Mitigation of CO_2 emissions

by stimulated natural rock weathering

Fast weathering of olivine in high-energy shallow seas

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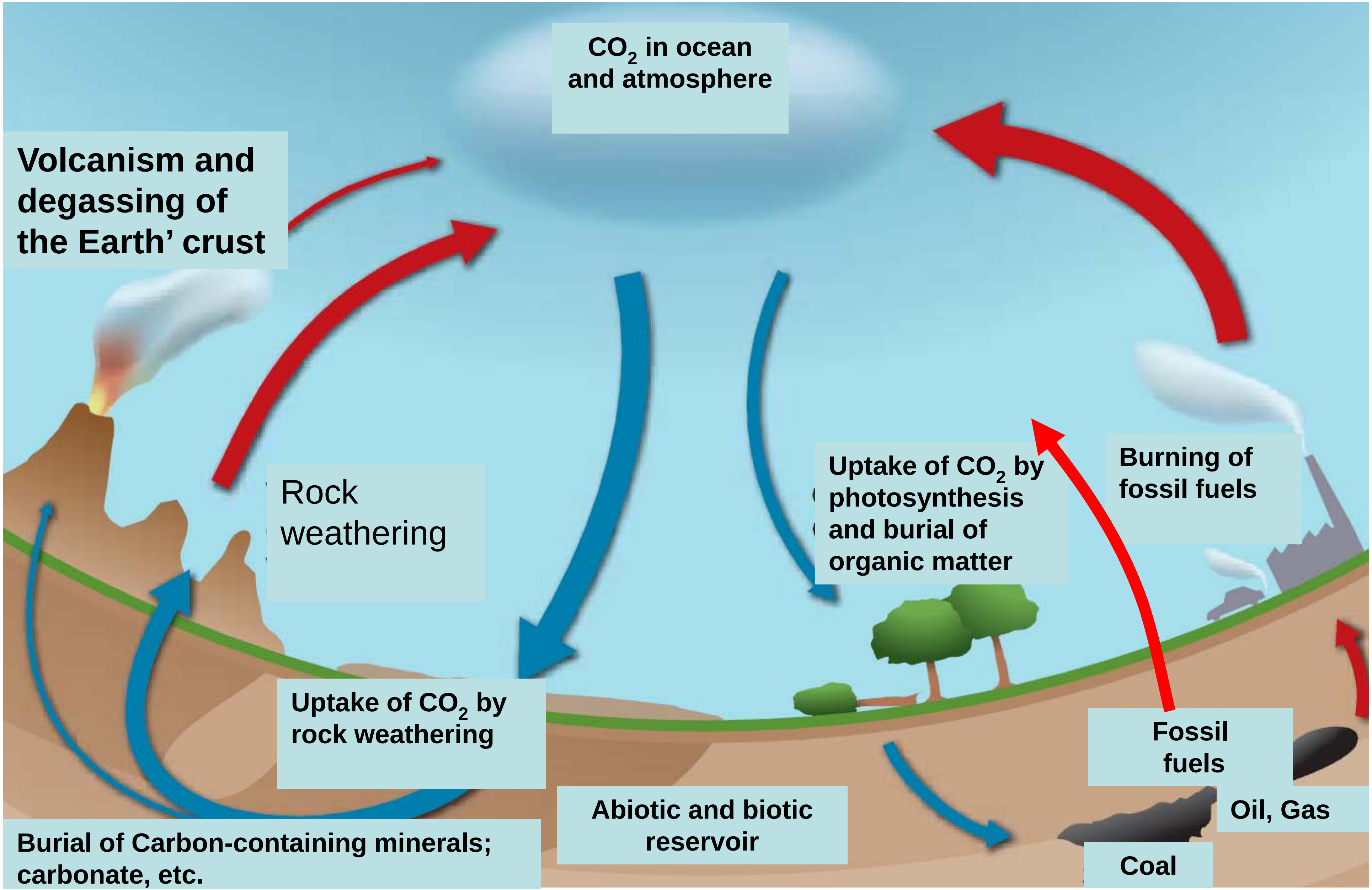
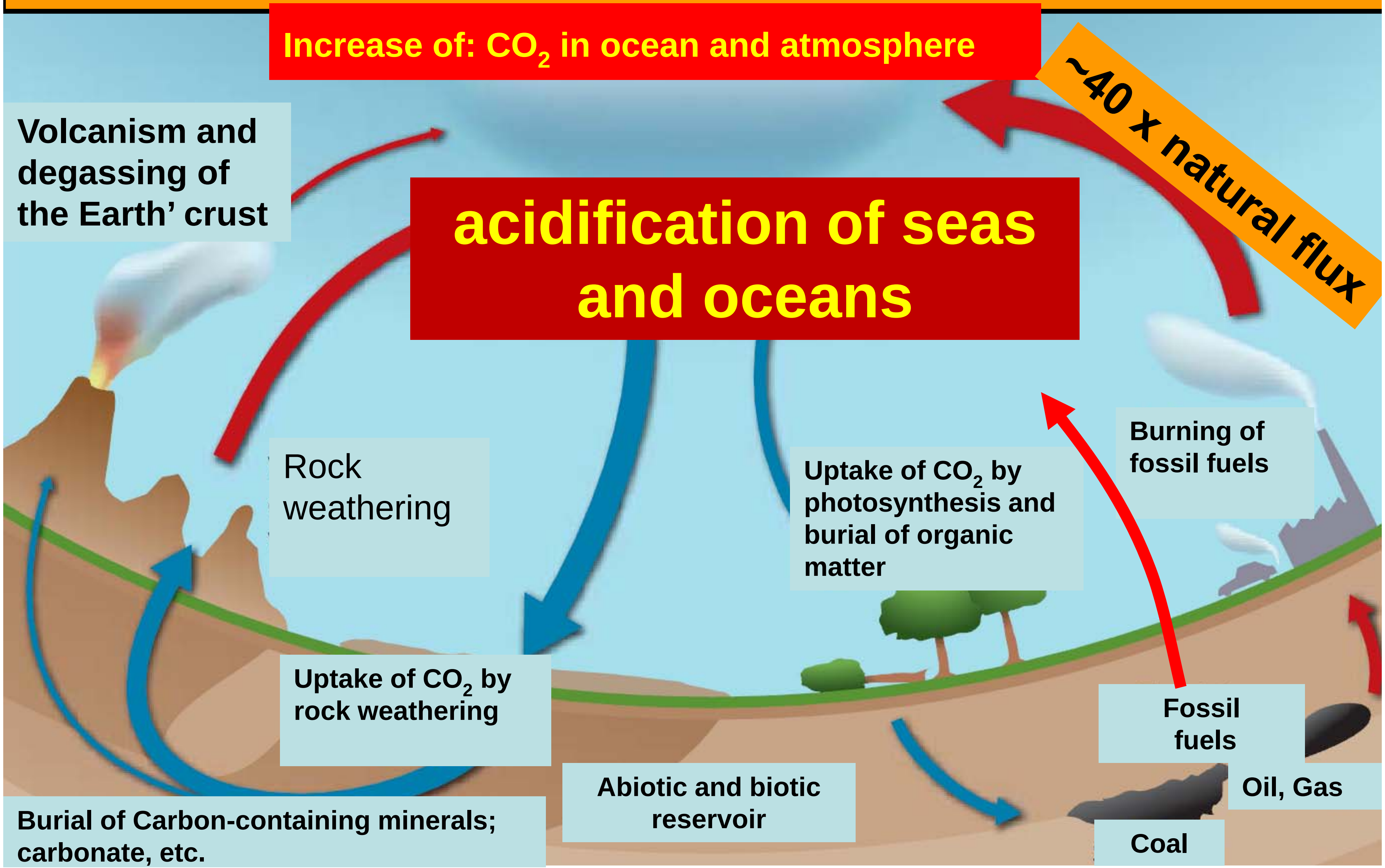
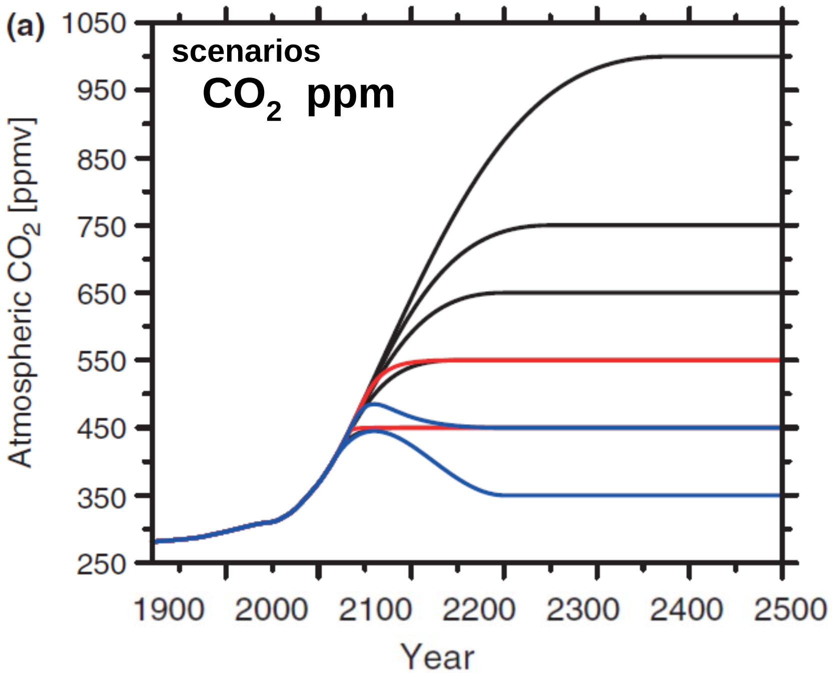
Questions put forward after the presentation in Petten on 19 October 2015, and answers can be found at the end

