Self-weight consolidation process of water-saturated deltas: Implications for delta morphology and lithification and delta formation timescale on Mars. M. Zhang[1], Q. Yan[1,2], Y. Xu[1], L. Xiao[3], J. Zhao[3,4], D. Song[5], J. Wang[3], S. Yu[1], Z. He[3], H. Liu[3], D. Cui[6], X. Zhang[1] [1]State Key Laboratory of Lunar and Planetary Science, Macau University of Science and Technology, Macau China (mayerzhang0110@163.com), [2]School of Mechanical Engineering and Automation, Harbin Institute of Technology, Shenzhen 518055, China, [3]State Key Laboratory of Geological Processes and Mineral Resources, Planetary Science Institute, School of Earth Sciences, China University of Geosciences, Wuhan, 430074, China, [4]Key Laboratory of Geological Survey and Evaluation of Ministry of Education, China University of Geosciences, Wuhan 430074, China, [5]Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China, [6]Faculty of Engineering, China University of Geosciences, Wuhan 430074, China

Introduction: Deltas are water-related sedimentary landforms commonly discovered on Mars and Earth. From source to sink, delta formation undergoes the following processes: hydrodynamics of source water, sediment transport, and, finally, sediment consolidation. During the consolidation, the sediment volume and porosity are reduced due to the expulsion of water and/or air under the delta's self-weight. Previous studies on the martian consolidation process either adopted the terrestrial consolidation rate[1] or ignored this process[2] altogether. However, the consolidation process may diverge on these two planets due to their different gravity regimes, which may further affect the delta's morphology and lithification and the estimation of the delta formation timescale. In this study, we carry out a series of laboratory experiments to determine the basic parameters for modeling consolidation using water-saturated martian sediment simulants. Several parameters are adjusted to the martian condition considering the reduced gravity of Mars. The consolidation process is modeled with Gibson's 1-D consolidation model for deltas with different initial thicknesses (20–150 m) and different types of base drainage conditions (rigid bedrock and loose regolith). Finally, we discuss the effects of the consolidation process on delta morphology and lithification and delta formation timescale on Mars.

Data and method: *Laboratory experiments.* The experiments are used to determine the important parameters of Gibson's model relating to the compressibility and permeability of the sediment, which is dependent on the sediment composition, grain size distribution, and grain shape. We use the PSI HX (Planetary Science Institute, Huo Xing) martian regolith simulants[3]. The mineral compositions and chemical components of our samples are made to be consistent with those of the reported martian regolith. The samples are sieved and selected based on the grain size distribution of in situ grain observation at the Link site in the martian crater Gale[4]. The grains are processed into subrounded to subangular shapes[5-6]. The consolidation experiment is then carried out along with the permeability test[7]. The experimental data are fitted by the relations of the void ratio-vertical effective stress (e-σ') and void ratio-vertical hydraulic conductivity (e-k) [7]. These relationships are adjusted to Mars based on the eq. $k = k'\rho w g/\mu$[8]. The water density ρ_w, the dynamic viscosity μ and the permeability k' are intrinsic parameters that are independent of the gravity acceleration g. Therefore, k is proportional to the gravitational acceleration g.

Numerical Simulation with Gibson's Model. Using the relationship between the void ratio-vertical effective stress (e-σ') and void ratio-vertical hydraulic conductivity (e-k) obtained by the laboratory experiments, we calculate the delta consolidation process on Mars and Earth by Gibson's 1-D nonlinear consolidation model. The variation of void ratio e over the settlement time t is expressed as[9-10]:

$$\frac{\partial e}{\partial t} = -\frac{\partial}{\partial a}\left[\frac{k(1+e_0)^2}{\gamma_w(1+e)}\frac{d\sigma'}{de}\frac{\partial e}{\partial a}\right] - \left(\gamma_s - \gamma_w\right)\frac{d}{de}\left[\frac{k(1+e_0)}{\gamma_w(1+e)}\right]\frac{\partial e}{\partial a} \quad (1)$$

where a is the distance away from the delta bottom, γ_s (= $G_s g \rho w$) and $\gamma_w = (\rho_w g)$ are the gravity-dependent (g) unit weights of solid particles and water. e_0 is the initial void ratio. The material comprising the crater floor at the delta bottom could be rigid bedrock with low permeability or loose regolith with high permeability. We model these two endmembers by considering two boundary conditions: (1) the single-drained condition, i.e., only the top of the upper layer is drained; (2) the double-drained condition, i.e., both the top and bottom of layers are drained[11-12]. For a delta with a given initial thickness a_0 (t = 0) and initial void ratio e_0, we integrate Eq. (1) to obtain the void ratio at a specific time and depth during the consolidation of the delta. We use the Crank-Nicolson finite difference method. We set the initial delta thicknesses a_0 (t = 0) to be 20 m, 50 m, 100 m, and 120 and 150 m, which covers most of the previously estimated delta thicknesses on Mars. The settlement amount of the delta s_t of the modeled sediment at the time t is calculated [11] (**Fig. 1**):

$$s_t = a_0 - \frac{1}{1+e_0}\left(a_0 + \int_0^{a_0} e(a,t)\,da\right) \quad (2)$$

