THE MINERALOGY OF THE GOSHOGAKE MUD VOLCANO FIELD, NORTHERN JAPAN, AND ITS IMPLICATION TO THE MECHANISM AND DRIVING FORCE.
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Introduction: On the Earth, mud volcanoes (MVs) have been reported both onshore and offshore [e.g., 1, 2, 3]. Also, on Mars, some specific landforms similar to MVs have been reported recently [e.g., 4, 5, 6, 7]. The extrusive mud should provide information on geology and biology at the deep interior under the extreme conditions (high temperature and pressure), and the rover can directly access it on Martian surface. Hence, it is important to investigate terrestrial MVs in detail and understand the source layer depth and driving force in the context of planetary geology and astrobiology.

Most terrestrial MVs have low temperature ranging from the ambient to 50˚C [e.g., 8] and are considered to erupt mud from a few to 10 km depth [e.g., 9, 10] due to the compression related to tectonic activity, rapid sedimentation, and/or dehydration of clay minerals [2]. On the other hand, the mechanism of high temperature MVs (>80˚C) has been relatively unknown. While the source depth at LUSI (Lumpur mud-Sidoarjo) in Indonesia, which is a high temperature MV, was estimated to be about 5500 m [9], its driving force has not been clear yet. Then, to make the cause and mechanism understood better, we chose the Goshogake MV field, which is also a high temperature MV system, and sampled the extruded mud. This Goshogake area is within a geothermal area, called the Sengan geothermal field [11], and it has been studied well in terms of geology and geothermal activity [e.g., 12, 13]. Especially, in this abstract, we tried to constrain the source and driving force by XRD and Vitrinite Reflectance (VR).

The Goshogake mud volcano field: We conducted fieldwork at the Goshogake mud volcano field positioned in between Akita-Yakeyama volcano and Hachimantai volcano, Tohoku region, Japan, where MVs are fed with a high-temperature fluid (from the ambient to 100˚C). Furthermore, the circulating water in the field is strongly acidic, with a pH range between 2 and 3 [14]. In this region, augite-hypersthene andesite is exposed, and under the Goshogake field, andesite, pre-Yakeyama lake deposit and Tertiary-volcanic rock lie [11, 15] sequentially from above. Based on the analysis of geology, gas, and mineral species, it was suggested that this MV field results from the combination of volcanic and sedimentary activities [14, 16].

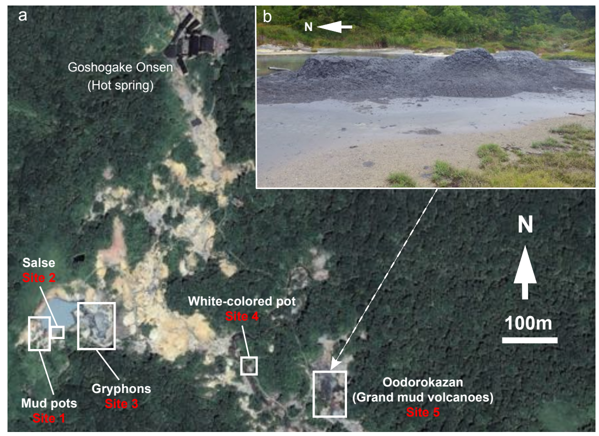

Fig. 1. The map and image of the Goshogake MV field. a) Field image map. The base map derived from Google Earth Pro (Image © 2017 DigitalGrobe). b) Oodorokazan (Site 5), which is a 22 m-long chain of gryphones forming a ridge and a group of big gryphones made by the extruded mud.

Materials and Methods: Mud samples were collected with plastic bottles in 5 sites (Fig.1). In order to determine the mineral composition, quantitative analysis by XRD, especially the internal standard method based on [17], was conducted. In addition, VR was measured. Based on the data of VR, the depth of source layer of extrusive mud was estimated and source layer was determined to compare to geology. After organic matters in mud sample were separated by using heavy liquid, only vitrinite particles were observed and their reflectance was measured using silicone-diode microphotometer. The reflectance was converted to temperature based on the kinetic calculation [18]. To calculate, the heating time was defined as 1.2 Ma or 2.5 Ma, which are the geological time of assumed source layer [19].

