Olivine Hills
Mineral water against climate change

Roelof D.Schuiling and Elke Praagman

Abstract
Rainwaters passing through olivine-bearing rocks are transformed into magnesium-bicarbonate mineral waters, thereby capturing CO_2 in a safe and sustainable way. It is estimated that this weathering of mafic and ultramafic rocks (silicate rocks rich in magnesium and calcium) accounts for an annual sequestration in the order of 2 to 2.5 billion tons of CO_2. In pre-industrial times this was enough to balance the input of CO_2 from the Earth's mantle. On a truly mega-engineering scale we propose to restore the balance by enhancing the rate of weathering of such rocks world-wide. As a small, but very visible part of this approach every town in the world that is genuinely concerned about climate change should erect a large hill of olivine powder in an attractive location in or around the town. Rain, or a nice fountain on the hilltop should provide water that will pass first through the topsoil and then through the olivine powder. When the water reacts with the olivine it will sequester CO_2. If any CO_2 -rich stack gases are available nearby, these can be injected near the bottom of the olivine pile in order to make the capture of CO_2 even more effective. As a bonus it can be mentioned that magnesium bicarbonate waters are very healthy, notably effective against cardiovascular diseases and diabetes. Olivine hills could also be constructed as a refuge in times of flooding, thus combining adaptation and mitigation on a modest scale.

Key words
CO_2 sequestration, climate change, weathering, olivine hills, mineral waters

Introduction
A famous European mineral water is Loutraki, from a spring near Corinth, Greece. This is a magnesium-bicarbonate water in an olivine rich rock type. The events leading to the formation of such waters are as follows. After falling on the ground, rainwater passes through the soil. CO_2 concentrations in soil atmospheres are easily 100-fold greater than in air, because animals living in the soil breathe, and plant litter decays (Schachtleben et al., 1982, Sumner, 2000). Both contribute CO_2 to the soil atmosphere. Waters in equilibrium with the soil atmosphere are enriched in CO_2, thus become acidic and aggressive. They react with the underlying olivine-bearing rocks. By their interaction with these rocks, they change into Mg-bicarbonate waters.

The weathering reaction is as follows

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

One can calculate that 140 gram of olivine will sequester 176 gram of CO_2.

We have experimentally imitated this process by shaking a bottle of Spa table water with 10 gram of olivine powder for one month. The Spa water is a low-mineralized sparkling water with a pH of 3.9. By the reaction with olivine the pH rose to 8.36 and its composition has become very similar to the Loutraki water, or other magnesium-bicarbonate waters of similar origin (see table 1).

Sample	pH	Mg_2^+	Ca_2^+	HCO_3^-	SiO_2
Loutraki	8.1	80.3	4.8	454	17
Exp.water	8.36	91.5	6.0	440	40
$Mg\text{-}HCO_3$	8.2	70	5.4	330	41

Table1. Composition (mg/liter) of Loutraki mineral water, experimental water made by reacting a sparkling table water with olivine powder, and average magnesium bicarbonate waters.

