Columnar joint: Geometric pattern analysis and analogue experiment using starch pastes

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Columnar joints are prismatic cracks that regularly penetrate the rock body. They are formed by contraction of cooled lava followed by sequential crack advances. Worldwide famous examples include: Giant's Causeway in Northern Ireland, Fingal Cave in the UK, and Devil's Tower in the United States.

Despite of much efforts reported thus far, a clear understanding for its formation mechanism has not yet been obtained, mainly because of the difficulty of experimental reproduction. In the last two decades, the situation changed drastically; it was discovered that regular crack structures, which look similar to columnar joints, can be realized very easily using starch paste. The way to make them is shown below. First, starch powder and distill water is mixed thoroughly to make paste. Next, this paste is poured into a container. Then, the surface of the paste is irradiated by an incandescent lamp, and it is left for a long time. As the moisture evaporates from the surface, the paste goes drying and causes cracking. As time elapses further, the cracks at the surface progress inward, and we finally obtain a prismatic structure which regularly penetrates the entire paste. After completely drying, a polygonal network pattern is generated on the surface of the paste.

Obviously, columnar joint and starch paste are different in the chemical composition, length scale, and crack initiation factors. But a similar prismatic crack is formed --- Why? This question motivated us to investigate the statistical properties of the polygonal pattern in both two systems.

Our drone aerial shooting of columnar joints was carried out at the following four domestic sites: (1) Tatami-ishi in Okinawa, (2) Tatami-ga-fuchi in Yamaguchi, (3) Tawara-iso in Shizuoka, and (4) Hi-no-misaki in Shimane. Importantly, the SiO_2content in constituent igneous rocks depends on the sites: the sites 1 and 3 are andesitic, the site 2 is basaltic, and the site 4 is rhyolitic. This difference would have influenced the statistical properties of the polygonal network pattern observed at present. Meanwhile, our starch-paste experiment was aimed at evaluation of the following two effects on the geometry of the polygonal crack pattern: (1) the fluctuation width in the size distribution of constituent starch particles, and (2) the degree of sphericity of the particles. To this end, we used two types of starch, corn starch and potato starch. We also examined the degree of correlation between the film thickness of the paste and the crack pattern obtained.

The first main finding was regarding the characteristic length scale of the polygonal network. For columnar joints, the length scale varies from sites to sites, probably because of the difference in the SiO_2 content. For the desiccated starch paste, the length scale increased with the film thickness only for the potato starch paste. The latter result can be explained from the water diffusion process in the paste and the spatial nonuniformity in the water concentration. Since both the water diffusion and concentration in the paste are directly affected by the size and shape of the constituent particles, our result indicates that the geometry of the dry crack pattern strongly depends on the particles' size and shape.

The second main finding was regarding the number of vertices in polygons. In columnar joint, pentagons and hexagons occurred in an almost equal frequency. On the other hand, in desiccated starch paste, only pentagons frequently occurred. This result can be interpreted by the difference in cooling/drying speed.

The third finding was regarding the probability distribution of polygon area. Both for the two systems, the distributions are well fitted on the curve of gamma distribution. This suggests the existence of a unified pattern formation mechanism which is common to both the cooling contraction of magma and the drying shrinkage of paste. Details of the results and its interpretation will be given in my talk of the session.

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