DEGASSING OF ARGON, HELIUM, AND WATER AND THE NATURE OF CRUSTAL FORMATION ON VENUS; Noriyuki Namiki, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, and Sean C. Solomon, Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015.

Introduction. The history of volcanic resurfacing and crustal formation on Venus are topics of an important ongoing inquiry. The apparently random distribution of impact craters and the small fraction of modified craters have led to the hypothesis that a catastrophic resurfacing event occurred 300 to 500 My ago [1, 2]. On the other hand, analysis of the cratering records on volcanoes and coronae and Monte Carlo models of resurfacing of craters have shown that volcanic activity of as much as 7 $km^3\ yr^{-1}$ has continued over the last 500 My [2-4]. Such magmatism transfers not only heat, but also magmatic volatiles from the planetary interior. Therefore the present abundance of atmospheric constituents can constrain the nature of postulated catastrophic resurfacing events and of post-catastrophe volcanism [5-7].

In this study, we focus on ^{40}Ar, ^{4}He, and H_2O. ^{40}Ar is generated in the planetary interior by the radioactive decay of ^{40}K. The ^{40}Ar abundance in the atmosphere increases with time through the processes of partial melting of mantle material and transport of magma to the surface or to near-surface reservoirs. ^{4}He is a decay product of U and Th. Unlike ^{40}Ar, however, ^{4}He escapes from the atmosphere with a characteristic residence time of hundreds of millions to a billion years [8]. Thus the abundances of these noble gases in the present atmosphere constrain the degassing history of the planet over different time scales. The abundance of H_2O and the D/H ratio in the present atmosphere provide similarly complementary constraints on degassing. Hydrogen escapes on a time scale of tens to hundreds of million years while deuterium remains in the atmosphere with a considerably longer residence time [9]. We attempt to constrain the rate and episodicity of magmatism on Venus by modeling the degassing history of these volatiles.

Degassing Model. We model the history of crustal production on Venus as repeated cycles of two different processes: episodic catastrophic resurfacing by lithospheric recycling, and steady magmatism. In a catastrophic resurfacing event, old crust is assumed to be thoroughly recycled into the mantle by transferring K, U, and Th and trapped ^{40}Ar and ^{4}He from the crust to the mantle. Accompanying recycling of old crust is the formation of an amount of new crust generated by partial melting of the mantle. K, U, and Th in the crust and ^{40}Ar, ^{4}He, and H_2O in the atmosphere increase in proportion to this new crustal mass as the radioactive elements and the volatile species in the mantle decrease. After cessation of a catastrophic resurfacing event, steady magmatism is assumed to transfer radioactive elements and volatiles among the three reservoirs. Such magmatism is assumed to take place at a constant flux. During this period of steady magmatism, H, D, and He are assumed to escape from the atmosphere.

We solve for the transfer of radioactive elements and volatiles among three reservoirs under the assumption that degassing coefficients are constant in time [10]. Because both radioactive elements and volatiles in the mantle are released and transported to the surface by partial melting of mantle material, the degassing coefficients are governed by the crustal production process: the partition coefficients between minerals and melt, the fractional degree of melting, and the rate of crustal production [10]. Present escape fluxes of H and He [8, 11] are extrapolated backwards in time by including the effects of a diffusion limit and an enhanced flux of extreme ultraviolet radiation from the young sun [e.g., 12]. By solving for the degassing coefficients that satisfy the presently observed abundances in the crust and atmosphere and by taking experimentally determined partition coefficients [13, 14], we derive constraints on past crustal production.

Numerical Results. For Ar degassing, the absolute abundances of K and ^{40}Ar in each reservoir are scaled by the total amount of ^{40}Ar in the present atmosphere. The calculated K concentration in the bulk silicate planet and in the crust then constrain a series of models parameterized by the rate of steady magmatism, Q_c, and the ratio T_c of the crustal volume produced during each catastrophic resurfacing event to the surface area (Figure 1). The K concentration in the bulk silicate planet is taken equal to the terrestrial value of 200 to 300 ppm (dashed lines in figure) [e.g., 15]. The K concentration at the Venus surface (except at the

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Venera 8 site) lies between 0.14 and 0.67% (dashed-dot lines) [16]. Models satisfying both constraints are shown by the shaded area in Figure 1. The quantity T_c trades off with the rate of steady magmatism, and the total crustal volume (again divided by surface area) integrated over 4.5 Gy is shown in Figure 1 to be between 70 and 120 km (solid lines).

For ^4He degassing, models are constrained by the ^4He abundance in the present atmosphere and by upper and lower bounds on the U and Th concentrations obtained from estimates for the bulk silicate Earth [e.g., 15]. However, the estimate of the present ^4He abundance includes an uncertainty of a factor 3 [17] and allows the entire range of models constrained by Ar degassing (the shaded area in Figure 1). For H_2O degassing, we invert for the initial water abundances in the mantle from the observed water abundance and the D/H ratio in the present atmosphere. The calculated initial water abundance in the mantle is less than a few ppm (Figure 2), i.e., two orders of magnitudes less than the estimated value for depleted mantle on Earth [e.g., 18].

