Formation process of lunar sinuous rilles by thermal erosion of basaltic lava flow. Chikatoshi Honda[1] and Akio Fujimura[1], [1]Institute of Space and Astronautical Science (ISAS/JAXA) (3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, JAPAN; e-mail address chonda@planeta.sci.isas.jaxa.jp).

Introduction: One of the major negative relief features on the terrestrial planets and satellites are sinuous rilles, which origin has been still debated. They possess conspicuous morphological characteristics of meandering channels or valleys, which is decreasing of depth and width. Normal rilles are straight or gently curved and considered to be graben-type faults. Crater chains in sometimes form irregular fractures like a rille, but they are excluded from the definition of sinuous rille. Lunar sinuous rilles are occasionally found in the maria and mare-highland boundaries, and most of them are concentrated around the Mare Imbrium and in the Oceanus Procellarum. According to [1], lunar sinuous rilles have typical dimensions of 30 – 40 km length and of less than 1 km width. The origin of these features differs on each planet or satellite; hence, we investigated the origin of the lunar sinuous rille due to existence of information for consideration of the origin (e.g., chemical composition of rock and elevation of rim and floor of sinuous rille).

Sinuous rilles on the lunar surface have been supposed to be related to the basaltic lava flow by many researchers, because the rilles usually observed in the lunar mare which is filled with basaltic rocks. The sinuous rilles have been proposed (1) to be collapsed lava tubes [2, 3, 4], (2) to be lava channels (lava flows) with natural levees [5], and (3) to be lava channels downcutting into a substrate by thermal erosion [6, 7, 8].

Since the temperature of lava flowing in a lava tube would gently decrease due to a rapidly-cooled surface crust of lava acting as an efficient insulator, the lava continues to flow over long distance before congealing. After the lava passes through the tubes, these tubes were collapsed by a number of projectiles or moonquakes. Finally, the collapsed pits become a continuous channel or valley (hypothesis (1)). As the largest lava tube that locates at north Queensland in Australia is up to about 20 m in width or depth, it is difficult to explain lunar sinuous rilles which have 1700 m in average width, even though the lunar gravity acceleration is one sixth of the Earth. On the other hand, we can see the double stream morphology of rilles with a narrow stream in the floor of wider rille. The tube formation mechanism may not simply explain these double streams. Therefore, we have excluded the lava tube hypothesis. According to hypothesis (2), lunar sinuous rilles seem to be natural levees of lava flows. This constructional origin has been proposed and discussed by [9] and [10]. We have excluded the channels with natural levees hypothesis, because close-up photographs on the rims of lunar sinuous rilles show little evidence of the levees, even though the channel-forming lava had very low yield strength, resulting in very narrow levees [11].

The potential of thermal erosion hypothesis to produce deep lava channel on the Moon is remained. The lunar lava flow could erode thermally into substrate base rock, because of a capability of high heat transfer due to a lower viscosity than that of terrestrial basalt [12]. This research aimed to understand of physical properties of lava flow which erupted on the Moon. And also, how this lava flow forms lunar sinuous rilles is clarified.

Morphology: Twelve sinuous rilles are classified into three types in respect to the depth profile. In general, the depth profile of lunar sinuous rilles becomes shallower increasingly [1]. Although the rilles whose depth decreases are not usual among our measurements, the depths of six rilles (Ivan, Handel, Telemann, Prinz, Beethoven, and Hadley) are decreasing with the increasing distance along the stream. This fact lets us expect that the ability of thermal erosion of lunar basaltic lava decreases quickly along the distance from the source vent, as a result of these lava flows that have thin thickness and high eruptive temperature assuming that the ther-mal erosion hypothesis is true. On the other hand, four rilles (Aristarchus VI, VII, Cleopatra, and Mozart) have a constant depth along the distance from a source vent. This characteristic indicates that the lava flow to have large thickness and low eruptive temperature produced these rilles, assuming as a mentioned above. However, there are exceptionally two rilles (Aristarchus VIII, Sibelius) that reveal an asperity of floor. It might be difficult for a simple eruptive lava flow to construct these rilles. Some lunar sinuous rilles would be inferred to owe their origin to an interaction of the various processes such as eruptions on the way of rilles.