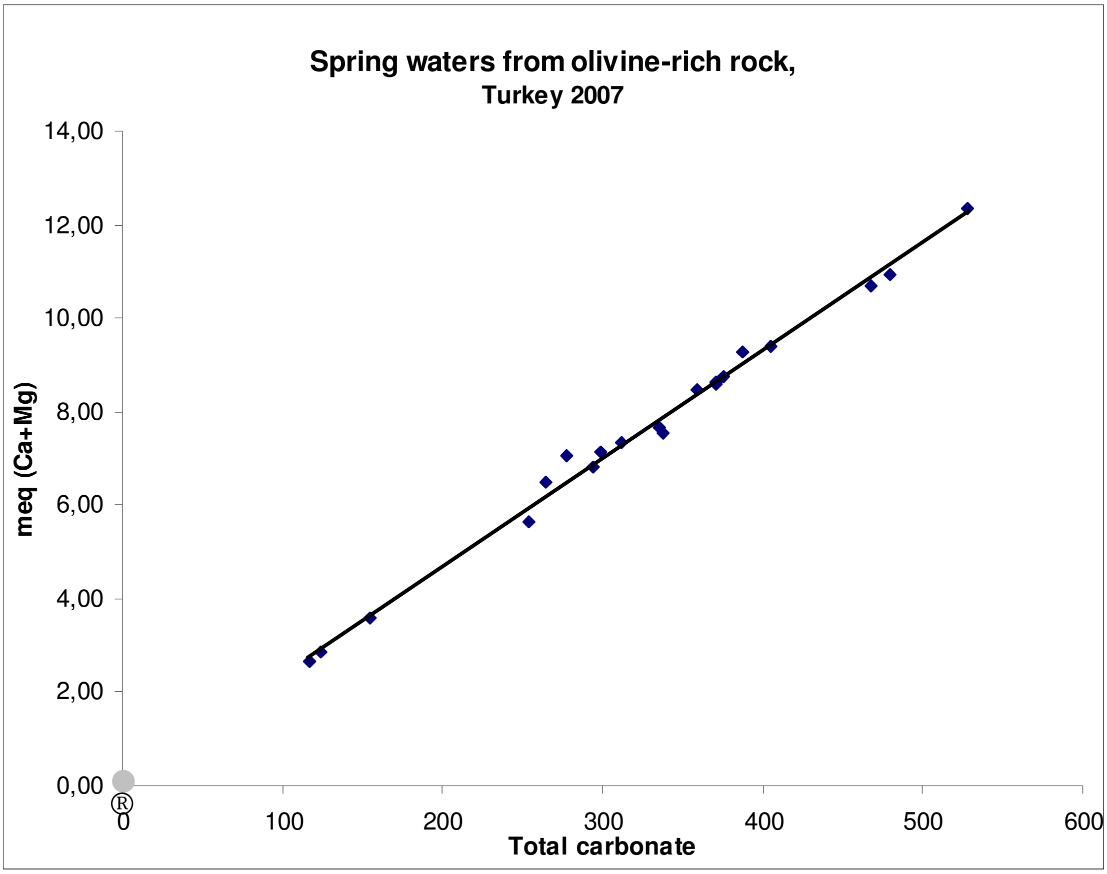

Fig.1: Concentration in meq $[Ca^{2+} + Mg^{2+}]$ in spring waters. Total carbon as mg CO_2.
® composition of rain water.

We have also collected samples from springs in olivine-rich rocks in Turkey. From the graph (fig.1) it is evident that there is a very close correlation between the sum of Mg and Ca (in milli-equivalents) released from the rock, and the amount of CO_2 fixed as bicarbonate in the water. The pH of these samples ranged from 7.6 to 8.8.

Lessons learned

It is evident that the process of weathering produces mineral waters, in which the greenhouse gas CO_2 is rendered harmless in the form of the bicarbonate ion. This is by far the major natural sink of CO_2. Sequestration of CO_2 as organic carbon, like in oil, natural gas or coal is a distant second. By way of ground water and rivers, these waters will finally reach the oceans, where they will counteract the ongoing acidification caused by rising CO_2 levels in the atmosphere (in chemical terms, we are adding alkalinity to the ocean waters). The ultimate fate of these bicarbonate waters is that they will form carbonate sediments (coral reefs, limestones, dolomites). This guarantees a sequestration of CO_2 for geological times.

It is evident that the process can't cope with the enormous additional amounts of CO_2 that are emitted by the combustion of fossil fuels. Mankind burns the reserves of fossil fuels in a few hundred years, while it took hundred millions of years to form them.

Can we benefit from weathering?

If we could increase the rate of weathering, we might benefit from the same natural process that has kept the CO_2 concentrations in the atmosphere within reasonable bounds during the Earth's history. We think that it is possible to avert a runaway climate change, although it will require a truly mega-engineering type world-wide effort (Schuiling and Krijgsman, 2006).

Weathering takes place at the outer contact of minerals and rocks with the (soil-) atmosphere. To enhance weathering, we need to increase the available contact area. This can be done by crushing reactive rocks, and spreading the mineral powder over land or in shallow seas and coastal zones. This is an example of geochemical engineering, which seeks to use geochemical processes and natural materials to solve environmental problems (Schuiling, 1998).

