Groundwater Upwelling into a Gale Crater Lake on Early Mars: A Source of Silica and Ferrous Iron. N. Noda[1,2], Y. Sekine[1], S. Tan[1,2], T. Shibuya[3], H. Genda[1] [1]Earth-Life Sci. Inst., Tokyo Inst. Tech., [2] Dept. of Earth Planet. Sci., Univ. Tokyo, [3] Dept. Subsurface Geobio. Anal. Res., Japan Agency Marine-Earth Sci. Tech. (JAMSTEC)

Introduction: NASA's Mars Science Laboratory Rover, Curiosity landed on Gale Crater, Mars, which contains a mound of lacustrine sediments [1]. The mineralogical and geochemical data of the lacustrine sediments provide essential information on the past climate and redox-based habitability on early Mars [1,2,3].

The Murray formation is 150-m-thick, lacustrine mudstones deposited within Gale Crater [1]. Parallel-laminated bedding (0.5-mm thick) of the lower part of the Murray mudstones suggests their deposition on lake floor under quiescent conditions [1]. Geochemistry and mineralogy of the lower Murray mudstones are characterized by authigenic depositions of high levels (~60%) of silica (opal-CT and amorphous silica) together with iron oxides (e.g., magnetite) [2,3], suggesting the presence of dissolved SiO_2 in the Gale lake.

One possible source of Fe^{2+} in the early Gale lake is upwelling groundwater [2]. Groundwater could have also contained high levels of dissolved SiO_2 given alkaline and high-temperature conditions in the subsurface [4]. Upwelling of groundwater, if occurred, is important because this would have provided reductants and greenhouse effect gas (e.g., H_2) to the surface [4,5]. However, little is known about the conditions of both climate and water table capable of upwelling groundwater into Gale Crater. Additionally, the chemical compositions of groundwater on early Mars— particularly, the determining factors of dissolved levels of SiO_2—have been poorly constrained.

The objectives of the present study are i) to investigate the past climates and water table levels capable of upwelling groundwater into Gale Crater using a hydrological model; and ii) to understand the determining factors of dissolved levels of SiO_2 in groundwater on early Mars by laboratory experiments. In the modeling, we use the existence of paleolakes within and near Gale as the constraint for reconstructing the past hydrological cycles. In the experiments, we investigate hydrothermal reactions using synthesized Martian rocks. Finally, we discuss the role of deep craters at low latitudes, e.g., Gale, for the past climate and habitability.

Hydrological simulations: We calculate surface and groundwater flows near Gale Crater using a three-dimensional hydrological simulator 'GETFLOWS' with Martian gravity (co-developed with Geosph. Environ. Tech. Corp.). The previous study constrains the paleo-aridity around the Gale lake using hydrological modeling; however, they do not consider a three-dimensional structure for the subsurface [6]. By contrast, GETFLOWS deals with fully-coupled surface and subsurface flows in three-dimensional grid blocks based on the hydro-geophysical equations (i.e., the mass conservation, Darcy's law, and Manning's equation) [7]. To describe unsaturated groundwater flows, GETFLOWS employs generalized formulations of multi-phase (air and water) Darcy's law [7].

The topographic data around Gale were assigned into the corner-pointed coordinate of three-dimensional grid blocks with a horizontal resolution of 4 km and vertical resolution increases from ~0.05 km to ~1.5 km with increasing depth from the surface from 0 km to ~15 km. The model parameters are a net evaporation rate (E_{net} (mm/24 hours)=[evaporation rate]−[precipitation rate]), permeability and porosity of rocks, and water table depth, h_0 (km), of outside boundary of the grid blocks. For a given parameter condition, we obtained steady-state vectors of water flow, surface water distribution, and water saturation at subsurface. In the present study, we varied two model parameters of E_{net} as 0, 0.1, 1, and 10 and h_0 as 0 and 1.

Figure 1 shows the simulation results of spatial distributions of surface water and stream lines of groundwater flows for different E_{net} and h_0. For $E_{net} < 0.1$, no significant upwelling of groundwater into Gale Crater occurs (Fig. 1). Groundwater moves almost horizontally from south to north according to topographic inclinations (Fig. 1). Under the low E_{net} and deep h_0 conditions, a closed-basin lake can form within Gale (Fig. 1). However, only a few lakes appear surrounding Gale because of the deep water table (Fig. 1). On the other hand, vigorous groundwater upwelling takes place for $E_{net} > 1$ (Fig. 1). Owing to effective evaporation from the surface, groundwater is locally pumped up from the deep subsurface, forming multiple lakes at local topographic lows (Fig. 1). Permeability and porosity of rocks would not change the threshold E_{net} (i.e., 0.1– 1) to cause upwelling of groundwater significantly but could affect mainly the velocity of upwelling.

Compared our results of surface water distribution with the observations of paleolakes near Gale Crater [8], high E_{net} (e.g., 1) and relatively shallow h_0 (e.g., 0) conditions can explain the observations (e.g., Case A of Fig. 1). The required high evaporation rates are consistent with (semi-)arid climates proposed by the previous hydrological modeling [6]. The effective evaporation around Gale may also agree with the recent view of a cold and arid early Mars [9]. Although our results may change depending on model setting (e.g., partitioning of rainfall between surface and subsurface), the presence of multiple lakes with different elevations surrounding Gale implies that upwelling of groundwater would have occurred, at least locally, in this area. In this case, the groundwater source would have been as deep as several kilometers beneath the surface (Fig. 1).

