many places under a large variety of conditions. In fact, the higher pH imposed on soils by the weathering of olivine will reduce the mobility of many metals.

11. Rate of weathering of olivine

Much of the debate on the potential of enhanced weathering using olivine grains to counteract climate change centers on the problem of the rate of weathering. The rate of weathering is enhanced in hot humid conditions, hence why this idea is focused on the application of crushed olivine in the wet tropical regions.

There are a number of reasons to focus on the wet tropics for large-scale applications:

- Weathering is faster under hot, humid climatic conditions
- Tropical soils are usually very poor, and can benefit from the addition of mineral nutrients.
- As almost all potential participating countries are developing countries with low wages, this lowers the cost of mining
- Olivine rocks sometimes contain marginal chromite, nickel, or magnesite deposits, and the related rock kimberlite is the normal host rock for diamonds. If the rock itself is also put to good use, and brings a profit in the form of carbon credits, instead of being considered as a mining waste, this may make such marginal deposits economical.

This does not mean that the olivine option is useless in temperate climates, it is just that the rate of weathering will be slower.

In abiotic laboratory experiments it was found that the surface of olivine grains retreats at a few tenths of a micron per year (22). This is described by the shrinking sphere concept. Such low rates would make it difficult to use enhanced weathering to mitigate the greenhouse effect. Fortunately, there is observational evidence on rates of weathering of olivine in the real world (see below), which shows that the rates are more than tenfold, and probably hundredfold larger than found in the laboratory.
Qualitative information on fast rates of weathering is obtained from volcanic terrains with rocks containing olivine. When volcanism started in the Eifel/Germany, synchronous Rhine sediments downstream in the Netherlands immediately started to contain a wealth of volcanic minerals, but **NO OLIVINE**, despite the fact that these volcanic rocks contain plenty of that mineral. Contrary to the other minerals of volcanic origin, olivine has not survived the short trip from Bonn to the Dutch border. Similar observations are reported from many other volcanic terrains in the world. Although suggestive of fast weathering, this evidence is difficult to quantify. In contrast, the rate of weathering of dunite massifs in the tropical zone can be quantified, or at least a minimum rate of weathering can be firmly established.
The first example is the dunite massif of Conakry/Guinea. This dunite occupies the entire peninsula on which Conakry, the capital of Guinea is situated. It has an approximate length of 50 km, and an average width of 5 km. Over its entire surface it is covered by a thick lateritic weathering crust, which is very clearly visible as a purplish red area on satellite pictures (see Figure 6). This lateritic crust, which is the iron-rich insoluble red residue of the dunite after deep tropical weathering, contains virtually no silica, magnesium- or calcium-oxides which were completely leached out during the weathering process (23). These components make up around 90% of the original dunite. This means that 1 meter of laterite is equivalent to 10 meters of dunite, or even more if the remaining components of the laterite were not completely immobile but have also been leached to some extent. The same author presents evidence that iron has in fact been fairly mobile and was partially leached out as well, which means that 1 m of laterite is equivalent to more than 10 meters of dunite. The weathering crust has a

to be > 3.1 micron/year, but the same positive corrections have to be applied as in the Conakry case.
From a global balance of weathering and erosion, similar minimum rates of weathering emerge. The average rate of erosion of the continents is 1 to 2 cm in thousand years [24]. As olivine grains from the interior of the continents don't make it to the oceans, this means that olivine rocks dissolve (= weather) at least at the same speed, which is 10-20 micron/year.
The most dramatic evidence for fast weathering of crushed magnesium silicate rocks comes from observations of weathering rates of mine dumps of such rocks (26). By measuring the amount of a suite of newly formed Mg-carbonates, it was shown that the mine tailings of two abandoned asbestos mines in British Columbia weather extremely fast. In this case it does not involve fresh olivine, but its hydration product serpentine ($Mg_3Si_2O_5(OH)_4$) that weathers and produces carbonates. This carbonation proceeds as follows:

(10) $Mg_3Si_2O_5(OH)_4 + 3\ CO_2 + 2\ H_2O \rightarrow 3\ MgCO_3 + 2\ H_4SiO_4$

At low temperatures magnesite seldom forms, but in its place hydrated magnesium carbonates like nesquehonite, $Mg(HCO_3)(OH).2H_2O$ are found instead (figure 7).