Olivine is the most abundant reactive mineral. We should open a number of large new open pit olivine mines, preferably in tropical countries. This has the following advantages:

- Weathering is fastest in hot humid climates
- Wages in most tropical countries are low, making mining cheap
- Transport costs can be reduced by spreading the olivine powder in the (wider) surroundings of the mines.
- Large mines profit from the economy of scale
- Employment in developing countries increases, boosting their economies.

At present, olivine is being mined at a rate of 10 to 20 million tons a year. It is used mainly as an additive to steel slags, making them less viscous. A shipment of crushed olivine in bulk, produced in a distant, small olivine mine in a high-wage country costs

around 23 Euro per ton in the port of Rotterdam. If olivine is going to be produced in large open pit mines in low-wage tropical countries, and transport is limited, the combination of these advantages will lead to a price of olivine between 10 and 15 Euro per ton. In turn this results in a price around 10 Euro per ton of captured CO_2, far less than the 60 to 100 Euro for the option to capture, purify and store underground the CO_2 emitted by coal-fired power plants, oil refineries or cement factories. This so-called CCS (Carbon Capture and Storage) unfortunately seems to be the only option that is considered at present.
If enhanced weathering is adopted instead, tropical countries will probably be the place where the bulk of CO_2-sequestration will take place. The major culprits, however, are the industrialized countries, with China and India catching up fast. Let us see in what ways the olivine option can be applied in these countries as well.

Enhanced weathering in temperate climates
One can think (and some of these projects have started already in the Netherlands) to replace quartz sand by olivine, which has a comparable hardness. This holds for example for sandblasting, for olivine sand in the top layer of major roads, for incorporation in concrete, for the top layer in pavement or making footpaths in parks with olivine, for the use of olivine in the soils of roof gardens or spreading olivine powder in lawns and gardens. Olivine buffers acid soils, so it can take the place of liming. Olivine does more than just absorb CO_2, because it also acts as a slow-release magnesium fertilizer. The purpose of this paper, however, is to highlight one particular future application, the olivine hills.

The olivine hills
Based on our experience with natural weathering of olivine rocks, and our experimental production of magnesium bicarbonate water from the reaction of low mineralized sparkling water with olivine powder, we propose the following. Towns, which produce directly or indirectly vast amounts of CO_2, can construct hills of olivine powder in a highly visible section of the town. An order of magnitude for such hills could be a height of 10 to 20 meters, covering a surface area of 400 to 1.000 m^2, or even larger if conditions permit. This is equivalent to between ten and fifty thousand tons of olivine powder. The olivine powder should be deposited over an impermeable bottom layer consisting of 2 planes making an angle of 170^0 (a side slope of 5 degrees each), forming a kind of very broad and shallow gutter (see fig.2). The gutter itself should have a forward slope of 5 degrees as well. The olivine must nicely cover this construction, which thus remains invisible from the outside. The more or less horizontal top of the hill, except for some minor landscaping, must be covered with a layer of soil, rich in humus (remember that soil atmospheres can be more than 100 times richer in CO_2 than air). In wet climates it will not be necessary to have special provisions for watering the hill, but in drier climates it may be advisable to have a fountain on top. Flowers, shrubs and even small trees can be planted on top of the hill and on its sides as well.
Water will infiltrate from the top and pass through the olivine powder, which will act as a slow trickling filter. The grain size of the olivine should be chosen in such a way that it will take a drop of water several weeks before it reaches the impermeable barrier at the bottom, in order to provide a sufficient residence time. This is necessary, because the

olivine-water reaction is slow. It is advisable, however, to use a coarser grain size of olivine both on top and at the bottom of the hill. On top it will guarantee that during excessively heavy rains the water will not form stagnant pools, or even run off the sides of the hill. At the bottom a coarser sized olivine on top of the impermeable plates will insure that the water, once it has passed through the hill, will easily flow to the lowest point (the end of the "gutter"), where it will leave the pile. Here a tap can be constructed, permitting people to drink their own home town mineral water, after it has been analyzed and declared safe for drinking. Drinking this water will reduce the risk of cardiovascular diseases and diabetes.
Each olivine hill is only a small part of the huge mega-engineering scheme to combat climate change by enhanced weathering. Even if a large number of cities take up the challenge as proposed here, it will only have a relatively minor effect on the CO_2 balance of our planet, much less than the spreading of olivine powder over vast areas in tropical countries. Even so, it will help to draw the attention of the public to the global problem of climate change, and show that everybody in his own small way can help to fight it. It is certainly helpful to remind people that magnesium bicarbonate waters are healthy, and are acknowledged to be effective against among others cardiovascular diseases and diabetes (FAO, 2002), whereas a lack of magnesium promotes premature aging. This is apparently realized by the population living near massifs of olivine-rich rocks. When we collected samples of these spring waters in Turkey, which are represented on fig.1, we often had to stand in line, because lots of people were filling their bottles and canisters with such magnesium bicarbonate spring waters.