Discussion. The results shown here are preliminary, and further work is required to investigate a wide range of parameters. A total crustal production between 70 and 120 km (Figure 1) is 2 to 4 times thicker than the estimate of the present average crustal thickness [19] and implies crustal recycling in the past. However, the crustal production value depends on the assumed partition coefficient of Ar and the fractional degree of melting [7]. A low partition coefficient and a low degree of melting increase the Ar concentration in the melt and the rate of degassing, and hence decrease the total crustal production. In contrast, the low initial value for mantle water (Figure 2) is relatively insensitive to the assumed parameters. One interpretation of this result is that the interior of Venus has been dry over the last 4.5 Gy. An alternative inference is that only a portion of Venus mantle has degassed and is depleted in volatiles at present. The latter possibility, however, has yet to be tested by Ar and He degassing models.

References. [1] G.G. Schaber et al., *JGR*, *97*, 13257, 1992; [2] R.G. Strom et al., *JGR*, *99*, 10899, 1994; [3] M.A. Bullock et al., *GRL*, *19*, 2147, 1993; [4] N. Namiki and S.C. Solomon, *Science*, *265*, 929, 1994; [5] T. Matsui and E. Tajika, *LPSC*, *22*, 863, 1991; [6] V.P. Volkov and M.Ya. Frenkel, *EMP*, *62*, 117, 1993; [7] N. Namiki and S.C. Solomon, *LPSC*, *25*, 971, 1994; [8] M.J. Prather and M.B. McElroy, *Science*, *220*, 410, 1983; [9] D.H. Grinspoon, *Nature*, *363*, 428, 1993; [10] Y. Hamano and M. Ozima, in *Terrestrial Rare Gases*, Japan Sci. Soc. Press, 155, 1978; [11] T.M. Donahue and R.E. Hartle, *GRL*, *12*, 2449, 1992; [12] D.M. Hunten et al., in *Origin and Evolution of Planetary and Satellite Atmospheres*, Univ. Arizona Press, 386, 1989; [13] C.L. Broadhurst et al., *GCA*, *56*, 709, 1992; [14] H. Hiyagon et al., *GCA*, *56*, 1301, 1992; [15] W.F. McDonough et al., *GCA*, *56*, 1001, 1992; [16] Yu.A. Surkov et al., *JGR*, *92*, E537, 1987; [17] U. von Zahn et al., in *Venus*, Univ. Arizona Press, 299, 1983; [18] P.J. Michael, *GCA*, *52*, 555, 1988; [19] M. Simons et al., *Science*, *264*, 798, 1994.

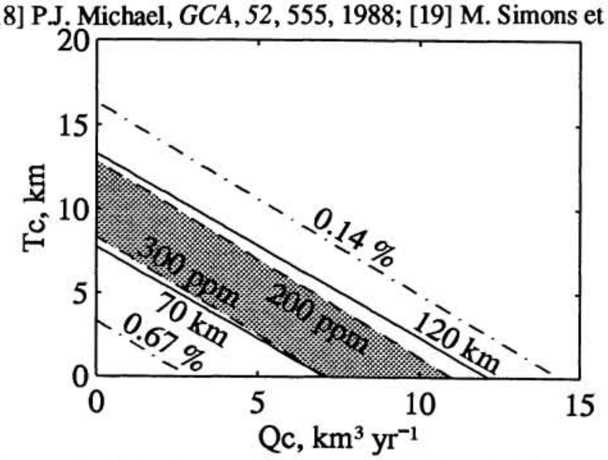

Figure 1. Contours of K concentration in the bulk silicate planet (dashed lines) and in the crust (dashed-dot lines), and contours of total time-integrated crustal volume divided by surface area (solid lines). The range of allowable models is shown by the shaded area. The event interval and the degree of melting are taken to be 500 My and 0.1, respectively.

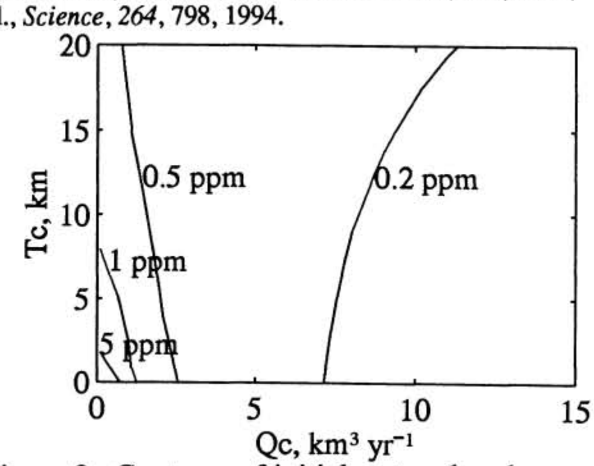

Figure 2. Contours of initial water abundance in the mantle calculated from the observed H_2O concentration of 30 ppm and D/H ratio of 0.16 in the present atmosphere. The event interval and the degree of melting are the same values as in Figure 1.