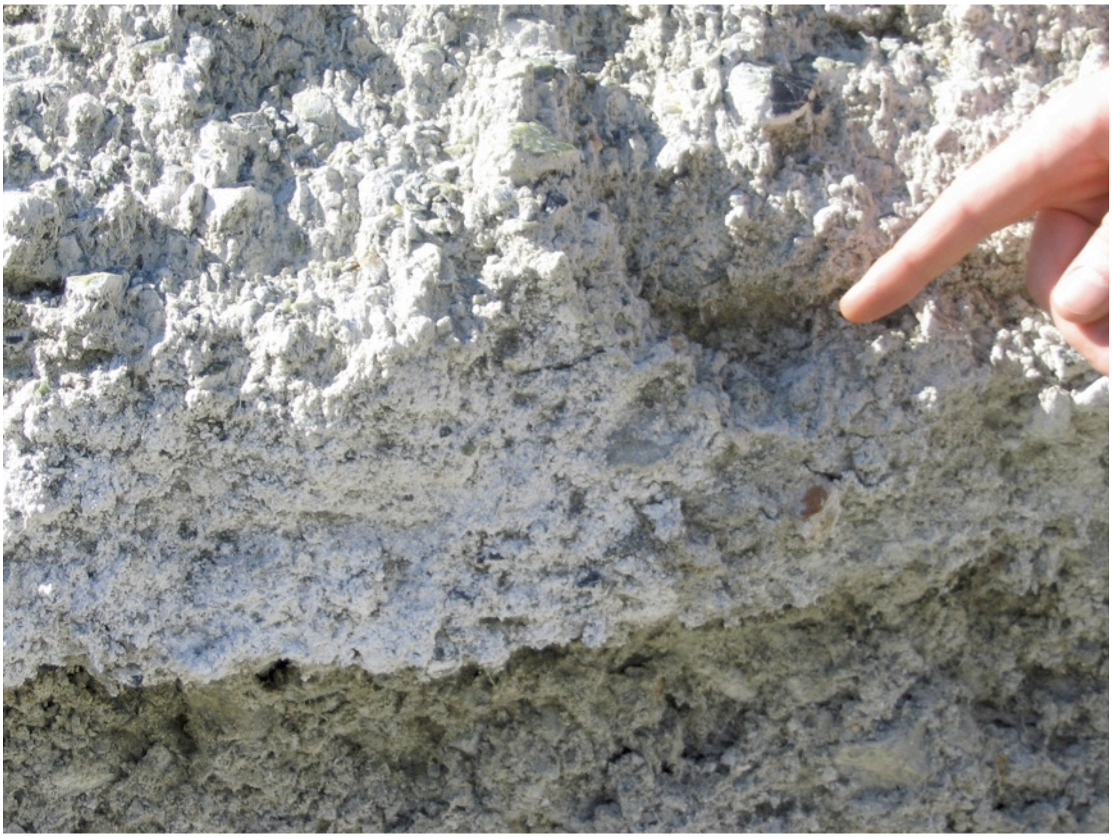

Figure 7: Efflorescence of nesquehonite on the serpentinite tailing heap at Clinton Creek. Photograph by S.A.Wilson.

In order to make sure that these carbonates have indeed newly formed, ^{14}C-analyses were performed on these carbonates which gave an age of about 0, showing that the carbon in these minerals really represents the sequestration of present-day atmospheric carbon (27). In one of the cases the mine dump, occupying a surface area of 0.5 km^2, had captured 82000 tons of CO2 between 1978 and 2004, more than fifty times the maximum ever recorded for natural weathering under the most favorable conditions. The real rate of weathering is even higher, because the authors have only taken the solid products into account, whereas the waters that percolate through the mine dumps carry an additional load of dissolved weathering products. These waters become quite alkaline, and their high silica content leads to small diatom blooms in a pool at the foot of the tailings dump and in at least one of the mine pits (27, 28, 29).

One may wonder why there is such a large discrepancy between laboratory experiments, showing low rates of weathering, and the real world, where weathering rates are 100 times larger. The answer is relatively simple. Higher plants live in symbiosis with mycorrhizal fungi in and around their root system. These fungi secrete low molecular organic acids like acetic acid, malic acid and oxalic acid that rapidly attack mineral grains in the soil (30). This liberates mineral nutrients that are subsequently taken up by the higher plants. In turn, the higher plants "reward" the fungi by providing them sugars. Lichens act in a similar way by secreting oxalic acid that "eats" the underlying rock (31). In the laboratory, mycorrhizal fungi and lichens are absent, and this is the reason why the abiotic reaction rates that were found in the laboratory are much lower than weathering rates in nature.

