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OLIVINE TO COMBAT CLIMATE CHANGE

Weathering of basic rocks, containing magnesium and calcium silicates, is the main mechanism to capture CO_2 in a sustainable way, with storage of organic carbon a distant second. The CO_2 emission by Man, due to the combustion of fossil fuels is at least ten times larger than the natural CO_2 emission from the Earth. Emission and capture are no longer in balance, and the concentration of CO_2 in the atmosphere is steeply rising. It is a logical step to investigate whether we can stimulate the natural process of weathering in such a way that the balance is restored. Weathering takes place at the surface of rocks, so we must increase the available surface area. This can be done by mining and milling suitable rocks, and spread the powder over land and in shallow seas. Factors that influence the rate of reaction, apart from grain size, are temperature, pH and water. This means that soils in tropical countries are best suited. Soil atmospheres are on average hundred times richer in CO_2 than air. This is caused by the decay of plant material and the respiration of soil fauna. A high CO_2-pressure causes a low pH, which is favorable for weathering. The most suitable rock type is dunite, which consists for more than 90 % of olivine. Dunite massifs are found in many countries on each continent. Large massifs occur among others in Guinea, Sierra Leone and Ivory Coast. By mining the olivine there, milling it and spreading a thin layer over the surroundings, climate change can be counteracted. Weathering is a natural process, that has kept the CO_2 level of the atmosphere within bounds for billions of years, thus no short term or long term negative ecological consequences are to be expected.

Olivine. It is proposed to speed up the natural process of weathering in order to capture more CO_2. Of all the common silicates, olivine weathers fastest. It is the main mantle mineral, but thanks to plate tectonics, large slabs of mantle material have been pushed up and are exposed at the Earth's surface. Olivine is a magnesium silicate, but part of the magnesium is always replaced by divalent iron, giving olivine a green color.

In weathering, we can distinguish between open and closed systems, open where the weathering solution is available in large quantities, and often replaced, closed where a limited amount of solution is more or less stagnant. The first situation is represented by soils which receive abundant rainfall, and by shallow agitated seas. The second situation prevails in dry climates, where the soil solution hardly moves. In open systems, the weathering reaction can be written as

$$Mg_2SiO_4 + 4CO_2 + 4H_2O \rightarrow \\ \rightarrow 2Mg^{2+} + 4HCO_3^- + H_4SiO_4^0. \qquad (1)$$

In closed systems, where the reaction products stay within the system, the reaction becomes

$$2Mg_2SiO_4 + CO_2 + 4H_2O \rightarrow \\ \rightarrow Mg_3Si_2O_5(OH)_4 + MgCO_3. \qquad (2)$$

It is evident that open systems are preferred, because then 8 times more CO_2 is captured with the same amount of olivine [7]. Reaction (1) is the fundamental reaction by which the CO_2 of the atmosphere is converted to HCO_3^- in solution. These bicarbonate solutions are transported by to the oceans, where they will ultimately lead to the formation of carbonate sediments (from coral reefs to dolomites). These carbonates form the ultimate sink for CO_2, but that process takes hundreds, if not thousands of years, so with respect to its effect on climate, reaction (1) plays the major role. Soil atmospheres commonly have around 100 times more CO_2 than the atmosphere itself [5, 9]. Weathering and CO_2 capture proceed faster under such conditions.

The application of the natural process of weathering to capture CO_2 is an example of geochemical engineering, the discipline that seeks to optimize natural processes and use natural materials to solve environmental problems [6].

Olivine mining against climate change. Sustainability is a big issue in mining. The concept is not limited to the mining phase, but it also involves the milling and the spreading of olivine powder over vast areas around the mines, where it will weather and capture CO_2. In that sense the Earth itself acts as a giant reactor.

Let us take the case of the dunite massif of Conakry-Kakoulima in Guinea. It extends in ENE direction along the peninsula for over 50 km, with an average width of 5 km (see satellite image, Figure). On the satellite image the massif is clearly marked by the reddish color of its lateritic weathering cap. The town of Conakry, the capital of Guinea, extends from the tip of the peninsula over 30 km, so a possible site for olivine mining must be sought between the eastern limit of the town and the Kakoulima Mountain.

