BEPPU HOTSPRING, JAPAN, AS A TERRESTRIAL ANALOG FOR ANCIENT HYDROTHERMAL SYSTEMS ON MARS.

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Introduction: Beppu Onsen (Hotspring) on the Kyushu Island, Japan, is famous for its touristic attractions but it is also scientifically important for the presence of hot spring pools with a wide range of mineral precipitation [1]. These hot spring pools harbor microbiological communities, and the implications for planetary environments such as Mars are significant.

Beppu Hotspring: The Beppu geothermal field is located at the eastern edge of "The Beppu-Shimabara graben" and is one of the largest geothermal fields in Japan. Fumarolic and hot spring activity spreads out up from the Tsurumi volcanic group down to the eastern coast of Beppu city, over a 5 km (E-W) by 8 km (N-S) range (Fig. 1). The Yufu-Tsurumi volcanic group is characterized by dacite and andesite rocks [2]. A variety of volcanic landforms including composite volcano (Yufudake), lava domes (Garandake) and scoria cone (Oninomiya) are observed. Pyroclastic flow and ash deposits from other Kyushu volcanoes cover the area. The central part of the hotspring field formerly subsided and was covered with debris-avalanches from the mountains behind, with the northern and southern edges of the field being bounded by two fault-systems striking along an almost E-W direction, respectively. The number of hot spring-wells drilled is ~3,000. Flow rate of the hot spring water including fumaroles and heat flow amounts to 50,000 tons/day and 350 MW, respectively.

Fig. 1. A bird's-eye view (Google Earth) of the Beppu geothermal field and volcanoes associated with the Beppu-Shimabara graben.

The highland region spouts fumaroles and hydrothermal water, whereas the lowland region bears hot spring water of diverse chemical composition. The range of phenomena and the regularity of their spatial alignment is a characteristic of the Beppu hotspring field.

Due to the high topographic relief, many sites of active and extinct surface alternation are scattered from 1300 m a.s.l. down to the sea (Fig. 2). We observe a marked zonation of the surface manifestations and alteration type according to the elevation of the sites. In the highest part (900 m to 200 m a.s.l.), acid-type surface manifestation like fumaroles, steaming ground, solfatara, and mud pools, develop intense silicification and advanced argillic alteration. In the intermediate part (200 to 100 m a.s.l.), the near-surface boiling of thermal fluids is expressed as warm or steaming ground, mud pools, hot springs which develop an argillic alteration type and limited silica sinter deposition. Development of an argillized cover leads to occasional hydrothermal explosions and mud volcanoes. The lower part of geothermal field (100 m a.s.l. to the sea) is characterized by the presence of now-extinct hot springs.

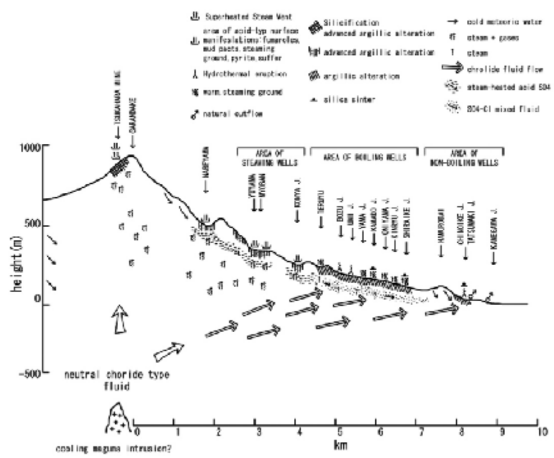

Fig. 2. Geothermal fluid flow system inferred from the chemical composition of the hot spring water, the surface manifestation and the distribution of alteration zone: A schematic E-W cross section of the northern part of the Beppu geothermal field [3].

Such manifestations are typical of geothermal systems developed in volcanic regions of high relief. These features are correlated with the inferred subsurface structure of the Beppu geothermal field (Fig. 2). Near the summit of Garandake, vigorous fumarolic activity and superheated steam vents are considered to be sites where steam and gases (H_2S, CO_2) from a vapor dominated zone underlain by a deep NaCl reservoir reach the surface. From this deep alkali chloride parent reservoir, lateral outflow spreads easterly towards the Beppu Bay. In the highest part, from the old Mine until the Konya site, steam and gases escaping from this deep outflow condense into meteoric groundwater producing perched, steam-heated, acid sulphate aquifers, and develop the acid type surface manifestations. In the intermediate part so called "Jigoku" (literally "hells"; fumaroles and steaming ground) area, mixing between the secondary acid sulphate fluids and the presumed gas-depleted, deep neutral NaCl fluids produce mixed chloride-sulphate waters which cause the observed argillic alteration and deposition of limited silica sinter.