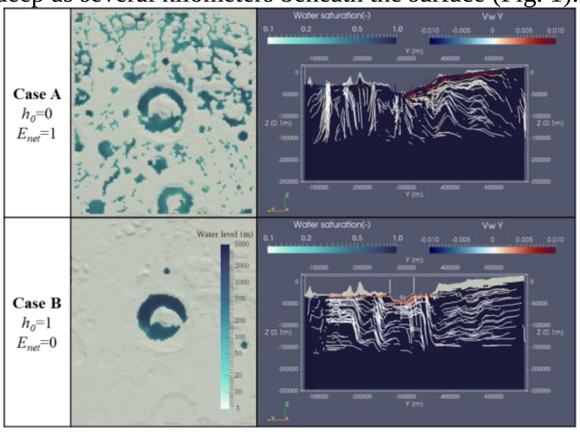

Fig. 1. Simulation results of surface water distribution and stream line of groundwater for different E_{net} and h_0.

Hydrothermal experiments: If groundwater was derived from the several-kilometers depth (Fig. 1), fluids would have experienced high temperatures, e.g., ~100°C, assuming high thermal gradient proposed for early Mars [4]. At these temperatures, metastable phases of secondary minerals might have controlled the chemical composition of groundwater.

In the experiments, we synthesized glass rock samples with the same chemical composition with conglomerates found at Gale [10]. We conducted hydrothermal experiments using a Dickson-type apparatus, which pressurized and heated a flexible gold reaction cell to 50–100 MPa and 100–200°C, respectively. Fluid samples were collected several times during the experiments for chemical analyses. After the experiments, mineralogical and chemical compositions of rock residues were analyzed using X-ray diffraction (XRD) and secondary electron microscope-energy dispersive X-ray spectroscopy (SEM-EDS).

Figure 2 shows the experimental results of time variations in aquatic chemistry during the experiment at 200°C and 100 MPa. This figure shows that the ion concentrations reach almost constant in ~100 hours of reaction time. The steady-state concentration of Si (=ΣSiO_2) is much higher than that of Fe^{2+} (Fig. 2).

The steady-state Si concentration shows a good agreement with that of the solution equilibrium of quartz, suggesting that the Si concentration in fluids is determined by dissolution of quartz produced in the experiment. This is supported by the XRD data showing the formation of quartz in the rock residue.

The results of XRD and SEM-EDS analyses also indicate the productions of Fe-saponite, Fe-serpentine, analcime, calcite, and trace magnetite in the rock residue in addition to quartz. Except for calcite, the mineral assemblage is consistent with the secondary minerals observed in altered crustal clays on Mars. The concentration of Fe^{2+} controlled by the solution equilibrium of Fe-serpentine is 4×10^{-6} mM; whereas that controlled by magnetite is 8×10^{-6} mM. Thus, both of these minerals would not be responsible for controlling the Fe^{2+} concentration in fluids. Further thermochemical calculations would be needed to determine the secondary mineral that controls the Fe^{2+} concentration.

Implication for Gale's lacustrine environments: Our results suggest that if evaporation predominates precipitation at early Gale lakes, silica-rich groundwater would have upwelled into the crater floor. Assuming the evaporation rate of 1 mm/24 hours and 1 –10 mM of dissolved SiO_2 in upwelling groundwater, the deposition rate of silica within the Gale sediments would be 0.02–0.2 mm/Martian year. This implies that the laminae, with a thickness of 0.5 mm with silica level of 60% [2], of the lower Murray formation might be varve, suggesting ~10^5 years of warming periods to explain the thickness of the Murray formation.

Although Fe^{2+} concentration is low (Fig. 2), an addition of Cl into the system would have increased total Fe^{2+} given the stability of $FeCl^+$. If this is the case, upwelling groundwater might have also provided Fe^{2+} into the lake, leading to formations of Fe oxides and H_2 [5]. Given similar (semi-)arid climates may have developed over low-latitudes of early Mars [9], deep equatorial craters, e.g., Gale and McLaughlin [4], might have played roles in upwelling groundwater, which may have contributed global warming and provided bioavailable energy on early Mars.

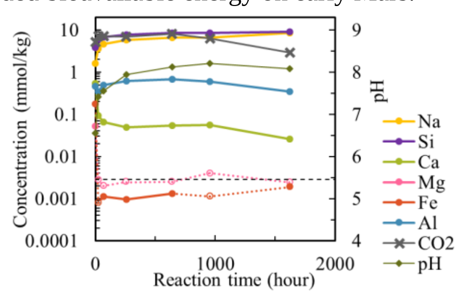

Fig. 2 Time variations in dissolved ions, CO_2, and pH during the experiment at 200°C and 100 MPa. Open circles represent upper limits of the concentrations

[1] Grotzinger et al. (2015) *Science*, 350, aac7575. [2] Hurowitz et al. (2017) *Science*, 356, eaah6849. [3] Rampe et al. (2017) *EPSL* 471, 172 [4] Michalski et al. (2013) *Nat. Geosci.*, 6, 133 [5] Tosca et al. (2018) *Nat. Geosci.*, 11, 635. [6] Horvath & Andrews-Hanna (2017) *GRL* 44, 8196 [7] Tosaka et al. (2000) *Hydrologic. Process* 14, 449 [8] Goudge et al. (2015) *Icarus* 260, 346. [9] Wordsworth et al. (2015) *JGR Planets* 120, 1201. [10] Mangold et al. (2016) *JGR Planets* 121, 353.