This all refers to weathering rates of olivine on land. Much less information is available for olivine on beaches, the surf zone or tidal flats. Olivine beaches are practically restricted to places where cliffs of olivine-rich rocks overlook the beach. Like on any other beach sand, the olivine grains are rounded, which means that they have lost little slivers of olivine when the grains were bumping or scraping against each other. This has the advantage that one does not need to mill the olivine at high cost to very small grain sizes, because the surf will take the place of the ball mill. These little slivers will quickly disappear by weathering. It is hard to draw much quantitative information from this evidence. It is proposed, therefore, to carry out a fairly large-scale experiment with a so-called olivine reactor, as follows; a long concrete box of 50 meter long and 4 meter wide is constructed perpendicular to the coast and filled with olivine sand (see fig.8). To obtain even more information from this experiment, the reactor can be partitioned lengthwise, and the two compartments can be filled with olivine sand of different grain sizes. On its coastal side there is a low inlet, permitting sea water to enter the box during high tide. The sea water will drain from the other side towards the sea during ebb, after having passed through 50 meter of olivine sand. By analyzing the water before and after it has passed the olivine reactor, one can calculate how much olivine reacts during each tidal cycle, and how much CO2 it can capture. Once the CO2 that is transformed into bicarbonate is in the sea water, it will take time before it is transformed into carbonates in the form of shells and corals, but no figures are available for this final uptake. It is reported that olivine weathers somewhat faster in a saline water than in fresh water (32)

Figure 8; the olivine reactor

For tidal flats a very different picture emerges. Tidal flats are inhabited by huge populations of lugworms (*Arenicola maritima*). The upper few centimeters of the mud pass on average three times each year through the guts of the lugworm. In its digestive system, weathering is 700 to 1000 times faster than outside (33). In experiments in which lugworms were fed with small fragments of basaltic rock, these pieces came out as small heaplets of clay (34). As basalt weathers much slower than dunite, it can be expected that spreading of olivine grains over tidal flats is a very effective application of enhanced weathering/sequestration of CO2.

12 .Costs

Except in cases where the required olivine-rich rock is already available in crushed form on mine dumps, for example of chromite, magnesite, asbestos or diamond mines or even small mines where peridot, the semi-precious variety of olivine is won, the application of enhanced weathering implies mining and milling of solid dunite rock from large open pit mines. In 2002 two Swedish mining engineers calculated the cost of mining and milling of bulk rocks in large open pit mines (35). This turns out to be 6 Euro/ton. After passing the primary and secondary crushers at the mine site, the granulated material must then be transported from the mine to the points of use. If we restrict the transport distance to a maximum of 300 km around the mine, this adds on average 6 Euro/ton for transport. From the stoichiometry of reaction (8), one can calculate that one ton of olivine will sequester 1.25 tons of CO2. This brings the price for the sequestration of CO2 to slightly under 10 Euro/ton, making it by far the cheapest method to sustainably capture CO2. In comparison, CCS, the most commonly discussed technology for the sequestration of CO2 costs between 70 and 100 Euro per ton of CO2 (36)
Even although the costs are modest, compared to other options that are considered, the cost to sequester all man-made CO2 emissions by enhanced weathering of olivine still comes to around 250 billion US$/year worldwide. Most other options that are being discussed would require in excess of 1 trillion US$, and for most of them it is doubtful if they could ever achieve the goal of capturing

25 billion tons of CO_2 annually. It is good to realize that even if we can reduce the cost of 1 ton of crushed olivine at the point of use by only 1 cent, such a trivial difference would still represent an annual saving of 250 million US$.
The energy costs, expressed in terms of the CO_2 expenditure for mining, milling and transport have been calculated in a LCA-analysis (life cycle analysis) (37). The total CO_2 requirement for the operation as a whole turns out to be 4% of the CO_2 that will later be captured by the extracted olivine. This is quite satisfactory if one compares it to the CO_2 expenditure of the CCS operation, which is around 29%. This means that the introduction of CCS will require 1 additional power plant to remove the CO_2 emitted by 3 to 4 power plants!

13. Mitigating Environmental and Social Costs
(This section is mainly based on a personal communication by Mrs.Gwendolyn Wellmann, community development specialist, Port Elizabeth, S.A.)

