$) can be compared to clay minerals. Making bricks from clay requires a lot of heat, and the same holds for serpentine. The heat of dehydration is in the order of 140 kJ/mole, or 500 J/gram. So, with 1 gram of serpentine one can cool 6 grams of lava by 100^0C. One gram of serpentinite when heated from room temperature to temperatures around 1000°C will additionally cool 10 grams of lava by 100 degrees for every gram of serpentinite added. When normalized to equal weights, decarbonation reactions with dolomites or limestones withdraw more heat from lava than dehydration reactions of serpentine, but even with serpentinites their contribution is still large. The use of serpentine, however, has some additional advantages in terms of CO_2 sequestration. Contrary to carbonates, their use is not producing CO_2 emissions, and after the lava has cooled down and solidified, any calcined serpentine will react fast with CO_2 and water, thereby sequestering CO_2 in a sustainable manner.

Conclusions

Almost all of the CO_2 that has ever leaked out of the Earth has been removed by its reaction with basic minerals. This reaction is known as weathering. The weathering products have formed carbonate sediments. These are Nature's sustainable storehouses of CO_2. Mankind has enormously increased the input of CO_2 by the burning of fossil fuels, and weathering cannot cope with this increase. In this chapter it is described how the rate of weathering can be increased by the mining, milling and spreading of olivine, and how this olivine option can be applied in many sectors of society.

Schuiling, Utrecht 2014

References

Andrade, A. and Schuiling, R.D. (2001) The chemistry of struvite crystallization. Mineralogical Journal (Ukraine), vol.23, nr.5/6, p. 37-46

Baker, A.J.M., and Brooks, R.R. (1989) Terrestrial higher plants which hyperaccumulate chemical elements – a review of their distribution, ecology and phytochemistry. Biorecovery 1, 81-126

Berge, H. ten, van der Meer,H.G., Steenhuizen, J.W., Goedhart, P.W., Knops, P., Verhagen, J. (2013) 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

Breemen, N. van (1976) Genesis and soil solution chemistry of acId sulphate soils in Thailand. Agric.Res.Rep.848, Pudoc, Wageningen

FAO Document Repository (2002) Human Vitamin and Mineral Requirements. Chapter 14, Magnesium
Hartmann, J., West, A.J., Renforth, P., Köhler, P., Wolf-Gladrow, D., De la Rocha, C., Dürr, H.H., Scheffran, J. (in press) Enhanced Chemical Weathering as a Geoengineering Strategy to Reduce Atmospheric Carbon Dioxide, a Nutrient Source and to Mitigate Ocean Acidification. Reviews of Geophysics. doi: 10.1029/2012RG000404

Renforth, P., Manning, D.A.C., and Lopez-Capel, E. (2009) Carbonate precipitation in artificial soils as a sink for atmospheric carbon dioxide. Appl. Geochem. doi:10.1016/j.apgeochem.2009.05.005

Schuiling, R.D. and Andrade, A. (1999) Recovery of struvite from calf manure. Environm.Techn., vol.20, p.765-768.

Schuiling, R.D. (2008) How to stop or slow down lava flows. Int.J.Global Env.Issues, vol.8, nr.3, *282-285.*

Schuiling, R.D. and Praagman, E.(2011) Olivine Hills: mineral water against climate change. Chapter 122 in Engineering Earth: the impact of megaengineering projects. pp 2201-2206. Ed.Stanley Brunn, Springer

Schuiling, R.D. and de Boer, P.L. (2011) Rolling stones; fast weathering of olivine in shallow seas for cost-effective CO_2 capture and mitigation of global warming and ocean acidification, Earth Syst. Dynam. Discuss., 2, 551-568, doi:10.5194/esdd-2-551-2011.

Schuiling, R.D (2011).: LANCELOT (Lake Nyos Carbon Emission Lowering by Olivine Treatment) Natural Hazards Volume 56, Issue 3. p 559-563

Schuiling, R.D. (2013) Farming nickel from non-ore deposits, combined with CO2 sequestration. Natural Science 5, no 4

Schuiling, R.D., Hoogesteger, A.W. and Praagman, E. (2012) From Spa to Corinth a Road for CO_2 Sequestration. Int.J.Earth Sciences and Engineering, Vol 05, no 6

Steen, B. and Borg, G. (2002) An estimate of the cost of sustainable production of metal concentrates from the Earth's crust. Ecological Economics, 42, issue 3, 401-413

Van der Werf, G.R., Morton, D.C., DeFries, R.C., Olivier,J.G.J., Kasibhatla,P.S., Jackson,R.B., Collatz,G.J. and Randerson, J.T. (2009) CO_2 emissions from forest loss. Nature geoscience, Vol.2, November 2009