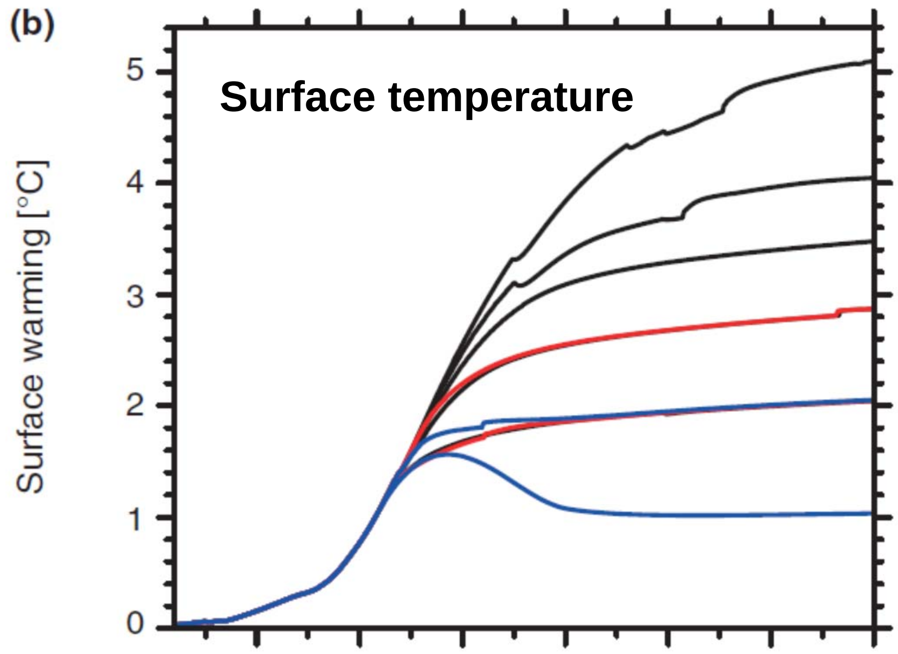
Geological past: first ~ 2 billion years: no life and thus only the left part of the diagram was active. Without CO_2 uptake by rock weathering, CO_2 pressure in the atmosphere would have been several hundred bars

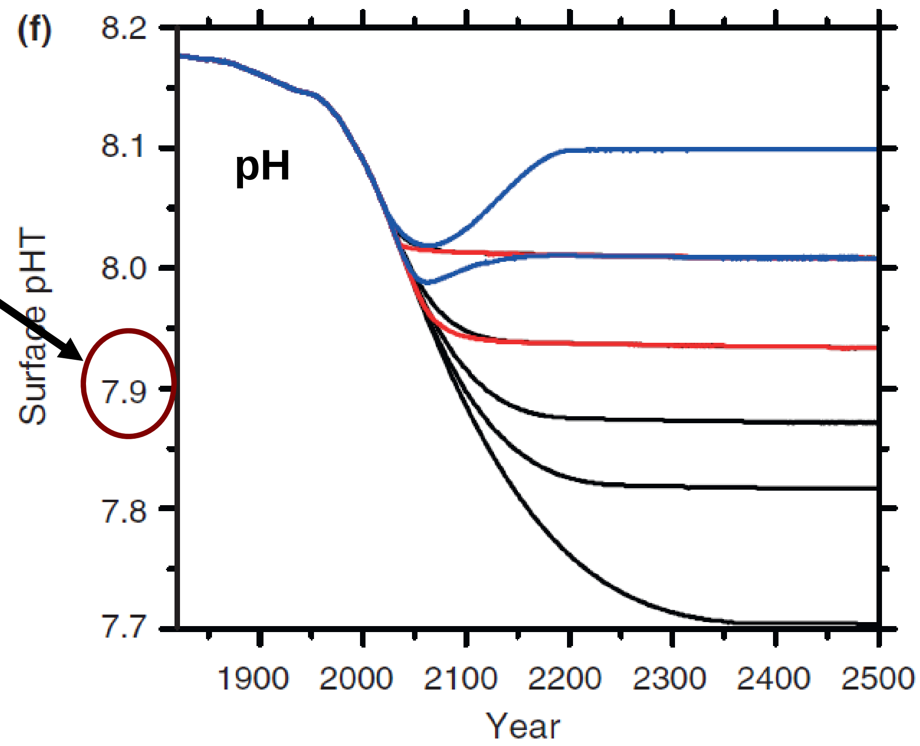


Today: burning of fossil fuels; ~40 x as much CO_2 produced as the natural CO_2 release from the Earth' crust and volcanoes









Greenhouse problem, but just as important:

today, parts of the North Sea;

drop of 0.3

pH is a logarithmic scale; so a drop of 0.3 implies a doubling of CO_2

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Current Opinion in Environmental Sustainability

Future biological and ecosystem impacts of ocean acidification and their socioeconomic-policy implications

Carol Turley[1] and Jean-Pierre Gattuso[2,3]

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Uptake of CO_2 by olivine weathering

$(Mg,Fe)_2SiO_4$ (olivine *) + 4 H_2O → 2 $(Mg, Fe)^{2+}$ + 4 OH^- + H_4SiO_4

4 OH^- + 4 CO_2 → 4 HCO_3^-

CO_2 is consumed, and Mg^{2+}, Fe^{2+}, H_4SiO_4, HCO_3^- and some Ni are produced

Reaction of serpentine is similar: $Mg_3Si_2O_5(OH)_4$ + 5 H_2O → 3 Mg^{2+} + 6 OH^- + 2 H_4SiO_4

followed by 6 OH^- + 6 CO_2 → 6 HCO_3^-

* Minable olivine consists, with minor variations, of 0.92 Mg_2SiO_4 (forsterite) and 0.08 Fe_2SiO_4 (fayalite)

Objections against the stimulation of natural weathering of Olivine:

Chemical weathering reaction would be far too slow

The amount of olivine needed annually would be far too great

Weathering products would detoriorate the chemical balans in seas and oceans, soils; would be poisonous, etc.

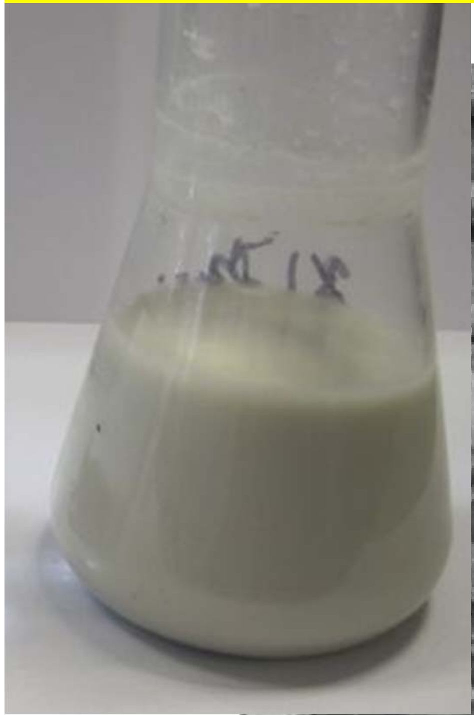
“Chemical weathering reaction would be too slow”

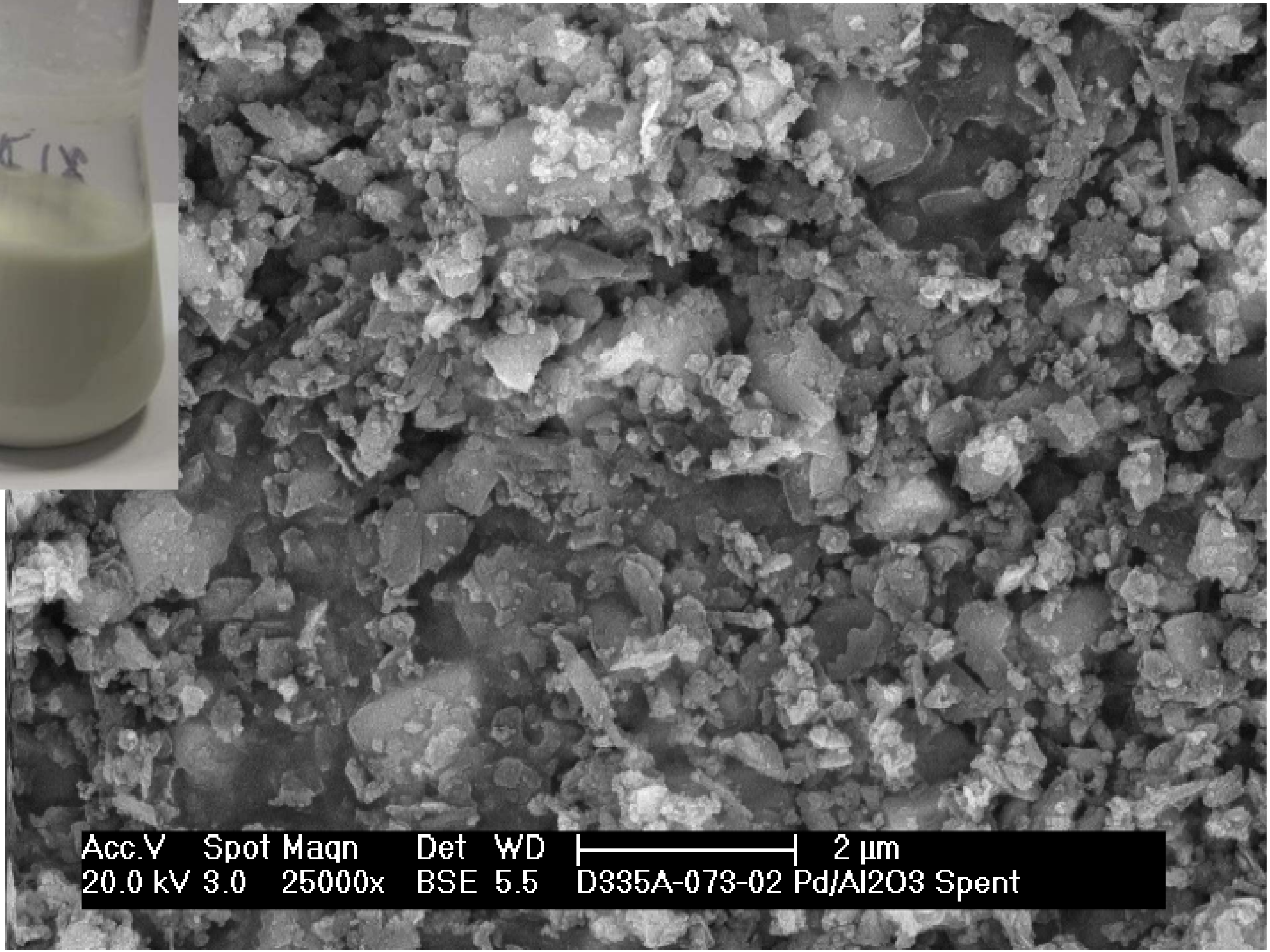
This is often quoted from old literature without any further check.
However this is only the case for olivine grains in the laboratory,
without any physical action and without biological processes