There are, however, also environmental costs (and benefits) to the olivine option. Every mining operation has a negative impact on the natural and social environment, even if the mining is done for the purpose of solving a worldwide environmental problem. Fortunately, there are ways to overcome the environmental damage, or at least diminish it. All dunite bodies in the tropical zone are covered by a thick laterite (laterite is the typical red soil of tropical countries, an iron-rich residue that is left after the weathering of rocks in tropical climates). Dunites contain on average 0.2 to 0.3 % nickel, which is not very soluble during weathering. As most of the major components (SiO_2, MgO, CaO) are leached out during weathering, the Ni-content of the residue rises accordingly, and may reach 2% to sometimes over 3% Ni, making these nickel laterites a rich nickel ore (38). In a number of countries (e.g. Brazil, Cuba, Philippines, Indonesia, New Caledonia, Madagascar, Malawi) these Ni-laterites are mined, or mining options are being studied. By continuing the mining below the laterite crust, and also mine the underlying dunite, one can avoid the impact of clearing a new mining site, the infrastructure for mining is already in place at such locations, and there is a local population that depends on mining for their living. The removal of the overburden consisting of Ni-laterite ore is an additional financial bonus for the mining of dunite below. This way one can save the environment, help the people, and at the same time make olivine mining cheaper.
Even though mining brings with it many positives to an area, including employment opportunities, infrastructure development and local economic development; and even if it is an olivine mine that will benefit the earth, mining also brings with it many negatives, such as an influx of job seekers, the increase of HIV/AIDS, violence and discontent. In terms of mitigating the negative impact on the social fabric in a mining area, what is most important is the attitude of the mining company. The majority of mining companies adhere to the International Council on Mining and Metals' '*Sustainable Development Principles'* (39), with its underlying message that the overall success of any mining venture in a populated area is to consult, consult, consult with the local people. This requires the company from the onset, which might mean as early as the time of exploration activities, to meet with the local people; gain their views; understand their concerns; seek first to understand what makes the local community tick, before expecting them to understand your needs; and to devise long-term mitigating actionable plans for the rehabilitation of the area.
Should an olivine mine be established in a poor, developing country, it is vital that as the mining company starts to invest in the community, whether through infrastructure, local economic development or alternative livelihood projects, it also invests in the development and promotion of a functional local government. This is important because the management and maintenance of these projects will ultimately be the responsibility of the local government. A weak, nearly non-existent local government will lack the correct policies, procedures, structures and

systems to ensure sustainability of any project invested in by the local mine. The result of this is that there is a tendency for both the affected communities and the government to rely on the mine to assume local government roles. This can be problematic as implementing local governance is not the mine's expertise or responsibility, and as has been demonstrated numerous times in many countries, when the community feels the lack of service delivery, they will express their discontent by attacking the mine. One of the ways of investing in local governance is to expand the skills base of local government officials through training. The skills that are most frequently lacking in these areas are those needed for planning, budgeting, project implementation, and public consultation. Once olivine mining is a certified means of obtaining carbon credits, it is recommended that it is supervised by a special international body.

14. Ways of spreading the olivine

In order to bring the olivine grains from the mine to the point of use, several transport systems can be considered. The first to come to mind is road transport, but road transport is fairly expensive, so it is worthwhile to consider other options first. Looking back to Figure 5, the dunite massif of Conakry, it is interesting to note that the capital Conakry, at the tip of the peninsula, is a major port from where huge volumes of bauxite are exported. Guinea, which is one of the largest producers of bauxite in the world, possesses two railroad lines which transport the bauxite ore from the interior to the port. These lines run along the entire length of the peninsula which is underlain by dunite rock. The railroad lines pass close by the most likely point where olivine mining could start. It becomes then a logical step to fill the bauxite trains with crushed olivine, when they return empty, to transport it to the interior, where it can be spread locally.

If farmers from the surroundings of the mines bring their products to the marketplace of the mine town by oxcart or truck, they can carry an olivine load back for a small financial compensation. As in poor countries the farmers have no money to buy expensive fertilizers, they will grab the chance to add mineral fertilizers to their land and even make some money by doing so.

On plantations around the mine, fertilizer spreading or pesticide spraying can be combined with spreading of olivine grains or spraying olivine slurries. This will save the owner of the plantation the cost of Mg-fertilizer, as the olivine will serve as such. In the Netherlands, several small projects of spreading olivine have been started, showing its beneficial effects on soils and vegetation.

It was stated already that the best places to apply the olivine option are the wet tropics, because weathering proceeds fastest in a hot and humid climate. That implies that there will be rivers nearby in most olivine mining sites. Transport by flat-bottomed barges is much cheaper than road transport. Boat transport does not have to be limited to bringing the crushed olivine from the mine to a particular location on the river, but the boats can be equipped with pumps and spray the river sides with olivine slurry.

These rivers in the wet tropics can also themselves be used as the means of transport. In the wet monsoon, when the rivers are swollen they burst their banks and become muddy from an increased load of suspended matter. In the wet season they may transport up to 8 kg of suspended solids per m^3. It is a simple operation to add a few hundred grams of olivine grains per m^3. In its lower reaches, where the river overflows and inundates its delta and deposits overbank sediments, the olivine grains will settle too and start to weather, assisted by biota.

