IMPACT-DRIVEN WATER REMOVAL ON STEAM-COVERED VENUS-LIKE PLANETS. K. Kurosawa, Planetary Exploration Research Center, Chiba Institute of Technology, 2-17-1, Tsudanuma, Narashino, Chiba 275-0016, Japan, kosuke.kurosawa@perc.it-chiba.ac.jp

Introduction: The reason for the lack of water on Venusian surface [e.g., 1] has been a long-standing problem in comparative planetology. Since Venus is Earth's twin, it would have obtained a similar amount of surface water to that of Earth's ocean during its formation. The mechanism responsible for causing a water deficit on the Venusian surface must be explored to understand the origin of the significant difference in the surface environment between Earth and Venus.

Previous studies on this topic suggested that the problem of the water loss from the early Venus comes down to the problem of the fate of a large amount of residual oxygen produced by a photochemical dissociation of water vapor [e.g., 2] because of the following reasons. Since a steam atmosphere on the early Venus is photochemically unstable, water vapor dissociates into hydrogen and oxygen by an EUV radiation from the young Sun. Then, hydrogen easily escapes into the space via a hydrodynamic escape driven by the EUV radiation [2]. Three processes have been proposed to explain the lack of a large amount of residual oxygen. Among them are: (1) frictional escape caused by drag-off by the escaping hydrogen flow [e.g., 2-4], (2) non-thermal escape by ion pick-up due to the solar wind [e.g., 5], and (3) oxidation of the Venusian crust/mantle [e.g., 4, 6]. However, the possible amount of oxygen removal by these processes is only ~0.3 TO, where 1 TO means the mass of oxygen within the current Earth's ocean. Although recent idea by [7], which is a giant-impact-generated deep magma ocean as a massive oxygen sink, is a promising hypothesis, it has not been investigated well possibly because the oxygen removal was not the main topic of their study [7].

The difficulty in the crust/mantle oxidation: In this study, I re-visited to the crust/mantle oxidation hypothesis [6]. If FeO in the Venusian crust/mantle down to ~90 km is oxidized into Fe_2O_3, the residual oxygen with the mass of 1 TO would be removed from Venusian surface. This process requires an exposure of non-oxidized fresh rocks on the Venusian surface all the time during the oxygen consumption. The most serious problem suggested by [4], however, is a lack of a driving force of such active surface replacement. The upper limit of the removed oxygen is estimated to be ~0.1 TO over 4.5 Gyr if such surface replacement occurs only by the volcanic activity on the Venus [4].

The role of hypervelocity impacts: I focused on the process of impact-driven excavation as the driving force of the surface replacement. Venus is expected to suffer intense impact bombardment during the terminal stage of planetary accretion as well as Earth, the Moon, and Mars [8]. Hypervelocity impacts produce fine-grained rocky ejecta and release them into an atmosphere. The ejecta would remove the residual oxygen from the hot atmosphere on the early Venus through high-temperature oxidation of iron-bearing silicates [e.g., 9].

The net oxidation reaction is described as $4FeO(s) + O_2(g) \rightarrow 2Fe_2O_3(s)$. First, I assessed whether the above reaction proceeds in the forward direction. Figure 1 shows the results of thermochemical calculations using the NASA CEA code [10]. The oxidation state of iron in a Fe-H-O system under a thermal/chemical equilibrium was calculated. The molar mixing ratio of O_2 to H_2O was treated as a free parameter from 0 to 0.7. The total pressure of the system was fixed at 300 atm. Ferric iron is stable if the molar mixing ratio exceeds 0.5 for a wide range of temperatures.

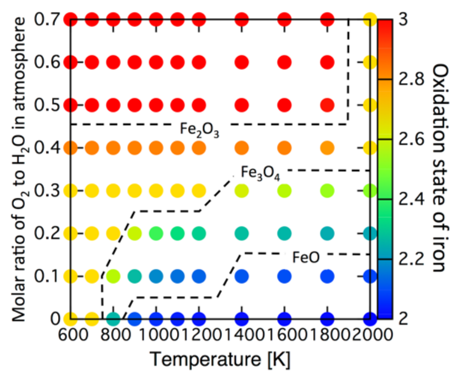

Figure 1. The oxidation state of iron as a function of molar ratio of O_2 to H_2O and temperature. The elemental ratio H:Fe was set to 2:1.

Above thermodynamic consideration indicates that the lack of of thick oxygen atmosphere on the current Venus could be explained as a natural consequence in the planetary accretion. Following that, I calculated the cumulative amount of the excavated non-oxidized fresh rocks due to the late accretion.

A stochastic bombardment model: I describe each part of the model to calculate the cumulative mass of impact ejecta in this section. I used a Monte Carlo approach with the Mersenne Twister algorithm [11].

Excavated mass and depth after each impact. I used a combination of the π-group scaling rules [e.g., 12] and a modified Maxwell's Z-model [13]. Figure 2ab show examples of the geometry of a transient crater and an excavated region for impactors with different sizes.

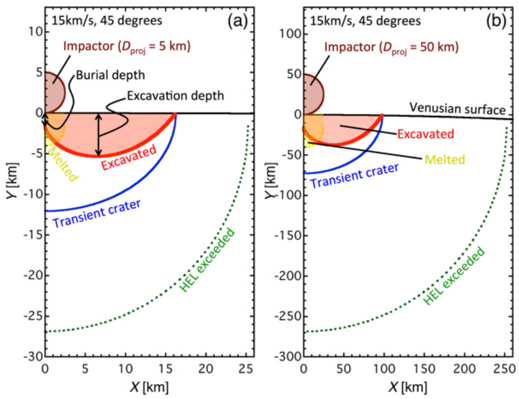

Figure 2. The geometry of crater formation for impactors with the size of (a) 5 km and (b) 50 km.