Indeed, when grains are immobile

Lab experiment

Fine-grained olivine produced during a week of shaking





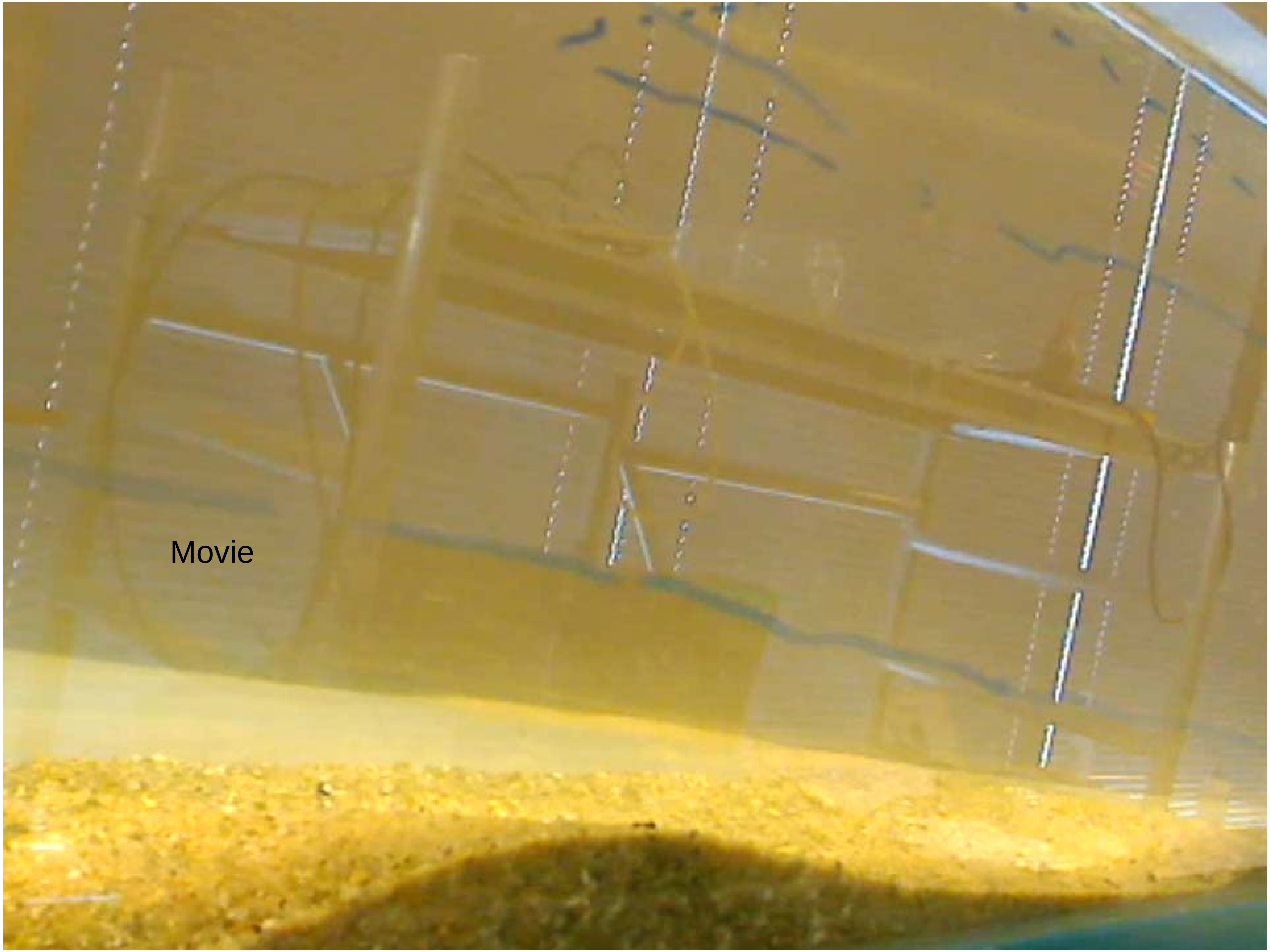
does it work also on a larger scale?

(of course it should; the process shown concerns a first principle)

coarse sand + 30% coarse olivine

current velocity ~ 40 – 60 cm/sec

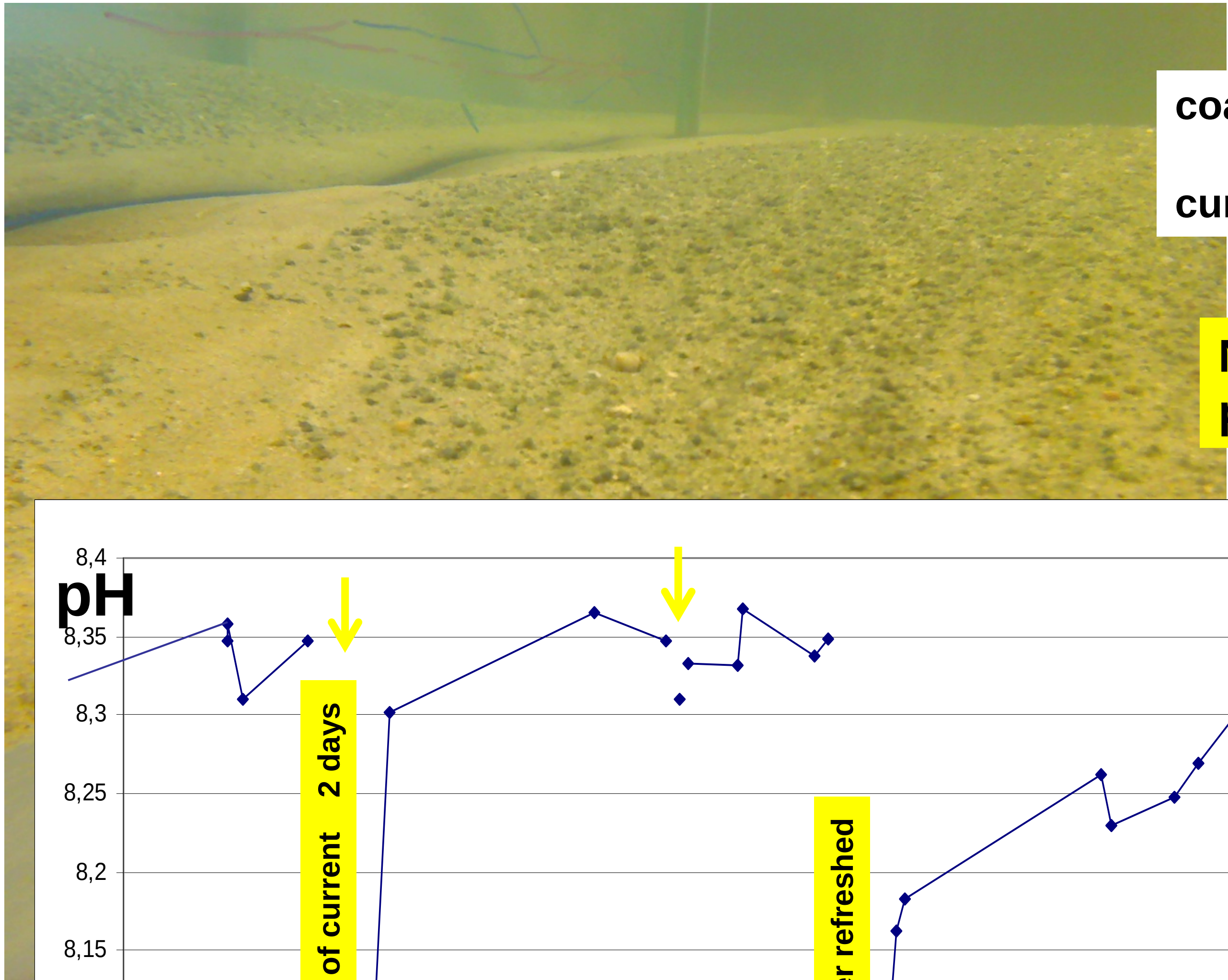
(= 1.44 – 2.16 km/hour)