A rather unusual way could be to make use of dust storms to spread the olivine. A single dust storm can carry millions of tons of dust. The olivine mine can add a small part of olivine dust by blowing it into the storm. Even if only one percent dust in the form of fine-grained olivine is added, this will save 1500 truck loads

on average for each dust storm. The dust particles that fall in the ocean will directly help against ocean acidification.
By making maximum use of the opportunities provided by local conditions, all such measures can help to further reduce the cost of enhanced weathering to capture CO_2.

15. Applications of the olivine option

It should be emphasized that the presence of liquid water is essential. This rules out all countries with a desert climate except along their coasts, where olivine grains will disintegrate in the surf, and be spread by wind and currents. The rate of reaction is increased by a high temperature. There are a number of arguments to focus on the wet tropics for **large-scale** applications:

- Weathering is fastest under these climatic conditions
- Wages are generally low, making mining cheaper
- It provides considerable employment to developing countries, and will boost their economies. Western countries can label part of the costs involved, although aimed at curbing CO_2 levels, as their development aid which, in effect, it is also.
- Tropical soils are usually very poor, and can benefit from the addition of mineral nutrients.

For all mines, not just the ones in the wet tropics, the following arguments hold:

- Large mines profit from the economy of scale
- Olivine rocks sometimes contain marginal chromite, nickel, or magnesite deposits, and the related rock kimberlite is the normal host rock for diamonds. If the host rock itself is also put to good use, and brings a profit in the form of carbon credits, instead of being dumped as a mining waste, this may make such marginal deposits economical.
- Once the olivine option is accepted as a legitimate means of carbon capture, the olivine mines can sell carbon credits.

The central premise of the crushed olivine method to enhance weathering is to apply the crushed material in the best climate for weathering, i.e. the wet tropics. This does not mean that the olivine option is useless in temperate climates. There are at least 2 valid reasons to look also for applications in the Western industrialized world. One is the ethical consideration that these nations should also make a visible effort to mitigate climate change themselves, as they are the main culprits for causing it. The second argument is that only when olivine-related projects are executed in their own neighborhood can the general public become familiar with the concept, and come to appreciate its beneficial side effects.
There may be additional novel or niche applications suitable to certain regions, such as using olivine sand instead of quartz sand to strew into Astroturf playing fields, using olivine gravel on tennis fields, spreading olivine grains on lawns to reduce the growth of moss, using olivine as the top layer on footpaths or bicycle paths, adding a layer of olivine as roof covering, using olivine instead of quartz in sandblasting, using olivine grit on icy roads, adding olivine powder to digesters to improve the quality of the biogas by transferring the CO_2 part of the biogas to bicarbonate in the liquid, using olivine sand in sound barriers along main roads. These are all fairly minor applications, although taken together they are not negligible.
A larger application that can be used in the tropics as well as in temperate climates is to cover beaches that are subject to erosion or tidal flats by olivine sand. Olivine is considerably heavier than quartz and will not be eroded and

transported away from the beach as easily as quartz sands. The tides will alternately wet the beach and drain the pore water. During such a tidal cycle the olivine will react with the sea water, thus adding alkalinity to the sea, which makes it possible to store more CO_2 as bicarbonate in the seawater without acidifying it. The olivine grains bump into each other or scratch each other when they are moved by the surf. They become rounded, and the tiny slivers that have come off the grains will very rapidly weather (40). At the foot of olivine cliffs along the coast, one finds olivine-rich beaches which are frequented by many tourists.

If marine constructions (dams or artificial reefs) are built with olivine blocks and sand, this will conceivably lead to well cemented structures after some time. Seawater is saturated with $CaCO_3$. If the water between the olivine pieces is only slowly replaced it can react with the olivine for some time. This raises the pH of the interstitial seawater, causing a shift in the carbonate equilibria. This leads to a supersaturation of calcite which precipitates as a cement between the olivine. This process is similar to the formation of beach rocks.

Filling the solution holes left by underground solution mining of salt with olivine powder serves two, possibly three purposes. After the cavity is filled with olivine, it is no longer necessary to keep the brine-filled hole permanently pressurized to prevent it from collapsing, because the olivine will support the cavity. By injecting CO_2 into the mixture of olivine and brine one captures CO_2 as bicarbonate. The heat of reaction of carbonatation + hydratation may heat the water sufficiently to use it for warm thermal medicinal baths, or swimming pools.

Some larger, or economically more important applications are described below.