Adaptation **and** *mitigation*
Olivine hills, apart from serving to capture CO_2 and providing healthy mineral waters, could also be used as a refuge in areas prone to flooding. Let us consider Bangladesh for example. Large tracts of the densely populated country are low-lying, and threatened by devastating floods caused by hurricanes or by rivers of the Ganges system bursting their banks. It can be expected that such calamities will happen more often as a consequence of sea level rise caused by climate change. Moreover, a well-meant but ill-advised program to replace surface water for human use in Bangladesh by ground water from dug wells has turned into a disaster, as many of these ground waters were found to contain high levels of arsenic, causing illness and death to hundreds of thousands people.
If one were to construct olivine hills in villages threatened by flooding on the one hand, and drinking water with high arsenic levels, olivine hills should be constructed in a central location of the village. It will be necessary to bring in the crushed olivine from abroad. There are no olivine mines in Bangladesh, nor in the neighboring countries, but there are vast reserves of olivine-rich rocks. Myanmar has some peridot mining (the gemstone quality of olivine) in the Mogok District, NE of Mandalay. Nagaland is said to have substantial reserves of olivine-rich rocks. The best bet, however, are the chromite mines in Orissa State, NE India. Chromite occurs here in dunites/peridotites, and the mine dumps must hold huge volumes of crushed olivine rocks (Satapathy and Gaswani , 2006) From the chromite mines this material should be transported to a sea port on the Indian coast, and from there transported to the point of use in Bangladesh. Once the olivine hill is constructed, cattle should not be allowed to graze on the hill, nor should any permanent housing be built on it. In normal times the hill will serve to produce clean

and healthy drinking water, from the rainwater that filters through the olivine. As described above, this water will exit the hill at the lowest point of the impermeable layers on which the hill is constructed. It is estimated that for a village of 400 people, a hill of 20 by 30 meters with a height of 10 meters could provide 4 liter a day of clean and healthy water per person. The water should be restricted for drinking purposes. It is up to the villagers to set up a system in which every inhabitant gets his fair share of clean water. In times of flooding, the whole population can seek refuge on the hilltop.

Acknowledgments
Mrs.Maria Segas from Loutraki kindly provided information on the Loutraki mineral water. Rosa Nettekoven and Nico Schouten, of the Fons Vitae Lyceum in Amsterdam, helped to determine the optimal grain size of olivine for the use in olivine hills. Martine Sluijs and Renske Zwart, of the Utrecht programme “Climate in order” are thanked for their enthousiastic support, which will hopefully soon result in the construction of the first olivine hill.

References

FAO Document Repository (2002) Human Vitamin and Mineral Requirements. Chapter 14, Magnesium.
Satapathy, R.K. and Gaswani, S. (2006) Mineral potential of Orissa State: a kaleidoscopic review. Orissa Review, May 2006, 1-14.
Schachtschabel, P., Blume, H.-P, Hartge, K.-H, Schwertmann, U. (1982) Lehrbuch der Bodenkunde, Ferdinand Enke Verlag Stuttgart, 442 p.
Schuiling, R.D. (1998) Geochemical engineering: taking stock. J.Geoch.Expl.**62**, p.1-28.
Schuiling, R.D. and Krijgsman, P. (2006)) Enhanced weathering; an effective and cheap tool to sequester CO_2 . Climatic Change, **74**, nrs 1-3, p.349-354.
Sumner, M.E. (2000) Handbook of Soil Science, CRC Press London, New York, Washington.

Caption for fig.2

Artist impression of an olivine hill at the campus grounds of the Utrecht University