Surface Morphology of Columnar Joints in Japan: Polygonal Pattern Analysis of Igneous Rock

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Columnar joint is a magnificent geological structure composed of polygonal prisms of igneous rock. Famous examples include Genbu-do in Japan, Giant's Causeway in Northern Ireland, and Devil's Tower in the United States. Such the prismatic column structures are formed by the stress of the lava flow as it cools and then shrinks; once a certain crack develops at the cooled surfaces of the lava flow, it continues to grow in the direction perpendicular to the surfaces, resulting in a regular array of polygonal columns. The beautiful unrealistic structures have attracted people's interest for over 300 years.

In the field of geophysics, many of the columnar joints present in the world have been investigated to unveil the statistical properties of polygonal crack patterns. Remarkable exceptions are those present in Japan. As is well known, Japan is one of the most volcanically active countries, thus having many columnar joints. An attractive example among them is the andesite columnar joint called "Tatami–Ishi", which is present in Okinawa prefecture, the southernmost part of Japan. The notable feature of the Tatami-Ishi is that the exposed surface is almost flat due to repeated erosion of sea waves. Such columnar joints spreading over a flat and wide space are extremely rare worldwide. Besides the Tatami-Ishi, many other examples of columnar joints are there in Japan, showing well-ordered polygonal cracking patterns at the exposed surfaces. However, only a few studies on their morphologies was reported. This background motivated us to conduct field survey of columnar joints in Japan and obtained aerial photographs using a drone in order to analyse the statistical properties of the polygonal cracking.

Field survey of columnar joints was carried out at the following four domestic locations: (1) Tatami-ishi in Okinawa, (2) Tatami-ga-fuchi in Yamaguchi, (3) Hi-no-misaki in Shimane, and (4) Tawara-iso in Shizuoka. At first, we took a lot of photographs from 10 m above the ground using a drone. Next, these photographs were merged into a single large-scale image by a software. After that, we conducted image analysis using the image processing software. Eventually, we obtained the numeric data on the column cross-sectional area and the number of vertices of the polygonal cracking patterns for each survey locations.

We have found that the mean value of the cross-sectional area is considerably different between the four locations. Tatami-ishi represents the largest mean value among the four locations, with the value of 2.5 m^2 ; Hi-no-misaki represents the smallest one of 7.7×10^{-3} m^2, two orders of magnitude smaller than the largest one. The diversity in the cross-sectional area can be explained by considering the difference in the cooling rate of lava. In fact, previous work based on field survey and crystal analysis of igneous rocks suggested that the fracture advance speed is inversely related to the fracture spacing of columnar joints. This implies that columns with relatively large diameter are formed by slower cooling than those with small diameter.

We also discovered that the probability distribution function of cross-sectional area varies significantly depending on the rate of wave erosion against the igneous rock. At the location along the sea coast, the curve of distribution has a sharp peak; this tendency is in oppose to those inland. In fact, "Tatami-ga-fuchi" located inland has not been strongly affected by repeated erosion of sea waves compared to the other three locations, all of which locate along the sea coast.

Another finding is with regard to the number of vertices; hexagons and pentagons frequently appeared overall. In particular, pentagons are the most common in Hi-no-misaki, and hexagons are the most common in the other three locations. This difference can be attributed to the ordering process when cracks propagate in the lava depth direction.

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