16. Olivine hills

Another eye-catching application are the olivine hills (17). Cities that want to display their concern over future climate change can construct a hill of olivine sand in a very visible spot in or around the city. It involves piling olivine sand over two impermeable layers which make a very obtuse angle with each other, thus creating a wide and flat gutter. The gutter itself should also be inclined, making one end the lowest exit point for any water that has passed through the olivine. The hill should be covered by a layer of soil, planted with grass and small bushes. Vegetated soils have a soil atmosphere which has a much higher CO_2 concentration than air. Rainwater that falls on the hill, after having passed through this CO_2-rich soil layer, will infiltrate the olivine and trickle downwards, on its way reacting with the olivine. This converts the rainwater into a magnesium bicarbonate water. Such waters, according to a handbook of the FAO (41) are very healthy and stated to be effective against cardiovascular diseases. After a tap has been mounted at the exit point, and the water has been analyzed and declared safe for drinking, one can collect the water and drink it. This way every city can proudly claim its own brand of mineral water, while at the same time making a contribution to carbon capture. Because such olivine hills are aimed at the public, they should be accompanied by a clear and attractive explanation of their meaning, and the role of olivine weathering as a mitigation approach to climate change.

A less playful application of the olivine hills concept may be to construct such olivine hills in villages in Bangladesh, threatened by recurring flooding. Bangladesh suffers not only from recurrent devastating floods, but has also been struck by a man-made environmental disaster. In a well-meant but ill-advised attempt to avoid the frequent cholera epidemics that were the result of drinking polluted surface waters, many wells were drilled throughout the country to provide the population with groundwater for drinking. Unfortunately, many of these wells turned out to contain very high levels of arsenic, causing death and illness to hundreds of thousands of people. By constructing such olivine hills in villages threatened by flooding as well as by arsenic-rich drinking waters, clean drinking water can be provided in normal times, while during flooding the population can seek refuge on the top of those hills. As a precaution it is advisable to use coarser grains of olivine for the top layer, to present the formation of pools, which may turn into breeding places for mosquitoes. And again, such hills sustainably capture CO2.

17. Nickel recovery by phytomining

A return to the nickel laterites mentioned earlier leads to a completely different application. The extraction of nickel from such deposits is polluting and energy consuming. It has been found that certain plant species growing on Ni-rich soils as found on dunites or serpentinites are hyper-accumulator plants for nickel. Figure 9 shows one of those hyperaccumulator plants, growing on a serpentinite in Cyprus.

Figure 9: The genus *Alyssum* knows several hyperaccumulator species for nickel. The picture shows the *Alyssum cypriacum.* The pictured Alyssum has a height of approximately 15 cm. Photograph Wouter Swart.

The ash of this plant contains almost 5% nickel, making it a rich Ni-ore. This opens the way to a new way of mining called phytomining (42), while at the same time capturing CO2, and saving CO2 emissions when the normal energy-intensive metallurgical road for nickel production is replaced by planting and harvesting nickel accumulator plants. If one collects broken Ni-laterite pieces and mixes them with crushed olivine and constructs a thick bed with this mixture, these hyperaccumulating plants can grow on it. These plants seem to require sufficient N and P fertilizers which can be obtained by using the age-old method of collecting and spreading urine. By harvesting and ashing these plants one obtains a rich Ni-ore while at the same time this constructed “farmland” has captured

CO2. It has been calculated that one can obtain several hundred dollars worth of nickel each year per hectare.
In those locations where a dunite is covered by a nickel laterite, but where there is no operating nickel mine, this lateritic overburden must first be removed before the dunite mining can start. In such cases the workers at the mine can put the nickel laterite pieces aside and mix them with crushed dunite over plots of land, plant these plots with nickel accumulating plants, harvest these plants from time to time and ash them. They can sell these ashes as a rich nickel ore to a nickel smelter, and in this way supplement their wages.

18. Olivine in biodigesters

A quite different application of olivine is in biodigesters. Biodigesters are installations where agricultural waste, urban sewage sludge and organic waste stream from industry are anaerobically digested; during digestion, the organic material is turned into biogas. The biogas that is produced consists for around 2/3 of methane and 1/3 of CO2. By adding olivine powder to the digester, part of the CO2 gas will be converted to bicarbonate in solution, so the quality of the biogas will improve. As yet unpublished experiments at the Wageningen Agricultural University have shown that this is indeed the case, but there were two unexpected additional positive results. Most of the smell disappears. This can be explained by the fact that the FeO that is liberated when the iron part of the olivine dissolves reacts immediately with H2S and forms solid iron sulfides. A second effect was even more unexpected. The methane did not only increase in relative amount, but also in absolute amount. In nature, serpentinization of olivine under exclusion of free oxygen is often accompanied by methane emissions. These are due to the following reaction

(11) $6\ Fe_2SiO_4 + CO_2 + 14\ H_2O \rightarrow \mathbf{CH_4} + 6\ H_4SiO_4 + 4\ Fe_3O_4$

Sometimes this leads to methane flames, like in the Turkish Yanartasi (the rock that always burns), where a peridotitic rock is being serpentinized at some depth and in Los Fuegos Eternos (the eternal fires) in the Zambales ophiolite complex on the main island of the Philippines, Luzon. The increase in methane production in the biodigesters is probably due to the same reaction.