Modeling: The heat conservation of the lava had been proposed by [13] and [14], and we improved the equation of the heat conservation assuming that the mechanism of heat loss at the top of the lava flow is a radiation.

Since the condition of lava flows to produce lunar sinuous rilles would been varying from turbulent to laminar along the downstream, we used the appropriate heat transfer coefficient with respect to the Re [15, 16]. The other mainly improved part in our model is the estimation of the thermal conductivity of the lava flow.

There are two expressions of the thermal conductivity of the lava due to conduction mechanisms [17]. In this study, these mechanisms are supposed to convert each other at liquidus temperature, whereas the thermal conductivity is ideally given by the addition of phonon and photon conductivities. Beneath theliquidus temperature, the phonon conductivity which is inversely proportional to T (ordinary conduction regime) is dominant. Over the liquidus temperature, the photon (radiative) conductivity which is proportional to T^3 (radiation regime) is also dominant [12].

To calculate the depth of thermal eroded channel, we emploied assumed initial temperature and thickness of lava flow, the slope of ground and width of each sinuous rille. Espetially, the parameters of temperature, thickness, and slope affect the result of the calculation.

Discussion and Conclusion: We have compared the calculated depth profile with the observed depth profile of sinuous rille. Most of sinuous rilles could be explained by our thermal erosion model, although one exceptional case exists (Rima Sibelius), whose topographic features of the floor of the rille are irregular. We supposed that this rille is not explained by a simple lava flow process, but by more than two stages of eruptions and/or by blanketing of ejecta due to cratering and more other reasons. As the thermal erosion hypothesis by single lava flow could mainly explain the morphology of lunar sinuous rilles, however, this fact encourages us to suppose that the conditions of initial thickness, initial temperature, and chemical composition of the lava are suitable for the formation of lunar sinuous rilles.

The effusion rate of eruption to explain the most sinuous rilles is in the range of 1.1 x 10^5 - 4.7 x 10^5 m^3/s which is more than that of the flood basaltic volcanism and largest historical one on the Earth (e.g., Clumbia River basalt; 1.2 x 10^4 $m^3/s/km$ and Laki; 8000 m^3/s). These effusion rates are reliable on the Moon [18]. Since the temperature of eruption strongly effects on the thermal erosion into the ground, the volume of lava necessary to produce a sinuous rille is also affected by the eruptive temperature. Estimated retention times of the volcanism that formed sinuous rilles are 1600, 30, and 5 days at the eruptive temperature of 1470, 1670, and 1870 K, respectively. Therefore, estimated volume to produce sinuous rilles are 12000, 510, and 190 km^3 at the eruptive temperature of 1470, 1670, and 1870 K, respectively. We supposed that 1.2 x 10^4 km^3 at 1470 K is too large to explain single eruption on the lunar surface, because the volume of a typical geologic unit in the mare is less than 10^3 km^3 [19]. We conclude that the lunar sinuous rilles had been potentially formed by the thermal erosion of basaltic lava flow with high eruptive temperature (Fig. 3). This fact let us to intend that thermal erosion of lunar basaltic lava flow with thermal conductivity characteristics especially in the radiation regime of the lava could explain the formation of lunar sinuous rilles. The high temperature condition had been obtained by the study of eruption of buoyant mechanism of basaltic magma on the Moon [20].

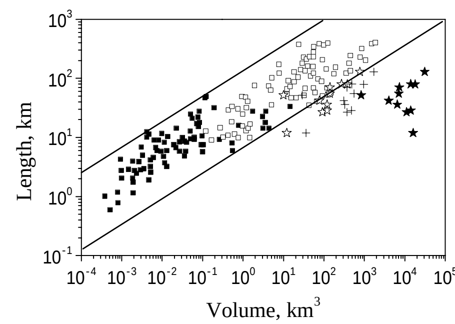

Fig. 3. The relationship between the volume of eruption and length of lava flows or lunar sinuous rilles. Solid and open squares reveal the lava flow on the Earth and Mars, respectively [21]. Solid stars, crosses, and open stars represent the results of initial temperature of 1470, 1670, 1870 K, respectively.

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