Like in all tropical countries (Cuba, New Caledonia, Philippines, Indonesia, Guinea, Sierra Leone), the dunite of Conakry is also covered by a laterite crust of around 30 meters thick, locally reaching a thickness of 100 meter [2]. Before olivine mining can be started, this crust must be removed. The Compagnie Mini re de Conakry has mined these laterites between 1953 and 1966 as iron ore. One can still see the quarries, which have become engulfed, by the city. The dunites that were once visible at the bottom of these quarries can no longer be seen. Because the dunite, the mother rock of these laterites, contains elevated chromium contents, the laterite also shows high chromium levels (see Table 1).

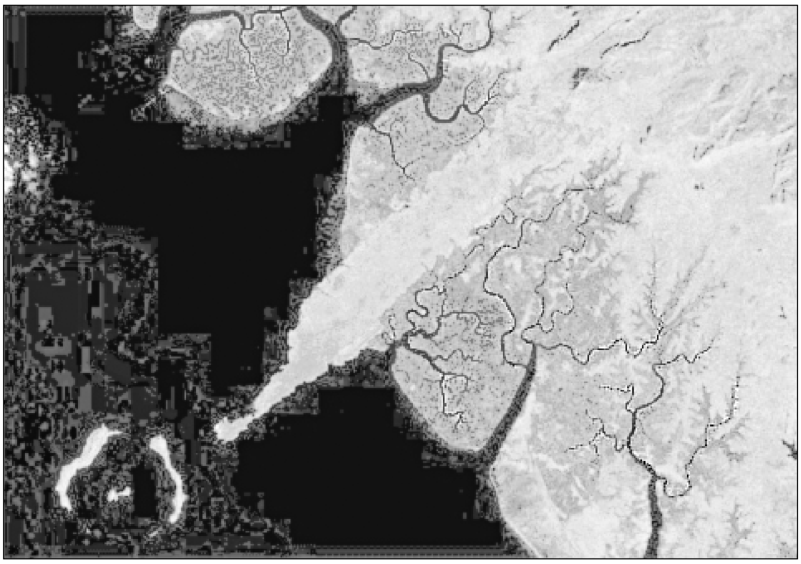
It seems that this makes the laterites less attractive as iron ore, even though most of the chromium ends up in the slag.

The concentrations as given in the table are approximate, and can vary rather widely [4].

For a large open pit mine with a surface area of 1 km^2, it will be necessary to remove in the order of 100 million tons of laterite. This is a volume of iron ore that could be interesting for steel plants, in view of the tense iron ore market. After all, if the primary aim is olivine mining, the main interest is to remove the laterite cap at minimal cost. Two railroad tracks, mainly used for bauxite transport, pass close by the most likely location for olivine mining, so the infrastructure to transport the laterite to the port is in place.

A laterite crust of 30 to 100 meter corresponds to a dunite of at least 300 meter thickness, because the major components MgO, SiO_2 and CaO making up 90 % of the rock have been leached out. Integrated over the entire massif, this means that weathering of this massif alone has captured more than 300 Gt of CO_2 since the rocks were first exposed.

Specifications for olivine, when used to combat climate change are less strict than for its use in slag conditioning. Neither a certain level of serpentinisation, nor a somewhat higher iron content of the olivine, nor a higher content of pyroxene are prohibitive. Pyroxenes, after all, also capture CO_2 during weathering, albeit a bit slower. This permits bulk mining of the rock as a whole, without having to resort to selective mining. The fact that the olivine from Conakry is somewhat richer in iron than commercial grade olivines (see Ta-



The dunite massif of Conakry

Table 1. **Chemical composition of the Conakry laterites (Results of 2 samples, taken in 2008 near Mount Kakoulima in parentheses), %**

Component	Fe	Cr_2O_3	NiO	P_2O_5	SiO_2	Al_2O_3
A layer	53 (49.6)	1.7 (1.0)	0.15 (0.06)	0.2 (0.7)	1.5 (3.8)	9.0 (11.2)
C layer	57 (49.8)	0.4 (1.5)	0.4 to 0.5 (0.7)	0.05 (0.05)	2 (3.8)	3 to 4 (7.7)

ble 2) is even an advantage, as iron-rich olivines weather faster than magnesium-rich ones [3]. When dispersed in the oceans, the higher iron content of these olivines, which will be bio-available, will contribute to the growth of biomass, and thereby to another form of CO_2 capture.