Size, velocity, and angle distributions. Dynamical transport of asteroids from the main belt to the early Venus was assumed. Although the size distribution for large impactors (>120 km) by [8] was used, the size exponent *q* for relatively small impactors (< 120 km) was treated as a free parameter because it is an important parameter in this matter and it at the time has not been constrained well. The impact velocity [14] and angle [15] distribution was employed.

Total mass of impactors. The previous studies on the late accretion showed that the possible impacted mass to Earth at this period is ranged from 0.5-6 × 10^{22} kg using a few independent methods [e.g., 16-18]. I assumed that Venus suffer a similar level of impact bombardment to Earth. Thus, the mass was varied at a range of 1-5 × 10^{22} kg.

Calculation of the cumulative mass of fresh ejecta. Treatment of nonrenewable oxidized deposits on the surface is key to quantitatively estimate the removed amount of oxygen. Under the assumption, which is the Venusian surface is well-mixed due to impact bombardment, referred to as “impact-induced convection” [19], I calculated the evolution of excavated fraction as a function of the depth from the Venusian surface after each impact, rather than detailed histories of impact ejecta during the calculation.

Results: Figure 3 shows the main results of this study that is the corresponding amount of removed water vapor from Venus including the effect of photochemical dissociation of water and subsequent hydrogen escape as a function of the total mass of impactors Venus. The oxygen in >0.6 TO is possibly removed during the late accretion if the total impactor mass exceeds 2 x 10^{22} kg, strongly suggesting that impact bombardment is a main contributor on the oxygen removal from the Venus.

Discussions and Conclusions: Although the estimate is an upper limit because I assumed that the entire

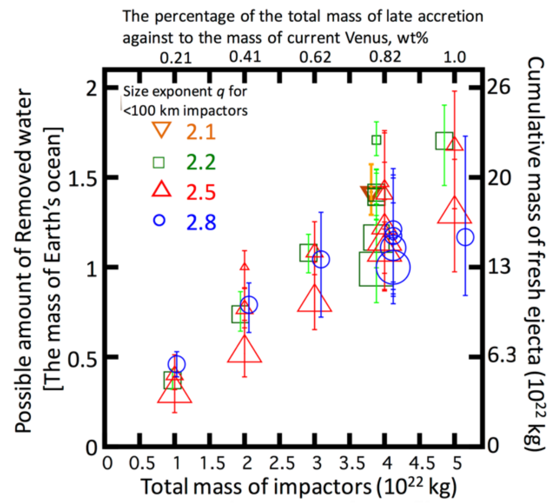

Figure 3. Possible total amount of removed water, as a function of total impactor mass, size exponent for <100 km impactor, *q*, and the maximum impactor diameter, D_{max}. Four different symbol sizes are shown, corresponding to D_{max} are 500 km, 1000 km, 1500 km, and 2000 km. The cumulative mass of nonoxidized “fresh” ejecta is also shown on the right vertical axis.

ejecta reacts with a hot atmosphere up to the stoichiometric limit, the process might not occur on the early Earth efficiently because a photochemical dissociation of water vapor would not proceed on an ocean-covered Earth-like planets. The form of surface water (i.e., ocean versus a steam atmosphere) is an important factor in determining the fate of surface water against to the impact bombardment.

This study has been already published in *Earth and Planetary Science Letters* [20].

References: [1] Donahue, T. M. et al (1982) *Science,* **216**, 630 [2] Kasting, J. F. and Pollack, J. B. (1983) *Icarus,* **53**, 479. [3] Chassefiere, E. (1996) *Icarus,* **124**, 537. [4] Gillmann, C. et al. (2009) *EPSL*, **286**, 503. [5] Kullikov, Y. N. et al. (2007) *SSR*, **129**, 207. [6] Lewis, J. S. and Prinn, R. G. (1984) *Planets and Their atmospheres*, Academic Press Inc. [7] Hamano, K. (2013) *Nature*, **497**, 607. [8] Bottke, W. F. et al. (2010) *Science*, **330**, 1527 [9] Monazam, E. R. et al. (2014) *Ind. Eng. Chem. Res*., **53**, 13320. [10] Gordon, S. and McBride, B. J. (1994) *NASA Reference Publication*, 1311. [11] Matsumoto, M. and Nishimura, T. (1998) *ACM Trans. Model. Comput. Simul.*, **8**, 3. [12] Schmidt, R. M. and Housen, K. R. (1987) *Int. J. Impact Eng.*, **5**, 543. [13] Croft, S. K. (1980) In: *Proc. LPSC 11th*, 2347. [14] Ito, T. and Malhotra, R. (2006) *AdSR*, **38**, 817. [15] Shoemaker, E. M. (1963) In: The Moon Meteorites and Comets, 1, 301. [16] Chyba, C. F. (1991) *Icarus*, **92**, 217. [17] Walker, R. J. (2009), *Chemie der Erde*, **69**, 101. [18] Jacobsen, S. A. et al. (2014) *Nature*, **508**, 84. [19] Senshu, H. et al. (2002) *JGR*, **107**, 5118. [20] Kurosawa, K. (2015), *EPSL*, **429**, 181.