We observe the different color of geothermal waters at the Beppu geothermal area (Fig. 3). Especially, at the famous "Jigoku" area, red, blue, white and dark-grey color hot springs are distributed. These colors are originated from different chemical, mineralogical (iron oxides, silica, clay, jarosite, etc.), physical, biological and sedimentological reasons [e.g., 4, 5].

Microbiological communities are known to exist in the Beppu geothermal field. For example, aerobic, sulfur-oxidizing thermophiles such as *Sulfolobus shibatae* and *Sulfolobus tokodaii* were isolated from its hot springs [6, 7].

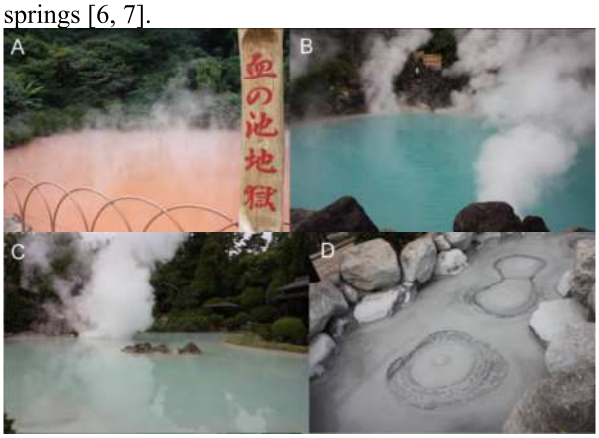

Fig. 3. Beppu hotspring pools. A) Chinoike-Jigoku. B) Umi-Jigoku, C) Shiraike-Jigoku, D) Bozu-Jigoku

Hypothesized ancient Martian hydrothermal systems and comparison to the Beppu geothermal field: Geothermal processes involving water have been debated extensively for their possible roles on Mars, sometimes highlighted by astrobiological implications. The proposed evidence for hydrothermal systems were in early days linked to the presence of certain landforms such as valley networks and impact craters where hydrothermal activities were hypothesized to have occurred [e.g., 8]. Localities such as Dao Vallis (Fig. 4A) originating from Hadriaca Patera have also been speculated to be the sites of hydrothermal activities [9]. In recent years, certain deposits rich in silica have been attributed to hydrothermal processes on Mars (Fig. 4B) [e.g., 10, 11]. For example, silica-rich deposits were found in the surroundings areas of the light-toned Home Plate at the Mars Exploration Rover Spirit landing site [10]. Combined with the interpretation that the layered sequence of Home Plate was produced by volcanic processes (pyroclastic flows or ash falls) [12], the silica-rich deposits were concluded to have formed by hydrothermal processes.

The hot springs at Beppu provide an excellent opportunity to observe spring pools where a variety of minerals precipitate. Silica is particularly relevant to Mars since its presence on the red planet has been hypothesized to be linked to the activities of ancient hydrothermal systems. Iron oxides have also been found on Mars [e.g., 13, 14], and their deposition is explained by various mechanisms including hydrothermal systems.

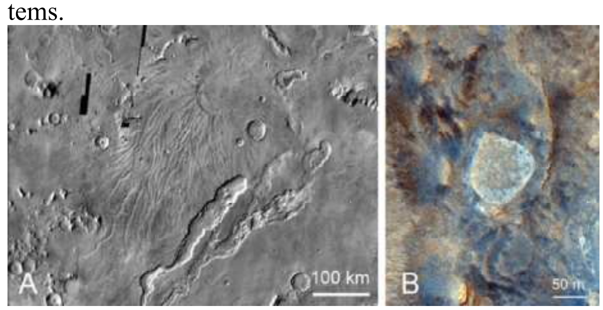

Fig. 4. Areas interpreted to be related to hydrothermal activities on Mars. A) Dao Vallis incised in the volcanic edifice of Hadriaca Patera. THEMIS image mosaic. B) The light-toned Home Plate and its surroundings where silica-rich deposits were found [10]. Mars Exploration Rover Spirit landing site. HiRISE image.

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