Treatment and spreading of olivine. Grinding is an established technology in the mining world. Grinding costs are normally between 1 and 2 euro/ton for grain sizes down to 0.1 mm. Spreading is another matter. In the example of the dunite of Conakry, there are several favorable conditions. Two railroads, transporting bauxite from the interior to the port of Conakry are passing close by on the peninsula. These railroads could also be used to transport laterite ore to the port, which is well equipped to handle bulk ore carriers. Once the laterite crust is removed and the olivine mining has started, part of the olivine could also be transported to the port for export. When the empty bauxite trains return they can transport olivine powder to the interior. The existing infrastructure thus is in place for the main transport.

Once arrived in the interior, the olivine must be spread. Wherever there are plantations (bananas, palm oil or others), the olivine powder can be mixed with fertilizer or pesticides before spreading. Where plantations are lacking, one would probably have to depend on the local population, which should receive a financial compensation for each ton of olivine that is spread. Deeply weathered tropical soils are poor in mineral nutrients, so it will also help to improve the soil quality at no cost to the population.

Table 2. **Chemical composition of Conakry olivine, compared to 2 commercial grade dunites from Norway, %**

Component	Conakry	Bryggja	Aheim
SiO_2	39.16	41.8	41.7
MgO	43.86	47.5	49.0
CaO	0.05	0.3	0.2
FeO	16.11	7.6	7.2
MnO	0.21	0.1	0.1
NiO	0.30	0.3	0.3
Cr_2O_3	0.00	0.4	0.4

Consequences of olivine mining. Like every mining operation, olivine mining is also affecting the local environment, even though the aim is to save the general environment of the Earth. One should strive to minimize the negative effects. The local population should be protected as much as possible against the nuisance of dust (even though the spreading of olivine dust helps to capture CO_2).

For a mining operation at kilometer scale, it will almost certainly be necessary to resettle some people. The laterite is extremely infertile, so the area fortunately is sparsely populated. In keeping with the IFC standards, it will be necessary to provide at least equivalent lodging and to restore livelihoods, and it would be wise to offer as far as possible employment at the mine. A new mining operation often brings about the risk of disruption of the social fabric of the population, and it is advisable to involve the population right from the start in the decisions to be taken.

The composition of the local ground water will change somewhat (a slight rise in magnesium concentration, bicarbonate and pH), but its quality will remain good. Magnesium bicarbonate waters are considered healthy, and are said to prevent heart failure [1]. A magnesium deficiency accelerates the aging process.

A large open-pit mine will lead to a lowering of the local water table. Fortunately the drinking water for Conakry comes from Coyah, farther inland, and the local waters have only limited importance as a source of drinking waters.

After an olivine production of 20 to 50 million ton a year for thirty to fifty years, the open pit mine will reach a depth of three to five hundred meters. If by that time the problem of excess CO_2 in the atmosphere still persists, it is probably better to extend the area of the mine, rather than going deeper.

After closure of the mine, the pit will probably be transformed into a lake. No negative ecological effects are expected. Weathering of common rocks is as old as the world, and it is evident that the weathering products are compatible with the natural environment, as they have always been. After all, hundreds of millions of people in the world live on such rocks and their weathering products, and eat the crops that grow on them. Thanks to its climate, and the presence of dunite rocks at the surface, which can capture, and have always captured large volumes of CO_2, Guinea, as well as several other countries in the region can play a major role in the abatement of greenhouse gases, and thus help to avoid a disastrous climate change, and reverse the ongoing acidification of the oceans.

Efficiency and costs. Almost all research on mineral carbonation to combat climate change is focused on the development of technologies to speed up the reaction. This can be achieved by mechanical, thermal or chemical activation of the mineral surfaces, or by treating the minerals in industrial autoclaves, with the possible addition of katalysts. All these attempts are doomed to fail, because the costs involved for these add-on technologies are prohibitive. If one limits the costs to mining and milling, estimated by Swedish mining engineers to be 6 Euro/ton of bulk rock [8] and leaves the weathering to nature, the process runs slower, but is cheaper by a factor of ten or more. Grains of olivine of 100 micron in the wet tropics weather completely in five years, well within the required time span. Selecting an abundant mineral like olivine, that weathers fast, and spreading it in a favorable climate is the cheapest sustainable way to remove CO_2 from the atmosphere. Besides, as one imitates the process that has always kept the CO_2-levels of the atmosphere within bounds, no negative effects on the environment can be expected.