19. Collateral benefits

a. Improvement of soil productivity
It was already pointed out in the report entitled "Geoengineering the climate" of the commission on geoengineering to the Royal Society that the consequences of enhanced weathering could be benign in principle (43).
One of the most obvious advantages of enhanced weathering is that it has the potential to mitigate ocean acidification, the decrease of pH in response to rising atmospheric CO2 concentrations (44). The ongoing lowering of the pH endangers the growth of coral reefs (2), and likely affects marine life in general.
A number of other collateral benefits of the olivine option can be mentioned. Tropical soils, except in areas with recent volcanism, are generally very poor, as they lack important mineral nutrients like magnesium, calcium, potassium and phosphate. A limited amount of these nutrients is recycled by the standing forest, but once this is cut, the trees are removed and the soil is used for agricultural crops, it loses its productivity very fast. Spreading crushed dunite rock will solve the magnesium problem, and the calcium problem as well to some degree. Kimberlites, the host rock of diamonds, are also olivine-rich, but in addition they contain a potassium mineral (phlogopite) as well as often some phosphate. In

order to provide a more balanced mixture of major nutrients, one should spread the crushed kimberlite of which hundreds of millions of tons are lying on the mine dumps of diamond mines. At the request of the author, seepage waters from kimberlite tailings in India and South Africa were analyzed. It was found that the waters that seep through these kimberlite tailings have a high pH and sequester large amounts of CO_2 as bicarbonate. Moreover they can contain significant concentrations of potassium (data from the de Beers mine tailings in S-Africa and the Panna diamond mine in India, Schuiling, unpublished). Again, one should avoid as much as possible mining wastes that contain chrysotile, although this white asbestos is considerably less dangerous than crocydolite (blue asbestos) or amosite (brown asbestos), which are not associated with dunites or peridotites. Recent research by Arcadis has shown that chrysotile weathers quite fast, and thereby loses its fibrous character. (45).
Mindful of the beneficial effects of volcanic rock on the fertility of soils, it may also be a good idea to spread mixtures of crushed dunite and rock meal like volcanic tuffs in areas with poor soils. Although the rock meal weathers considerably slower than dunite powder, and thus contributes much less to CO_2 sequestration, the combination is likely to increase productivity of the soil for a number of years, by which it can contribute to world food production. In view of the scarcity of potash fertilizer and its high price, it is recommended (46) to use powdered nepheline syenites to provide potassium to poor tropical soils, as the nepheline $(Na,K)AlSiO_4$ weathers considerably faster than potash feldspar.
Acid sulphate soils form another problem that can be solved by spreading olivine. The Mekong delta, as well as a number of soils in estuaries along the East coast of Australia suffer from high acidity, once the soil is plowed in preparation for agriculture. This exposes the pyrite in these soils to the oxygen in the air. The pyrite oxidizes and produces sulfuric acid, which reduces their rice productivity (Mekong) or sugarcane production (Australia) considerably (47). If crushed olivine is spread on these acid sulphate soils, its weathering will neutralize the acid and thus increase their productivity. If the neutralization reaction is very simplified to:

(12) $2\ FeS_2 + 2\ Mg_2SiO_4 + 7.5\ O_2 \rightarrow 4\ MgSO_4 + Fe_2O_3 + 2\ SiO_2$

this would mean that 1 ton of soil with 1 % of pyrite would require close to 12 kg of olivine for complete neutralization.

b. production of biofuels from siliceous algae
In a very different manner olivine can help to produce biofuel from algae instead of from land-based crops which use up land that is thereby lost for world food production and cost large amounts of scarce irrigation water (48,49). Diatoms (siliceous algae) grow very fast and are a proven raw material for the production of biodiesel, as they have a lipid content around 50%. Their growth, unfortunately, is often limited by the availability of silica, which they need to build their silica skeletons. During weathering, olivine releases large amounts of silica in solution. If one constructs a lagoon, preferably where the coastal waters carry large loads of urban or agricultural waste, diatoms can be grown in the following manner. The lagoon should be along a coastal stretch where the beach can be covered by olivine sand. A dam must be constructed around the lagoon to separate it from the open sea, except for one or a few U tubes through this dam. These U tubes permit the exchange of water between the lagoon and the open sea. The opening on the lagoon side of each tube should be covered by a perforated metallic plate, which acts as a support for a plankton net. During high tide the water will flow into the lagoon and wet the olivine sand on the beach. During low tide there will be an outflowing current of the water, including the part that formed the pore water between the olivine grains on the beach that is drained during ebb. This outflow will also carry the diatoms, but these are

