Coupled Evolution of the Atmosphere-Ocean, Continent, and Interiors;
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In recent years Matsui and Abe have proposed that the surfaces of proto-Earth and-Venus were covered by magma oceans due to the blanketing effect of impact-induced steam atmospheres (1). In the case of Earth, the steam atmosphere became unstable with decreasing impact flux thus forming the proto-ocean (2). This, however, is not the case for Venus due to a higher solar flux (2). The proto-atmosphere just after the formation of the Earth was mainly composed of CO_2, which is the second most abundant volatile species of Earth's present surface environment. The question is how such a CO_2-rich atmosphere evolved to the present N_2-rich atmosphere. Dissolution equilibrium of CO_2 between the atmosphere and ocean is not a solution to this question, since the partial pressure of CO_2 in the proto-atmosphere would not have decreased to a level lower than several tenth of bars at the aqua-planet stage (3). We proposed last year that the formation of the continents played a major role in decreasing the amount of CO_2 the atmosphere to the present level (4). However, in the previous studies, we did not take into account the effect of regassing back into and also degassing from the mantle (4). In this paper we discuss the long-term evolution of the CO_2 atmosphere by using a simple geochemical model of the CO_2 cycle between five reservoirs: atmosphere, ocean, seafloor, continent and mantle.

Model and numerical procedure: We assumed that the silicate- carbonate geochemical cycle is a major process in the CO_2 cycle, as proposed by Walker et al. (5), but that the tectonic environment (such as degassing of CO_2 due to metamorphic magmatism at subduction and continental growth zones), and the solar luminosity are time variable. A schematic diagram of the CO_2 cycle is shown in Fig. 1. The Mass balance of carbon, calcium and magnesium between five reservoirs is numerically solved. We assumed that chemical equilibrium is always achieved between the atmosphere and ocean and the distribution of C between them is dependent on the pH of the ocean. The weathering rate was assumed to be a function of the partial pressure of CO_2, surface temperature, and surface area of the continents. We studied several cases with respect to continental growth. The Degassing rate due to metamorphic magmatism and the spreading rate of the seafloor were assumed to be proportional to the heat flow from the interior. Precipitation of $CaCO_3$ was assumed to occur when the amount of solubility product exceeds some critical value. We considered both rapid and slow degassing from the mantle.

Numerical results: An example of the numerical results is shown in Fig. 2. The main results are summarized as follows:

(1) Even if we take into account the effects of degassing from and regassing back into the

mantle, continental growth plays the key role in controlling the amount of carbon at the surface, as proposed by previous studies.

(2) If there were no continent on the Earth, cations would not be supplied, which means there would be no precipitation of $CaCO_3$ after the Mg in the ocean was exhausted by volcanic-seawater reactions. The Partial pressure of CO_2 would be about 2 bars in this case.

(3) The formation of the continents makes the supply of cations possible. Then we can consider two cases. If there occurs no accretion of $CaCO_3$ into the continents, carbon stored in the sea-floor increases with a decrease in tectonic activity. If there occurs accretion of $CaCO_3$, carbon in the atmosphere-ocean system decreases to the present level with an increase in carbon in the continents. The fraction of $CaCO_3$ accreted to the continent should be around 0.7 for the present carbon budget.

(4) The silicate-carbonate geochemical cycle plays an important role in stabilizing the surface temperature through the entire history of the Earth except for the cases of no continents, infinite residence time of sea-floor, 100% accretion of $CaCO_3$ into the continents, and much larger (more than 2 times) continental volume.

References: (1) Matsui, T. and Abe, Y. (1986), Nature 319, 303- 305; Abe, Y. and Matsui, T. (1987), J. Geophys. Res. 90, C545- C559. (2) Matsui, T. and Abe, Y. (1986), Nature 322, 526-528; Abe, Y. and Matsui, T. (1988), J. Atmos. Sci. 45, 3081-3101. (3) Walker, J. C. G. (1985), Origins of Life 16, 117-127. (4) Matsui, T. *et al.* (1988), Lunar and Planetary Science XIX, 740-741; Matsui, T. and Tajika, E. (1988), Abstracts of "Origin of the Earth" Conf., pp.54-55. (5) Walker, J. C. G. *et al.*, (1981), J. Geophys. Res. 86, 9776-9782.

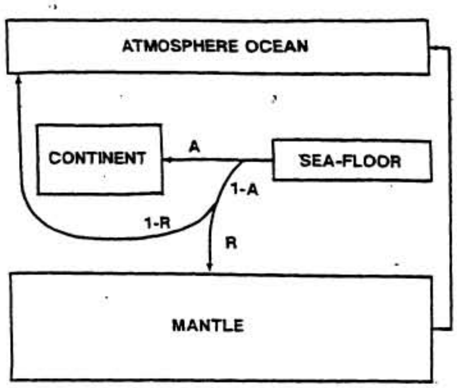

Fig.1

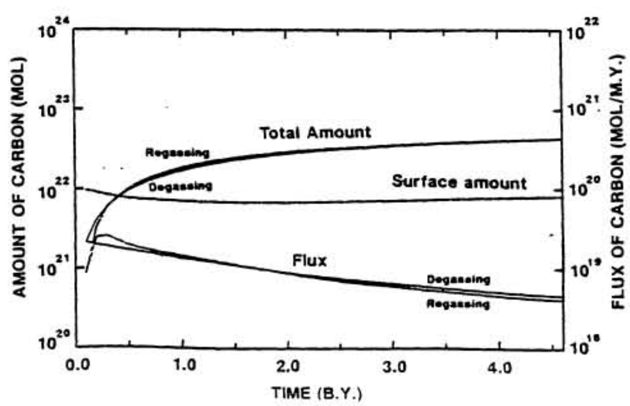

Fig.2