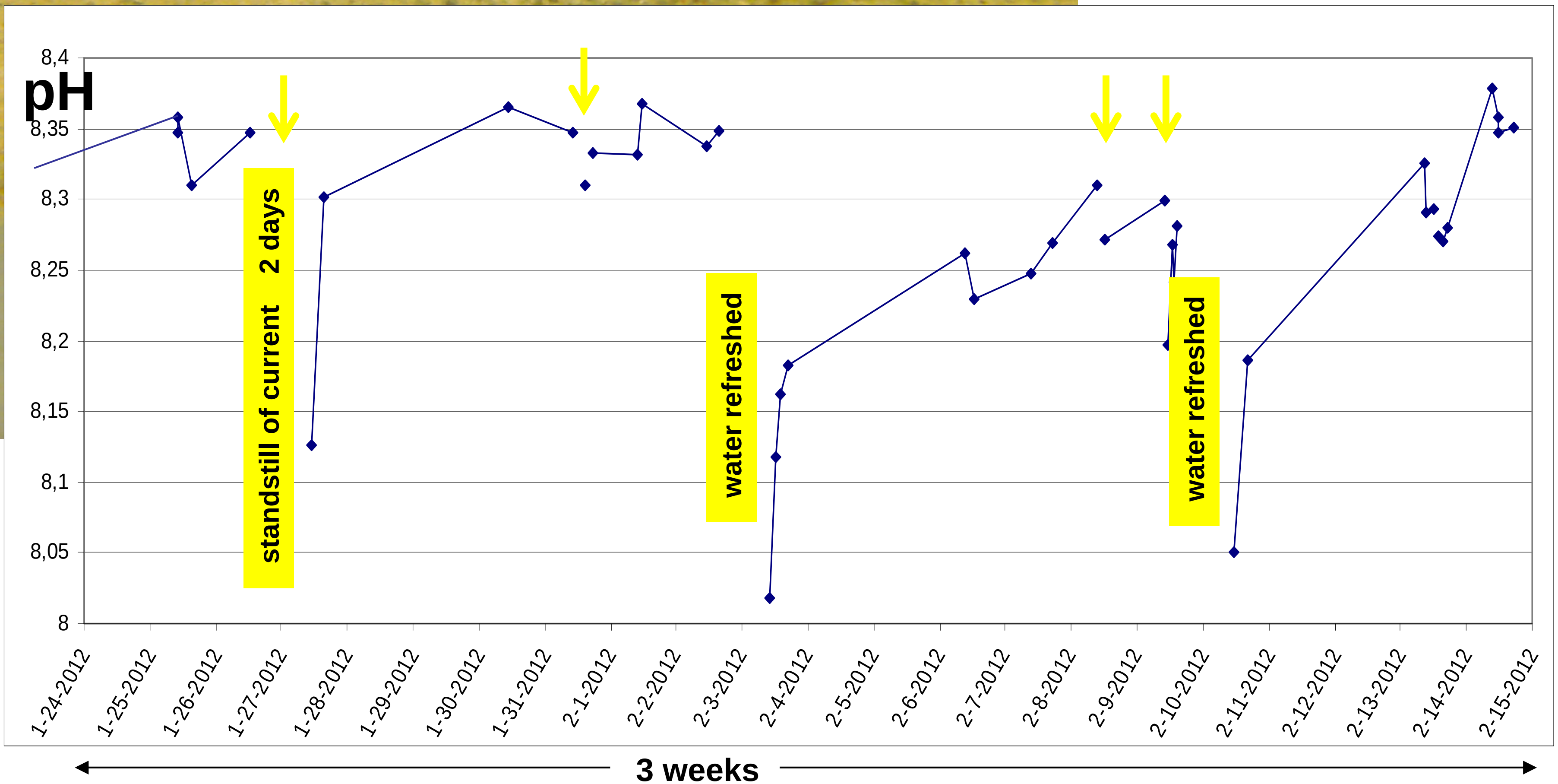

Movie

coarse sand + ~30% olivine

current velocity 40 – 60 cm/sec

Non-connected measuring points: standstill of current



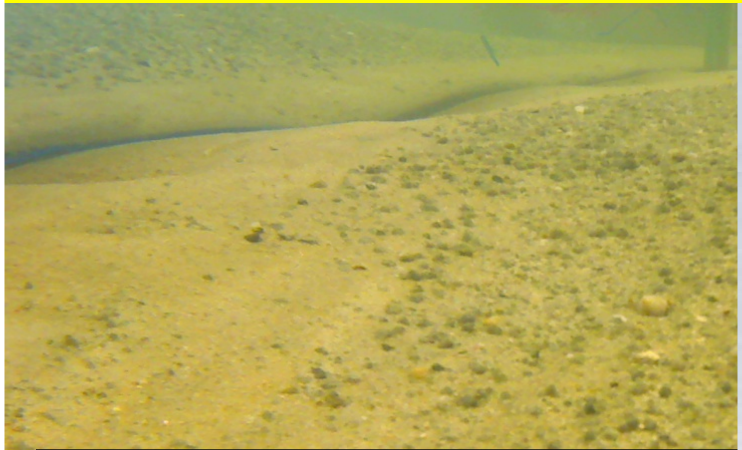


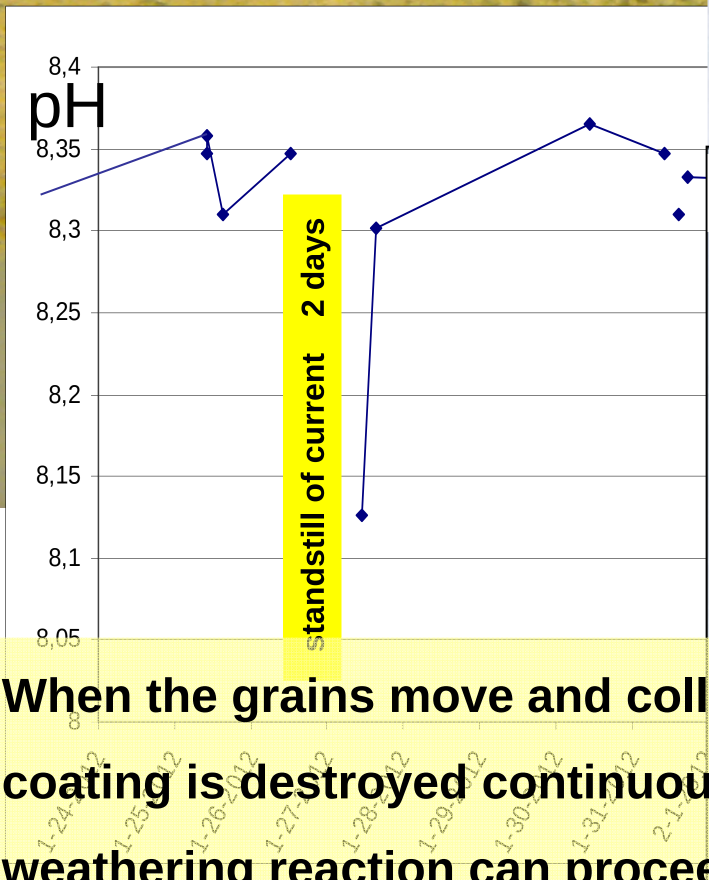
Thus, the previous slide demonstrates that with an addition of 30% olivine grains to course-grained sand that had been used in flume experiments during previous months, and after all fine-grained sediment (clay and silt) had been removed, pH rises to about 8.35 when the water current transports the olivine sand.

When the current is stopped for 2 days, grain collisions stop, and the pH of the water falls to less than 8.15, demonstrating a rapid uptake of CO_2 by diffusion through the water-air interface. Also during short stops of some hours pH falls, demonstrating the uptake of CO_2.

Renewal of the water shows the same process.

If grains do not move, a silica coating develops

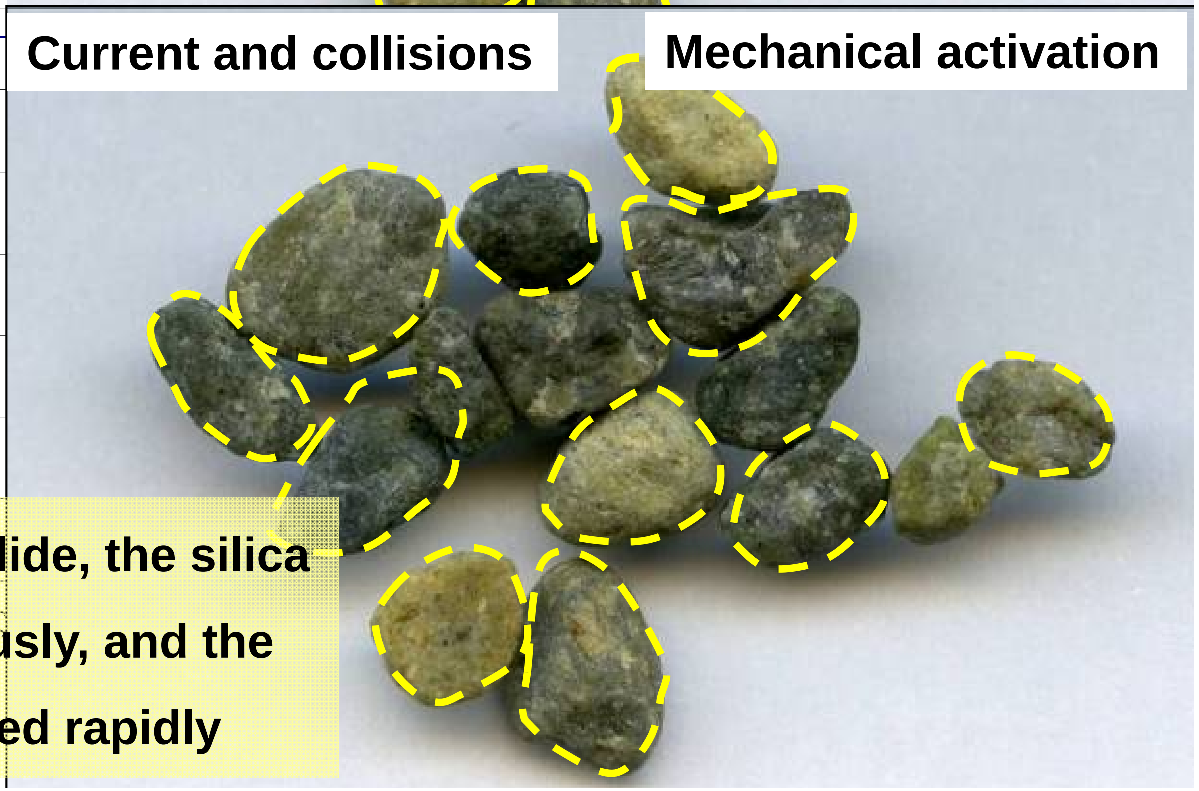




Silica-coating: H_4SiO_4

Current and collisions

Mechanical activation



When the grains move and collide, the silica coating is destroyed continuously, and the weathering reaction can proceed rapidly