retained on the plankton net, where they can be harvested to be used as the raw material for biodiesel production. It is expected that in such diatom farms almost pure diatom cultures will form, as they have a competitive edge over organisms that don't use silica.
The growth of diatoms might also be stimulated for quite a different purpose. More and more often coastal waters are threatened by poisonous dinoflagellate blooms ("red tides"), causing massive fish kills, and threatening human health. The main reason is believed to be the supply of untreated urban waters that contain high levels of nutrients. If one could stimulate the growth of fast-growing and non-poisonous diatoms to consume the contained nutrients in these coastal waters, this may reduce or eliminate the dinoflagellate blooms. Besides, diatoms are an excellent fish food. The stimulation can be done by applying the same method, covering the beaches with olivine sand which will provide the silica that is necessary for the growth of the diatoms.

20.Geopolitical implications of the olivine option.

Although many scientists realize that CCS is a very costly operation (29), and is unlikely to solve the CO_2 problem at the required volumes, it is still the most widely discussed and preferred option, particularly among Western politicians as well as among parties that see large profits from the use of their abandoned oil and gas fields, from selling the technology to recover and purify CO_2 from the flue gases of coal-fired power stations, from the sale of large compressors to inject the CO_2, and from those scientists and large research institutes that depend on the research projects associated with CCS. This makes for a powerful lobby.
Environmentalists urgently call for a reduction of CO_2 emissions, by increasing efficiency, changing our lifestyle and switching to sustainable energy (wind, water, solar power, biomass, geothermal energy or even nuclear energy). In the long run mankind will be obliged to make the change to renewable energy anyhow, as our reserves of oil and gas are dwindling. Although there are still vast reserves of coal, these too are not endless. It is evident that the world should reduce its carbon footprint as quickly as possible. The most fanatic environmentalists even don't want to see any solution for the problem of rising CO_2 levels, as this would give people an excuse not to change their wasteful style of living. This is undoubtedly true for many people. As soon as science will have found a solution how to sequester CO_2 cheaply and sustainably, they will relax and go on driving big cars and fly often to the most distant destinations for their holidays. It may help to portray such irresponsible people publicly as social outcasts and environmental hooligans, but for the moment they draw more admiration and envy than disgust from the general public. So, trying to change people's attitudes and lifestyles is necessary, but that will be a slow process, whereas the danger of climate change requires immediate action. The two sides have a different time frame, and both are needed to avoid the imminent climate change caused by rapidly rising CO_2 levels in the atmosphere.
The picture is complicated by the fact that the largest industrializing nations (China, India, Brazil and South Africa) all possess vast coal reserves, and want to lift the standard of living of their people as quickly as possible. One requirement to reach that goal is the unlimited access to cheap energy. Reduction of emissions is, therefore, not their top priority, and besides they rightly argue that the Western world has profited over the past 200 years from the possibility of emitting unlimited amounts of CO_2, by which they have reached their high standard of living, so the industrializing nations reject emission cuts and say "now it is our turn to develop our economy".
This deadlock can be broken by allowing, or even by stimulating these nations not to curb their emissions, but instead to compensate them by the use of olivine. All

four industrializing nations mentioned also possess vast reserves of olivine rocks. They can exploit these with their own workforce for 10% of the cost of CCS for the same amount of CO2 sequestered, and it will give them large employment opportunities. Moreover, if they produce more olivine than required to meet their own agreed quota, they can sell surplus carbon credits to the West for 15 Euro per ton of CO2, and still make a nice profit. This will permit them to continue to use their cheap energy based on coal, while still doing their part in counteracting climate change.

21. Future directions

A number of niche applications of the concept of enhanced weathering of olivine have already been set into motion, like the inclusion of olivine in roof coverings, the addition of olivine to fertilizers or potting soil, or the covering of (bicycle) paths with olivine sand. Several other niche applications are under development. A breakthrough, though, depends on the certification of the olivine option for carbon credits, and the start of large-scale olivine mining,
In the global climate debate, enhanced weathering can play a major role to reconcile the views and aims of the West and those of the emerging economies (China, India, Brazil, South Africa), if it is accepted that these countries may continue to use their vast coal reserves as a source of cheap energy, on condition that they compensate their CO2 emissions by enhanced weathering of olivine.

22. References

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