Conclusions. Olivine mining in Guinea has the following advantages. 1. Weathering of rocks and concomitant capture of CO_2 proceed fastest under tropical conditions.

2. Salaries are still low, so mining is relatively cheap.

3. The existing infrastructure is favorable (railroads in the vicinity, and a port that can handle ore carriers).

4. A large olivine mine will provide work for thousands of people and stimulate the economy of the country.

5. Guinea is familiar with mining. It has several large bauxite mines, and possesses the largest bauxite reserves of the world.

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ИСПОЛЬЗОВАНИЕ ОЛИВИНА В БОРЬБЕ С ИЗМЕНЕНИЯМИ КЛИМАТА

Выветривание основных пород, содержащих магниевые и кальциевые силикаты, служит основным механизмом поглощения CO_2 в течение продолжительного времени с длительным сохранением органического углерода. Выделение CO_2 при сжигании ископаемых топливных материалов, по меньшей мере, в десять раз выше, чем выделение CO_2 Землей. Равновесия между выделением и поглощением уже не существует и концентрация CO_2 в атмосфере постепенно растет. Необходимо выяснить, возможно ли стимулировать естественный процесс выветривания таким образом, чтобы восстановить это равновесие. Выветривание происходит на поверхности пород, следовательно, необходимо увеличить имеющуюся площадь поверхности. Это можно сделать, добывая и измельчая пригодные для этого породы и рассеивая порошок над землей и мелководными морями. Факторы, влияющие на скорость реакции, без учета размеров зерен, — температура, pH и вода. Следовательно, наиболее пригодны для этого почвы тропических стран. Атмосфера почв в среднем в сотни раз более обогащена CO_2, чем воздух, что обусловлено распадом растительного материала и дыханием почвенной фауны. Высокое давление CO_2 понижает pH, что служит бла-

гоприятным фактором для выветривания. Наиболее подходящим типом пород является дунит, состоящий более чем на 90 % из оливина. Массивы дунитов обнаружены во многих странах на каждом континенте. Большие массивы этих пород наряду с другими странами расположены в Гвинее, Сьерра-Леоне и на Берегу Слоновой Кости.

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ВИКОРИСТОВУВАННЯ ОЛІВІНУ В БОРОТЬБІ ЗІ ЗМІНАМИ КЛІМАТУ

Вивітрювання основних порід, що містять магнієві і кальцієві силікати, є основним механізмом поглинання CO_2 протягом тривалого часу з тривалим збереженням органічного вуглецю. Виділення CO_2 під час спалювання викопних паливних матеріалів, щонайменше, вдесятеро вище, ніж виділення CO_2 Землею. Рівноваги між виділенням і поглинанням вже не існує і концентрація CO_2 в атмосфері поступово зростає. Необхідно з'ясувати, чи можливо стимулювати природний процес вивітрювання так, щоб відновити цю рівновагу. Вивітрювання відбувається на поверхні порід, отже, необхідно збільшити наявну площу поверхні. Це можна зробити, видобуваючи і подрібнюючи придатні для цього породи і розсіюючи порошок над землею і мілководними морями. Чинники, що впливають на швидкість реакції, без урахування розмірів зерен, — температура, pH і вода. Отже, найбільш придатні для цього ґрунти тропічних країн. Атмосфера ґрунтів в середньому в сотні разів більше збагачена CO_2, ніж повітря, що обумовлено розпадом рослинного матеріалу і диханням ґрунтової фауни. Високий тиск CO_2 знижує pH, що є сприятливим фактором для вивітрювання. Найпридатнішим типом порід є дуніт, складений більш ніж на 90 % з олівіну. Масиви дуніту знайдені в багатьох країнах на кожному континенті. Великі масиви цих порід поряд з іншими країнами розташовані у Гвінеї, Сьєрра-Леоне і на Березі Слонової Кості.