Uptake of CO_2 by olivine weathering

$(Mg,Fe)_2SiO_4$ (olivine *) + $4\ H_2O \rightarrow 2\ (Mg, Fe)^{2+} + 4\ OH^- + H_4SiO_4$

$4\ OH^- + 4\ CO_2 \rightarrow 4\ HCO_3^-$

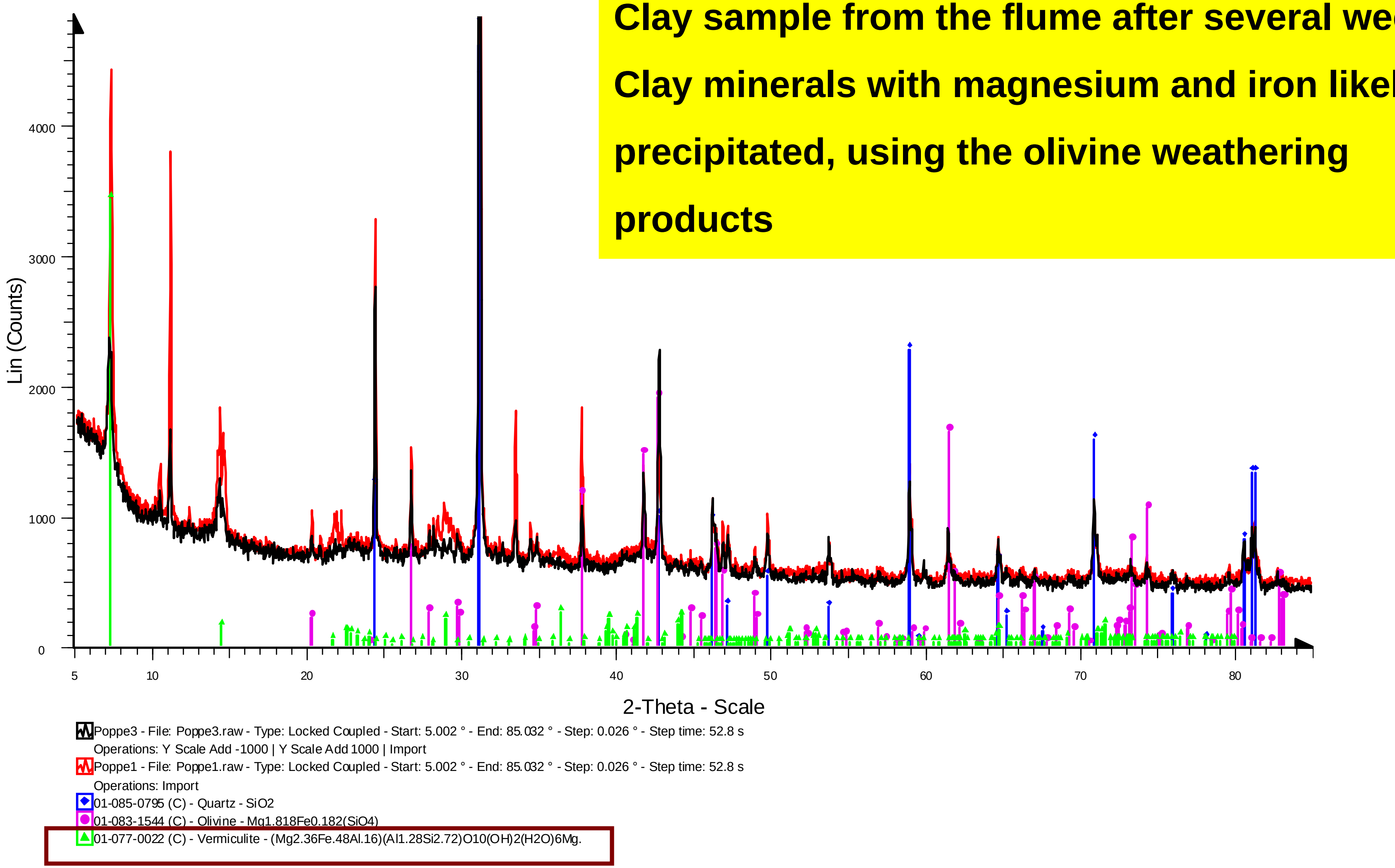
CO_2 is consumed, and Mg^{2+}, Fe^{2+}, H_4SiO_4, HCO_3^- and some Ni are produced

* **Minable olivine consists, with minor variations, of 0.92 Mg_2SiO_4 (forsterite) and 0.08 Fe_2SiO_4 (fayalite)**

The **H_4SiO_4** produced during the weathering process, forms a silica coating around the grains (yellow line around the grains on the previous sheet) that greatly retards the reaction.

Only when the grains are kept in motion and collide with each other, the silica coating is disrupted (interrupted line on the previous sheet), and the weathering reaction can continue rapidly.

Clay sample from the flume after several weeks; Clay minerals with magnesium and iron likely precipitated, using the olivine weathering products



Vermiculite $(Mg,Fe,Al)_3((Al,Si)_4O_{10})(OH)_2 \cdot 4H_2O$

Saponite $Ca_{0.25}(Mg,Fe)_3((Si,Al)_4O_{10})(OH)_2 \cdot nH_2O$

Applicable on a large, real-world scale?

(The amount of olivine needed annually would be far too great)

