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The long-term carbon cycle on Mars

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Abstract

It has been recently shown that several valley networks, like Naktong Vallis [1], have been formed during the Hesperian, 3.6-3.7 Gyr ago. According to the same authors, liquid water could have flowed at the surface of Mars until the early Amazonian, 3.1-3.2 Gyr ago. To explain such a residual hydrological activity, a minimum CO_2 pressure of 0.6 bar seems to be required. At this pressure level, the scattering of infrared radiation by CO_2 clouds could have maintained a global temperature above 0°C [2]. It is generally assumed that a CO_2 pressure of at least 1-2 bar is required to maintain water liquid at the surface of Mars during the formation of valley networks.

If 1-2 bar of CO_2 have been present in the Martian atmosphere until the early Amazonian, 3 Gyr ago, where did this CO_2 go? It may not have escaped mainly because during this period non-thermal escape processes were no more efficient [3]. To explain the persistence of a dense CO_2 atmosphere during the whole Noachian, when water was liquid at the surface of Mars and should have formed massive carbonate layers, it has been suggested that carbonates were recycled to the atmosphere due to thermal decomposition of carbonate rocks induced directly and indirectly (through burial) by intense, global scale volcanism [4]. The quantity of CO_2 released by volcanism since the middle-Noachian has been estimated to correspond to a CO_2 global pressure of 400 mbar [5], which one third (150 mbar) would have been emitted during the Amazonian. Whatever is the origin of this CO_2 (crustal carbonates, mantle), it has been necessarily lost to the crust, since escape is unable to have removed more than a few mbar.

The recent discovery of methane in the Martian atmosphere [6,7], with a significant estimated release rate, suggests that the carbon inventory of the atmosphere could double in a few tens million years [8]. Thus methane could be an important source of atmospheric CO_2 over time and adding to the amounts thought to have been released by surface volcanism [5]. If this methane is the result of serpentinization in crustal hydrothermal systems, the carbon in the released methane could originate from subsurface carbonates that were decomposed by hydrothermal fluids.

We provide an estimate of the integrated flux of methane to the atmosphere since the late Noachian and show that it could be substantial, of the same order as the volcanic flux of carbon (a few hundred millibars). For this purpose, we assume that the hydrothermal activity has remained proportional to the extrusion rate of volcanic lava, estimated from existing geomorphological analysis of the Martian surface [5]. Because CO_2 is more than 100 times less abundant in the present atmosphere than if volcanic and hydrothermal carbon would have accumulated since the late Noachian, we suggest that atmospheric carbon is recycled to the crust through subsurface hydrological activity. In this way, the production of CO_2 through CH_4 release, and the removal of CO_2 from the atmosphere, could have a common origin and be two facets of a currently, although progressively damping with time, active hydrological system.

We propose a typical scenario for the CO_2 pressure evolution since the late Noachian (Fig. 1) assuming a progressive sequestration of carbon, cycled to the crust, then transported by crustal liquid water and deposited under the form of carbonates within the crust (Fig. 2). These carbonates may be decomposed from time to time due to episodic magmatic activity and recycled to the atmosphere under the form of CO_2 by volcanism and/or CH_4 through the reaction of CO_2 with H_2 formed by serpentinization in deep hydrothermal systems. From geochemical modelling, it has been suggested that an extensive reservoir of carbonate minerals, equivalent to an atmospheric pressure of carbon dioxide of at least one bar, could have been sequestered beneath the surface by widespread hydrothermal activity in the Martian past [9]. The present work reinforces this idea, and provides a CO_2 evolutionary path accounting for both (modest) escape to space and storing in carbonates.

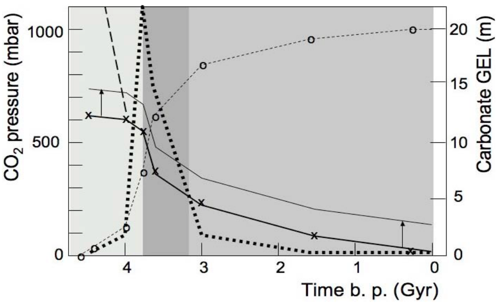

Figure 1 : (i) Evolution with time of the atmospheric CO_2 pressure, assuming the amount of CO_2 adsorbed in the regolith today is negligible (crosses, solid line), with an indication of the effect of impact erosion before 4 Gyr b.p. (dashed segment), (ii) same by adding the equivalent of 140 mbar adsorbed in the present regolith (thin solid line), (iii) evolution of the carbonate content of the crust, in units of a global equivalent layer of carbonate (right vertical scale) (dotted line with circle). The thick dotted line represents the hydrothermal flux of H_2, as scaled on volcanic extrusion rates, in arbitrary units. The period in light grey (Noachian), with low hydrothermal activity, is dominated by CO_2 escape. The major sink during the period in dark grey (Hesperian) becomes carbonate formation, by contrast with the Noachian. The transition from the period in dark grey to the period in middle grey (≈3.2 Gyr b. p.) corresponds to the very end of Hesperian valley network formation [1].

Our hypothesis that large amounts of carbon released by volcanism and hydrothermalism are sequestrated in the crust under the form of carbonates is self-consistent. First, it provides a general CO2 pressure evolution curve (Fig. 1) in good agreement with our view of Mars evolution, with the disappearance of liquid water at the end of the Hesperian or even early Amazonian, ~ 3 Gyr ago. Second, it allows to explain that most of the carbon released to the atmosphere has been converted back to crustal carbonates (Fig. 2). Third, carbonates are a plausible source of the carbon involved in the formation of CH_4, which seems more likely than a mantellic source, which cannot be excluded, but should be less effective because serpentinization may occur at relatively low temperatures, more representative of the global thermal state of the Martian crust. Contrary to the steady state carbon cycle at work on Earth, a progressive damping of the carbon cycle has occurred on Mars due to the absence of plate tectonics and the progressive cooling of the planet.

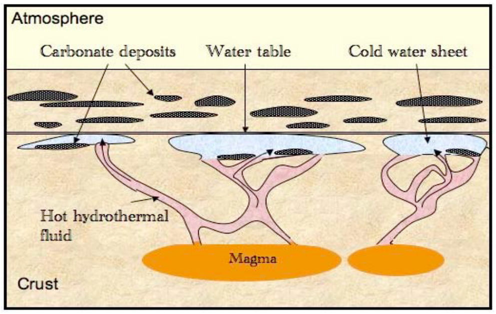

Figure 2 : Schematic view of carbonate precipitation through mixing of hot hydrothermal fluids and cold water in subsurface water sheets in the course of the shrinking of the water table.

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