Discussion: *Implications for delta morphology and lithification*. Based on the modeling results, the settlement rate on Mars is lower than on Earth during delta consolidation (**Figure 1**). This suggests that martian deltas are looser and more erodible than their terrestrial counterparts considering the effects of the consolidation process alone. Thus, channels over the martian deltas should be theoretically easier to develop. In addition, less compaction indicates lower cohesion between sediment particles (**Figure 1**). During delta consolidation, the looser sediments of martian deltas are thus more easily disturbed by seismic shaking, impacts, and paleoclimatic events to form a larger amount of soft-sediment deformations (e.g., gravitational slumps, slides, folds, convolute bedding, brittle fractures, and dikes) and brittle deformations [13]. Moreover, due to the smaller final compaction of deltas on Mars compared to the Earth, a higher amount of delta post-deposition erosion before significant cementation on Mars is expected under similar climate conditions. Furthermore, since martian deltas' constituent materials have more pores and deformations following consolidation, more cementation/recrystallization is needed for martian deltas to be lithified in comparison to Earth.

Implications for calculation of fluvial duration. We determine the fluvial duration T by a new formula:

$$T = \frac{V_s(1 - \lambda_2)}{Q_s} \quad (3)$$

where λ_2 is the porosity of the consolidated deltas. Eq. (3) means the fluvial duration time T can be calculated by the pore-free delta volume, $V_s(1 - \lambda_2)$, divided by the total pore-free sediment flux, Q_s. Our modeling results show that the final porosity λ_2 after consolidation is 0.45–0.46. Therefore, the timescale T obtained by Eq. (3) is about 32%–44% of the results[14-15].

Martian deltas may experience repeated hydration-dehydration cycles, i.e., the reduction or reintroducing of water in the delta, in which the dehydration process induces further consolidation and thus reduces the final porosity (λ_2) of the delta[16]. However, the hydration process barely affects the delta porosity[17]. Martian deltas are also possibly formed in an icy environment. Unlike consolidation in a warm environment (modeled in this study), consolidation in an icy environment is accompanied by freeze-thaw cycles and the grounds below the deltas are expected to be frozen with lower permeability. The freeze-thaw cycle reduces the uniaxial compressive strength of sediments[18], and probably lowers the final porosity (λ_2). In addition, our results have shown a rigid base lowers the consolidation rate but does not change the final porosity of the delta (**Figure 1**). Therefore, frozen grounds similar to the rigid base are expected to have little effect on the porosity (λ_2). In conclusion, deltas formed in an icy environment or the subsequent dehydration process produce a lower final porosity, corresponding to a longer consolidation process. Following this consequence, the modification for the previous estimations on the timescale represents an upper limit.

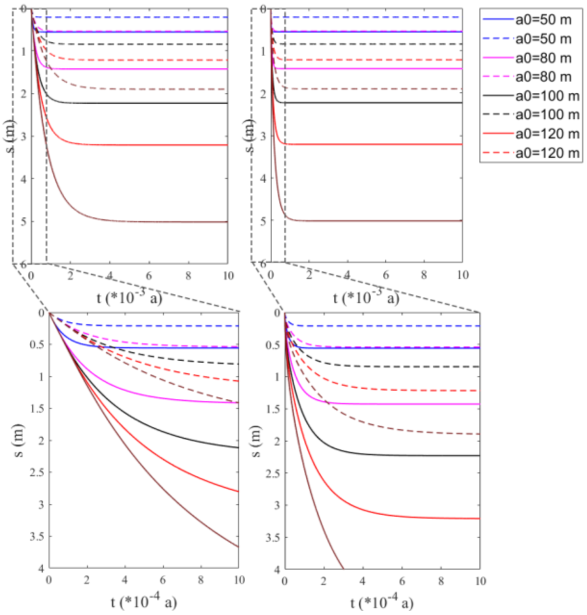

Figure 1. Settlement amounts s vary with settlement time t under different initial thicknesses a_0 on Mars (dashed lines) and Earth (solid lines): (a) single-drained condition. The Black dashed box indicates the location of the Figure. 1c; (b) double-drained condition. The Black dashed box indicates the location of the Figure. 1d.

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