RED: currents capable of transporting gravel

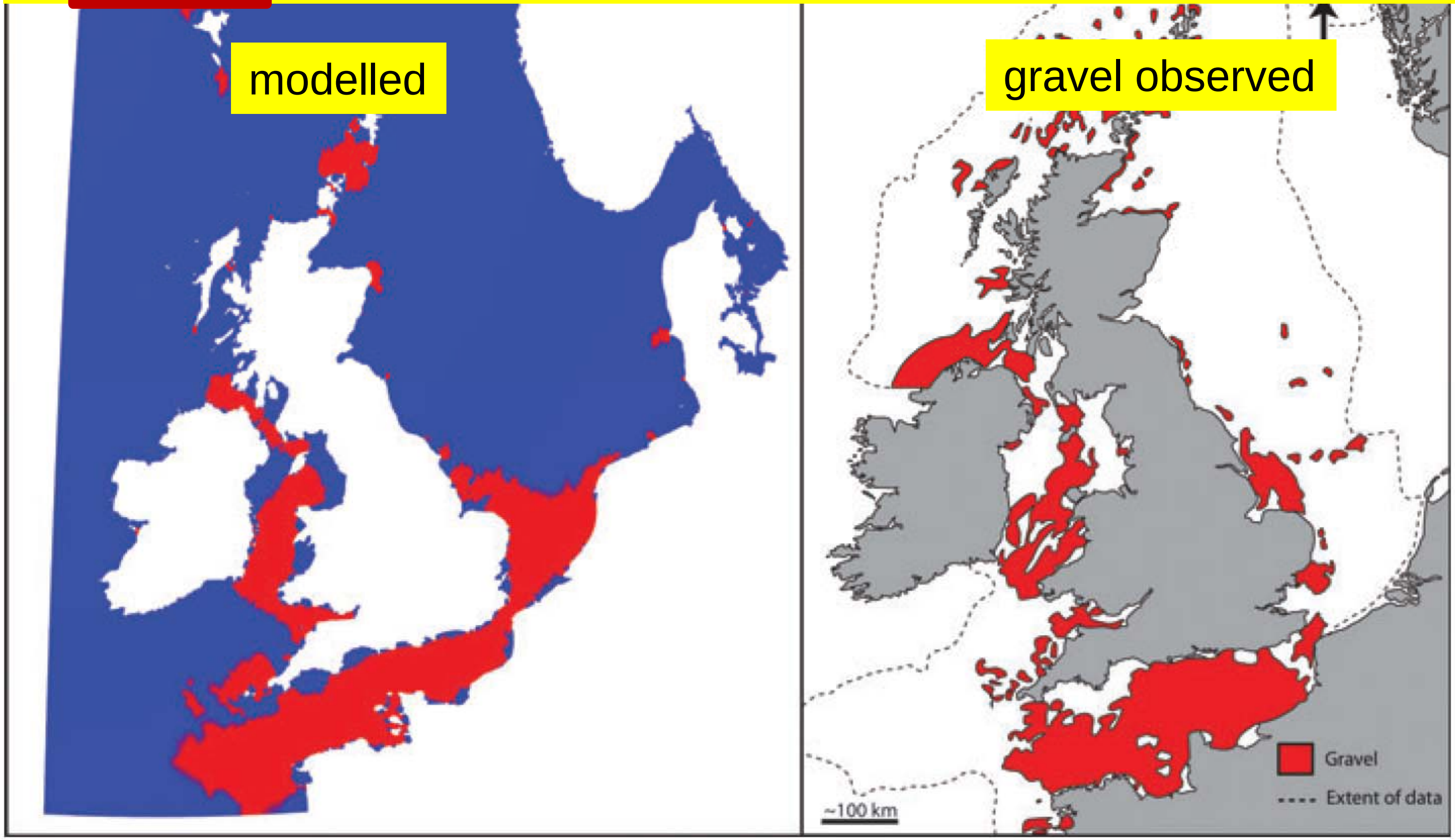


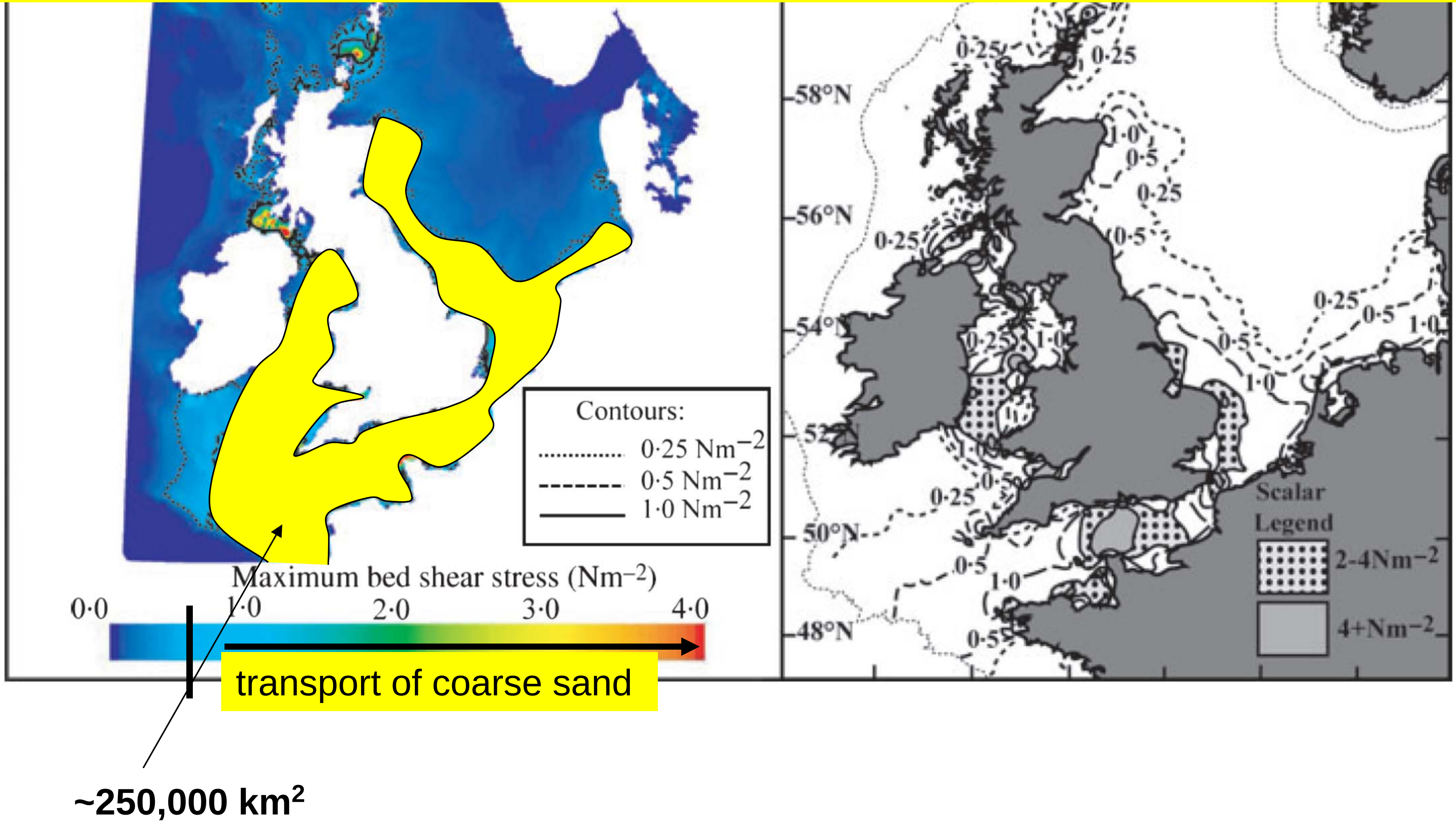
Fig. 5. ICOM prediction of bed shear stresses capable of transporting gravel (shaded red) (A) and the observed gravel grain-size distribution for the North European shelf seas (B) (modified from Graham & Straw, 1992).

Sedimentology (2010) **57**, 359–388 doi: 10.1111/j.1365-3091.2009.01082.x

Modelling tidal current-induced bed shear stress and palaeocirculation in an epicontinental seaway: the Bohemian Cretaceous Basin, Central Europe

ANDREW J. MITCHELL*, DAVID ULIČNÝ†, GARY J. HAMPSON*, PETER A. ALLISON*, GERARD J. GORMAN*, MATTHEW D. PIGGOTT*, MARTIN R. WELLS*[1] and CHRISTOPHER C. PAIN*

Weathering of a 1 cm thick carpet of olivine grains spread out over an area of *35,000 km²* would suffice to compensate CO_2 produced by fossil fuel burning in France, Belgium, Netherlands and the UK in one year



In the area marked in yellow on the previous slide, large amounts of sand are transported continuously.

Thus there is no need to spread the olivine sand/gravel in a layer of uniform (1 cm) thickness. Currents and waves will spread the olivine, also in areas where much thicker layers of olivine sand are being dumped.

As the area where currents are strong enough is about 7 times greater than the 25,000 km^2 needed, different areas can be used in subsequent years.

35,000 km^2 x 1 cm thick → 1.2 Gigaton (10^{15} kg)

1.2 Gt : 3000 megacarrier loads of 400,000 metric tons of olivine

1.5 GT CO_2 thus would be removed *annually*

Worldwide:

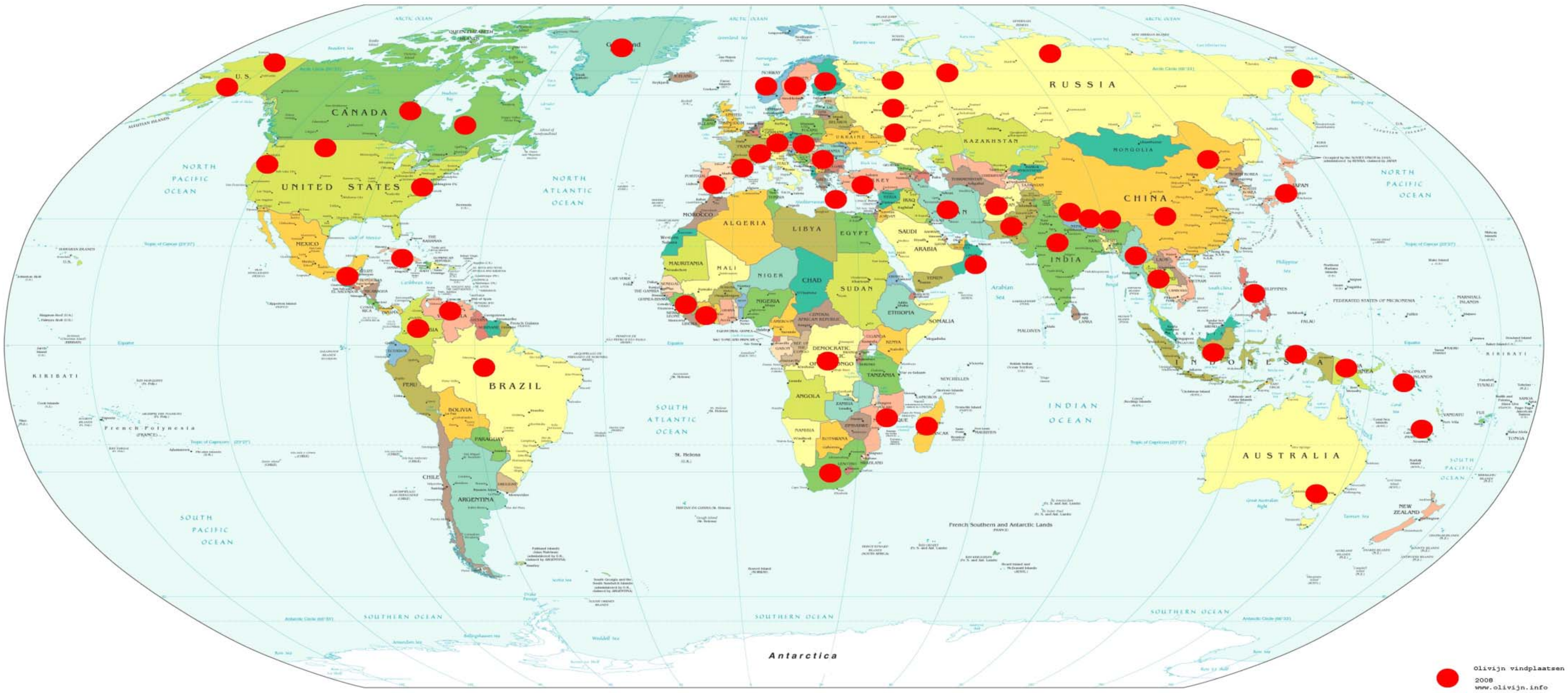
Some 1000 megacarriers would be needed to continuously carry olivine from mining areas to nearby high-energetic seas for the compensation of worldwide CO_2 emissions

Quantity of olivine needed to compensate the *global* CO_2 emissions ~ 7 km^3 each year

Amount of fossil fuels mined annually (in oil equivalents) ~ 10 km^3 per year

Bingham Canyon Mine, Utah, U.S.A. ~ 25 km^3

Olivine-rich rock occurrences



Based on Norwegian mine-employment data:

1.5 million mine workers would be needed worldwide

(in China alone much more people are involved in coal mining)

Costs?