Results: We present the data of mineral composition of mud samples by XRD. While the amount of clay minerals such as kaolinite is about 10 to 40 %, the amount of amorphous silica (opal-A and opal-CT) is about 40 to 75% in each sample. Also, VR was measured at Site 5 (Fig. 2). The data showed that measured R_{mode} is 1.4%. To estimate the depth, the temperature based on R_{mode}, the geothermal gradient (214 K/km)

[20] and the surface temperature near Site5 (50˚C) [21] were used for calculation. As a result, the source depth of mud was estimated to be at ~700 m depth.

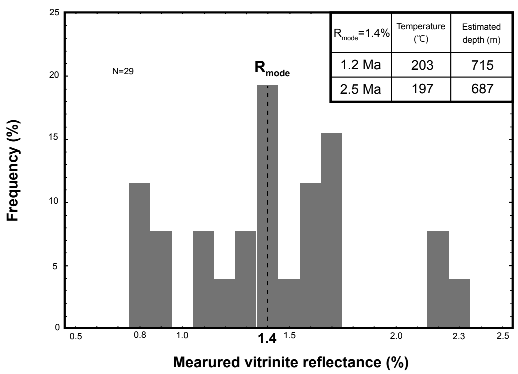

Fig. 2. Histogram of measured VR at Site 5. The mode is used as VR (R_{mode}). R_{mode} was converted to the temperature [18]. The depth was estimated by the calculation of the temperature from R_{mode} and the geothermal gradient [20].

Internal structure and driving force: Based on the mineral composition and estimated source depth, it was estimated that the source layer is the Ishigedozawa formation, which is a lacustrine sediment deposited in a caldera lake [22]. This sedimentary environment was similar to that of low temperature MVs, and the rapid sedimentation may have been important for producing an overpressured condition. On the other hand, the amount of clay minerals detected is less than that in other MVs [e.g., 23, 24]. In addition, the amounts of amorphous silica (opal; $SiO_2 \cdot nH_2O$), cristobalite, and tridymite detected are very high (50–75%). Opal-A (amorphous silica) dehydrates and alters to Opal-CT (cristobalite and tridymite type), and then the water is released [25]. This water makes the source layer compressive. In this MV, the overpressure according to the dehydration of both much opal and clay minerals could contribute to the driving force. The source layer of the Goshogake MV estimated in this study is much shallower (~700 m) than other MVs (a few km). This may come from the higher geothermal gradient in this region due to heat energy supplied by the volcanic activity than other MVs area and/or the composition of source layer that has originally included more opal and less clay minerals. We summarized the difference and similarity between high and low temperature MVs in Table 1. In conclusion, the Goshogake MV has the shallow source layer in which the dehydration of opal contributes to the compression and driving force.

Terrestrial analog: Mud erupts from a source layer at the depth, as if it is a "window", and we can obtain on surface the information on geology and biology of deep subsurface. The Goshogake MV field results from the eruption from the shallow source layer (~700 m). It

	Low-T MV	**Goshogake (High-T MV)**
Depth	a few ~ 10 km	~ 700m
Driving force	Tectonic activity, rapid sedimentation, and/or dehydration of clay minerals	Rapid sedimentation and dehydration of both opal and clay minerals
Source temp.	Low (100~150˚C)	High (~200˚C)
Source layer	Sedimentary	Sedimentary (caldera lake)

Table 1. Comparison between low temperature MVs and Goshogake (high temperature MV) based on this study and [1, 7, 9, 21].

indicates that some high-temperature MVs has the potential to obtain information not necessarily of deep (a few km or more) but of relatively shallow subsurface (several hundreds meters) geology and biology, and the same may apply to Mars. The Martian surface has many craters and ancient crater lakes have been postulated [26, 27]. Such environment may have been similar to that of lacustrine formation at Goshogake. Thus, the Goshogake mud volcano field may become a good terrestrial analog for future astrobiological explorations and comparisons with Martian paleoenvironment.

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