Some 1000 megacarriers would be needed to continuously carry olivine from

Quantity of olivine needed to compensate the *global* CO_2 emissions ~ 7 km^3 each year

CO_2 emissions

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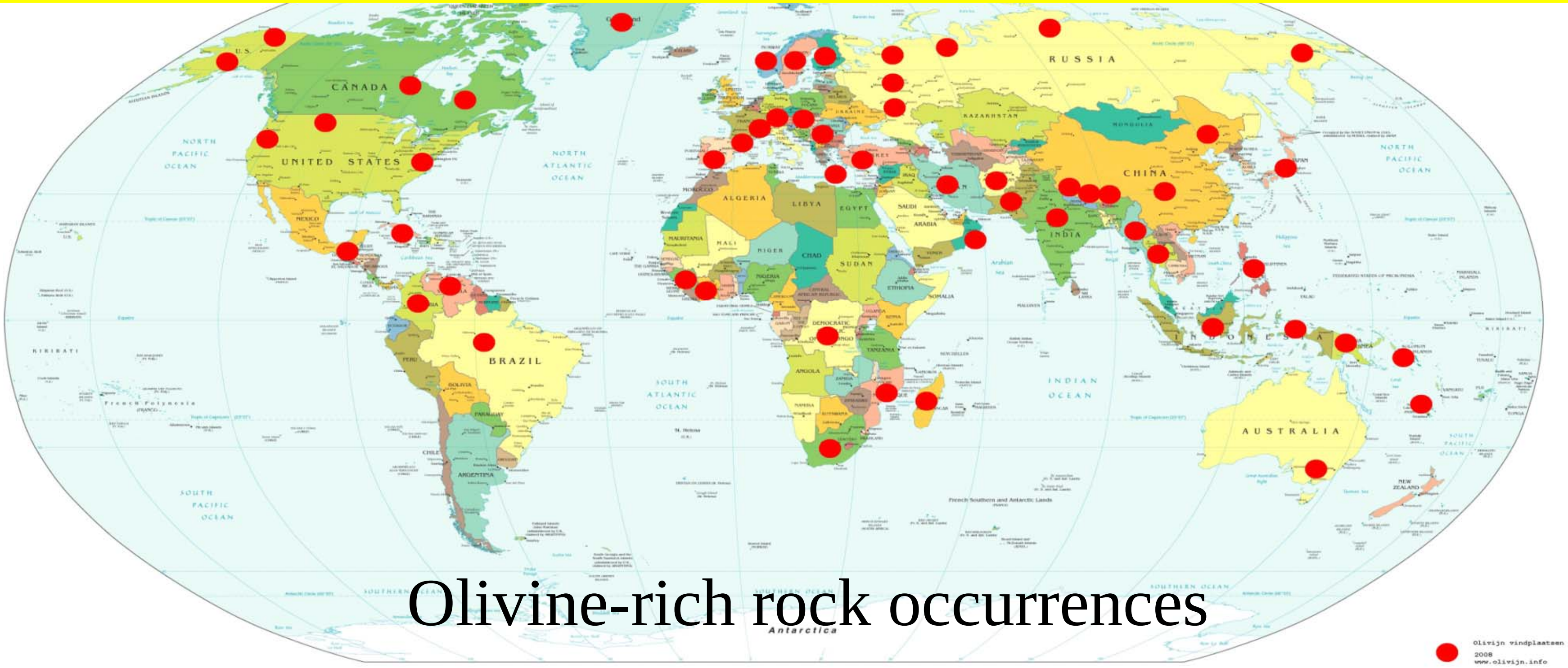

Olivine-rich rock occurrences

Costs of mining and crushing granites and porphyrites for gold;

Open pit mining; 5.000 tonnes/day

US$ 7.32 / metric ton (***less*** when upscaled); based on western U.S. mining operations

http://costs.infomine.com/costdatacenter/miningcostmodel.aspx

Transport: (self-discharging megacarriers; up to 400,000 ton)

Loading and unloading of a 200,000 megacarrier ~ 2 x 4-5 days = 10 days

Speed 15.4 knots (28.5 km/h; 17.7 mph) ~ 650 km/day

Travel ~ 2000 km; 2 x (outbound and inbound) = 4000 km = 6 days

Cost of 200,000 ton megacarrier order of US$ 40,000.- / day

Loading-travel-unloading-and-back 16 days (less, due to partial unloading underway)

16 days x USS 40,000.- = US$ 640,000.-

US$ 640,000.- / 200,000 ton = US$ 3.2 /ton

Total costs US$ 10.- to US$ 11.- per ton olivine (captures 1.25 ton CO_2)

Weathering products would detoriorate the chemical balans in seas and oceans, soils; would be poisonous, etc.

Uptake of CO_2 by olivine weathering

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CO_2 is consumed, and Mg^{2+}, Fe^{2+}, H_4SiO_4, HCO_3^- and some Ni are produced

Reaction of serpentine is similar: $Mg_3Si_2O_5(OH)_4 \rightarrow 3\ Mg^{2+} + 6\ OH^- + 2\ H_4SiO_4$

followed by $6\ OH^- + 6\ CO_2 \rightarrow 6\ HCO_3^-$

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Mg

The Mg/Ca ratio has varied in geological history from <2:1 to 5:1 today and in an absolute sense Mg has varied more than a factor two.

After 100 years of weathering of 7 km^3 ground olivine added to the marine domain annually, Mg in ocean water will have increased from 1296 ppm to 1296.6 ppm.

Si

Si is a limiting element for diatoms and radiolarians (both marine algae with a silica shell/exoskeleton). Thus olivine weathering will result in additional CO_2 uptake and in an increase of diatoms relative to other phytoplankton.

Fe

A prime limiting element for ocean productivity; thus results in extra productivity and uptake of CO_2

Ni

Nickel Olivine contains order of 0.2% Ni

Nickel in sea water 0.5 – 2 ppb

After 100 years of weathering of 7 km^3 ground olivine added to the marine domain annually, Ni in ocean water will have increased by about **0.1 ppb**; that is a ***relative* increase of 5% - 20%**

Phytoplankton	1 - 10 ppm nickel
Lobsters	0.14 - 60 ppm nickel
Molluscs	0.1 - 850 ppm nickel
Fishes	0.1 - 11 ppm nickel

(all dry weight)

Moreover, no reports found about any negative health effects in people and animals living in areas where the (sub)surface consists of (weathered) olivine

Question: how if this olivine would not fully weather in one year

Answer: no problem if it would take longer, e.g. 5 or 10 years. When adding the same amount of olivine grains each year, a dynamic equilibrium will be reached in which the same amount of olivine added is weathered *annually* removing **1.5 GT CO_2**

Question: this is a mega-intervention in the marine environment; are there any negative side-effects, pollution?

Answer: any side effects should be compared to greenhouse warming and ocean acidification as the side effects of fossil fuel burning.

Secondly a comparison should be made with the negative effects of other approaches, such as CCS, i.e. a heavy energy penalty and additional CO_2 output, potential leakage of CO_2 from filled reservoirs, catastrophes in case of masssive CO_2 escape, etc.

Question: you calculated that the annual addition of 7 km^3 olivine to the shallow marine domain during 100 years would increase the Magnesium content of sea water from 1296 ppm to 1296.6 ppm. However, that is an average for all the water in seas and oceans, whereas enhanced olivine weathering is a local proces. Thus the increase may be much larger locally.

Answer: yes that is correct. But realize that olivine is to be put in active marine environments where the renewal of the water mass is relatively rapid. E.g. the water mass of the North Sea is renewed, on average, every one to two years, and the water of Wadden Sea (where biological processes play an additional important role in olivine weathering; not discussed in the presentation) is refreshed in some weeks. Thus the Mg produced will be diluted continouosly.

Question: part of the olivine grains may be buried and not participate in the surface collisions anymore. They then might react at the much lower rate seen in the laboratory.

Answer: if olivine is put in highly dynamic areas where no net sedimentation occurs, it will continue taking part in the weathering process.
If part of the grains, e.g. 50%, would nevertheless be temporarily removed from the dynamic system, that would (in the short run) double the price of a ton removed CO_2 from € 10.- à € 11.- to € 20 - € 22.-, still considerably less than the estimated costs of CCS (per ton captured CO_2 € 60.- and higher).

Question: are there sufficient shallow seas to apply this method as mitigation for the worldwide fuel combustion?

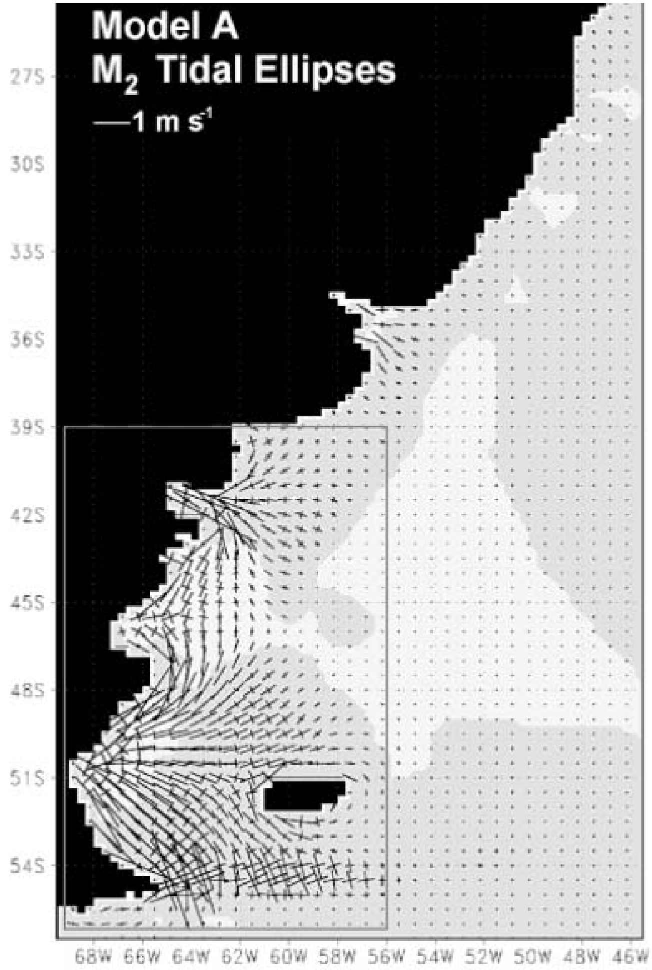
Answer: In the example of the Soutern North Sea and the Irish Sea, only about 15% of the suitable area is used for olivine weathering. The capacity of this continental shelf area thus could be 7 times higher, i.e. for the removal of about 10 Gt CO_2 produced per year. That is one quarter to one third of the global human CO2 emisions (including cement).

Elsewhere on the world sufficient shallow seas with strong tidal and wave reworking are available to scale up and mitigate all human CO_2 emissions. *See e.g. next sheet: shelf offshore East Argentina.*

Journal of Coastal Research	20	3	893–912	West Palm Beach, Florida	Summer 2004

A Set of 3-D Nested Models for Tidal Propagation from the Argentinean Continental Shelf to the Río de la Plata Estuary—Part I. M_2

C.G. Simionato[1,2,*], W. Dragani[2,3,4], M. Nuñez[1,2] and M. Engel[5]



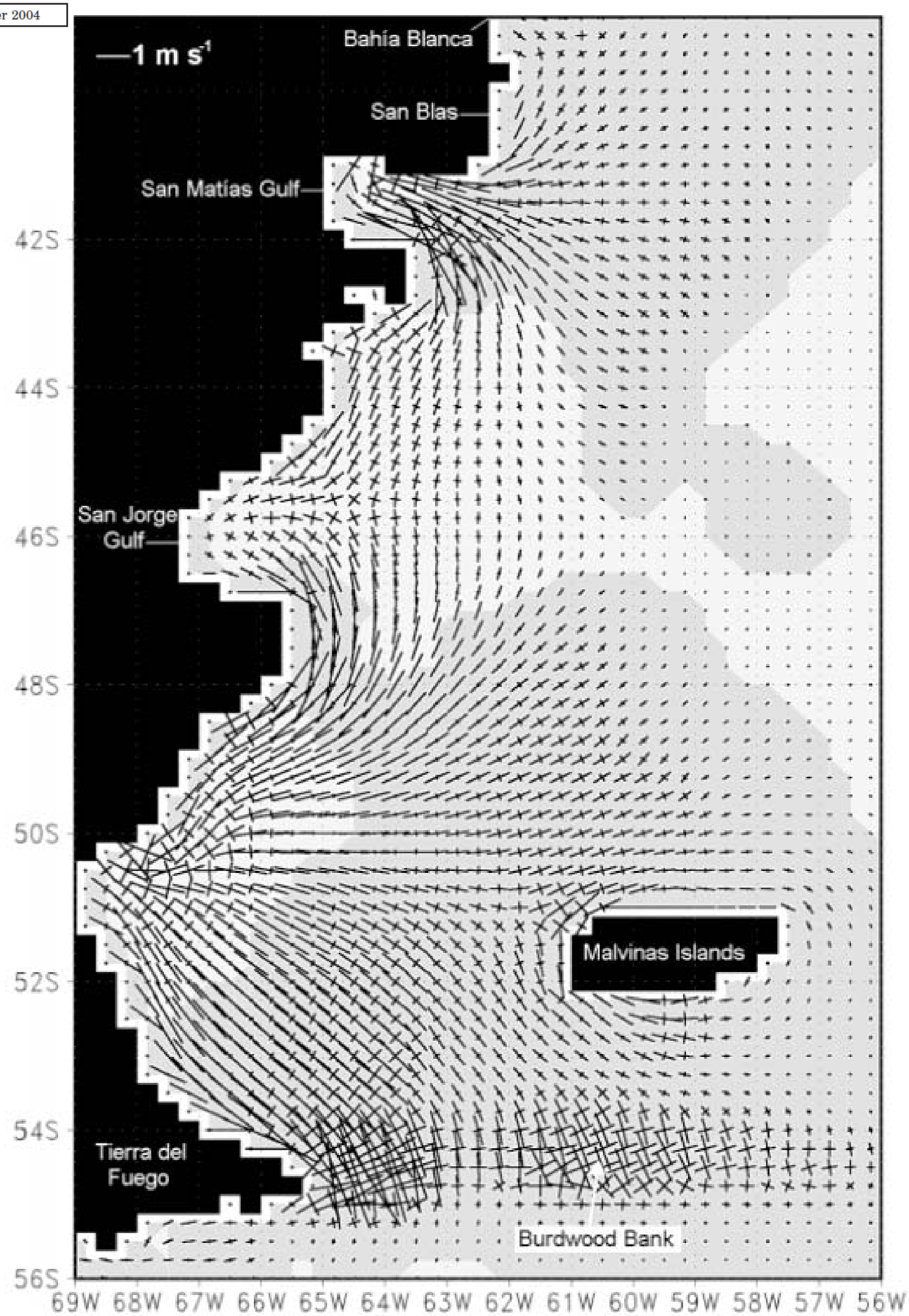


Figure 9. M_2 tidal current ellipses derived from Model A (left panel) and a zoom over the Patagonian Continental Shelf (right panel). Shaded zones indicate counterclockwise rotation of the ellipses.

Question: by dumping large amounts of olivine on the sea floor, local benthic life will suffer greatly

Answer: yes indeed, it will lead to the local destruction of benthic life (life at the sea floor).

This should be compared, however, with the complete, worldwide, extinction of species due to rising temperatures and ocean acidification.

As olivine dumping destructs benthic life only locally, restoration of the local ecosystem will occur (gradually). Restoration time (weeks to years) depends on the type of organism, the size of the disturbed area, local temperatures, etc.

Question: how much energy would be needed

Answer: If we make a short-cut and assume that the costs of $ 10.- $ 11.- would be solely energy costs, than – at the current price level this would be 30 liter of diesel oil per tonne of olivine extracted, transported and poured into shallow seas. However the cost estimate is based on publications from several years ago when fuel prices were considerably higher than today, and the costs, moreover, also include labour, etc. Thus the energy needed would be considerably less.

Remark: this would need quite an expansion of the fleet of bulk carriers

Answer: Indeed, but less than a doubling, whereas the olivine can be mined at many places on Earth and transported to nearby shallow seas.

This in contrast to bulk carriers carrying ores half over the globe and the vast amount of oil and gas tankers doing the same.

In this respect: in some cases (e.g. Sliggers in “Milieu” 2012, nr 3, “Geo-engineering met olivijn, remedie tegen broeikas effect?”) the method described here is made ridiculous, e.g. by stating that bulkcarriers would need 100 days travel between the site where olivine is mined and loaded and the destination harbour; that they cannot pass the Suez Canal; that a row of thousands of kilometres of lorries would be needed, etc.

On the basis of such overexaggerated assumptions, the above author arrived at an estimate of € 18.3 per ton CO_2 (in 2012 when fuel prices were higher than today).

However, olivine occurs at many places at the Earth’ surface, and bulk carriers may need only 10 days for a round-trip between the mining area and the shelf sea area where the olivine can be dumped (see above). Dumping can occur directly in the open sea, so no expensive harbour facilities, etc. are needed.

Thus the costs per ton CO2 will be much less than estimated by the above author.

Another point brought forward is that the stimulation of natural rock weathering focuses on mitigating the effects of fossil fuel burning, while preference should be given to measures focusing on the source of the problem, i.e. fossil fuel burning itself.

Both issues are serious concerns, and have to be discussed within the moral framework of ecological responsibility. Only minimizing pollution and not mitigating the effects of pollutions from the past would be comparable to an approach in which contaminated soils would *not* be cleaned with the argument that only the source of the pollution should be dealt with.

The immanent threat of permafrost methane release and evaporation of deep-marine methane hydrates which the risk of run-away greenhouse warming, urges to also mitigate CO_2 pollution from the last 150 years.

Further reading:

Six commercially viable ways to remove CO_2 from the atmosphere and/or reduce CO_2 emissions
http://link.springer.com/article/10.1186/2190-4715-25-35/fulltext.html

Rolling stones; fast weathering of olivine in shallow seas for cost-effective CO_2 capture and mitigation of global warming and ocean acidification
http://www.earth-syst-dynam-discuss.net/2/551/2011/esdd-2-551-2011.html

Mitigation of CO2 emissions by stimulated natural rock weathering – fast weathering of olivine in high-energy shallow seas
ftp://ftp.geog.uu.nl/pub/posters/2013/Mitigation_of_CO2_emissions_by_stimulated_natural_rock_weathering%e2%80%93fast_weathering_of_olivine_in_high-energy_shallow_seas-Schuiling_deBoer-November2013.pdf