MANDELBROT'S INFERNO: EXPLORING THE FRACTALITY OF LAVA FLOW MARGINS IN ICELAND AND HAWAII.

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Introduction: Fractals are patterns that appear similar over a wide range of scales. Coastlines and clouds are two natural examples, and previous work has suggested that the planform margins of lava flows may be yet another example [1]. If so, quantifying the fractality of these margins—even at the scale of orbital imagery—could provide insight into lava flow type and surface roughness at scales far finer than directly observed.

Indeed, Bruno et al. [1] found systematic differences in fractality for margins of ‘a‘ā versus pāhoehoe flows (the two end-members of basaltic lava flows), and these differences extended from the scale of decimeters to the scale of kilometers. In these initial studies, Bruno et al. [1] focused on "simple cases", where factors such as substrate topography and post-emplacement modification (e.g., by aeolian mantling or, on the Moon, impact gardening) were not significant. They also had to use tedious analog field methods for measuring the margins, which limited the size of their datasets, and they only collected field data for lava flows in Hawaii.

Do these promising early results generalize to lava flows outside Hawaii, less-than-ideal cases, and much larger datasets? Is there a remote measurement technique that can provide robust interpretations even if ground truth is absent, for application to bodies such as Mars and the Moon? Does margin fractality also correlate with surface roughness, and if so, how do the scales of one compare to those of the other? These are some of the critical outstanding questions that we are actively exploring.

Methods: In the field, we traversed lava flow margins using Trimble R8 (Hawaii) and R10 (Iceland) GNSS rovers in Real Time Kinematic mode, which allowed us to continuously collect points with a sample spacing on the order of centimeters. Because this approach is qualitatively similar to the digitizing technique used to map lava flow margins in aerial and orbital imagery, it provides a consistent methodology across field and remotely sensed scales.

We then used the "divider method" (or "structured walk") to calculate how the apparent length of the margin changes when measured with virtual rods of different lengths [2, 3]. Each such measurement results in an approximation of the original line with inter-vertex segments equal to the rod length. These measurements are then plotted as in **Fig. 1**. If the measurements have a linear trend, the flow margin is fractal with a fractal dimension $D = 1 - m$, where m is the slope of the trend [2].

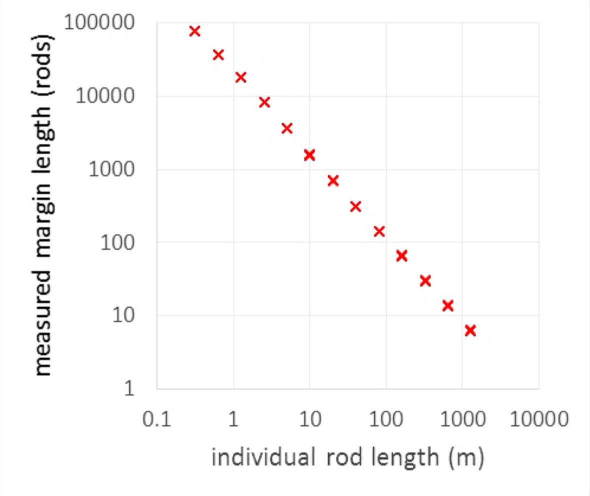

Fig. 1: Fractal analysis results for Holuhraun data calculated by virtually walking rods of various sizes along the flow margin. Note that superposed at each "X" are 50 results for a given rod size, starting at different random points along the margin, to give one approximation of error. Here, $D = 1 - m = 1.14$, $R^2 = 0.9998$.

We select rod lengths such that the smallest rod is twice the (approximately consistent) mean spacing between points, with each greater length twice that of the previous length, consistent with common practice [1-3]. Where the first rod is placed can significantly affect the final measurement, so we repeat the measurement at each rod length from 50 randomly selected starting points along the margin [2].

Results: The pilot study in Hawaii resulted in 13 traverses spanning 10 unique margin sections measuring between ~100 m and ~1 km in length. Each traverse contains from several hundred to several thousand point measurements. Consistent with [1], each traverse exhibits its fractal behavior across length scales spanning a factor of ≥16, with D values for ‘a‘ā and pāhoehoe flows differing systematically and typically lying in the respective nominal ranges found by [1] (**Fig. 2**). There are only two exceptions. A section of the Mauna Ulu flow margin transitions from slabby pāhoehoe with lesser ‘a‘ā to fully ‘a‘ā along its length and has an overall D value intermediate between the respective nominal ranges for ‘a‘ā and pāhoehoe (but within the extremes observed for ‘a‘ā by [1]). We also find a D value marginally in the pāhoehoe range for a section of a pāhoehoe flow in the Ka'u Desert that has been significantly embayed by sands. The linear fit for the log-transformed data (from which *D* is derived) is extremely high for all margins (R^2~0.996 for one traverse, $R^2 \geq 0.999$ for all others).

As a complement to the Hawaii pilot study, the Iceland field campaign [4] focused on a single continuous margin, namely, the northern margin of flows from the 2014 Holuhraun eruption. Over the course of one week, two teams traversed 25 km, collecting over 150,000 points at a mean spacing of 15 cm. This large dataset enables fractal analysis on length scales spanning a factor of ~4000 (30 cm to 1.3 km). The overall *D* value is within the extremes observed for pāhoehoe by [1] ($R^2 > 0.999$) (**Figs. 1** and **2**). The margin is dominated by fresh spiny pāhoehoe.

Discussion: All the data from Hawaii and Iceland indicate that the margins of basaltic lava flows are strongly fractal over large ranges in scale. In addition, even the special cases of the transitional and Ka'u Desert margins in Hawaii and the Holuhraun margin in Iceland plot closer to their respective nominal ranges than to that of the other end-member (**Fig. 2**).

Moreover, the correlation between margin fractality and flow type may indicate a correlation between lava flow margin and surface roughness. Even where *D* values for flows differ from the nominal range, their displacement relative to that range is qualitatively consistent with the observed smoothing (by aeolian mantling in the Ka'u Desert) or roughening (due to the presence of fresh spiny pāhoehoe at Holuhraun) relative to the nominal surface, respectively.

Nonetheless, fractal analysis likely does not provide a *naïve* way to cheat the limits of orbital resolution. What more sophisticated approach could reliably succeed, even in the absence of ground truth? We are currently exploring this question, but initial results suggest a complication. Using 1 m/pixel USGS digital orthographic quadrangle images, we mapped the same margin sections that we walked in Hawaii and analyzed these traces. The resulting *D* values seem to be effectively "muted" toward values intermediate between ‘a‘ā and pāhoehoe. Because this result contrasts with those of [1] from aerial imagery and with the consistent *D* observed for a very broad range of scales at Holuhraun, it may indicate that what we mapped as a single margin from remote imagery may instead be a composite of adjacent ‘a‘ā and pāhoehoe margins. If this interpretation is correct, it poses a hazard to planetary applications wherever different lava flow types are in close proximity, a condition that may be difficult to infer without ground truth.

Finally, the exceptionally long and high-resolution Holuhraun traverse presents several unprecedented opportunities for analysis, which we have just begun. We also plan to collect additional traverses at Craters of the Moon National Monument in Idaho and during a return trip to Hawai‘i Volcanoes National Park.

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References: [1] Bruno B. C. et al. (1994) *Bull. Volcanol., 56,* 193–206. [2] Andrle R. (1992) *Geomorphology, 5,* 131–141. [3] Klinkenberg B. (1994) *Math. Geol., 26,* 23–46. [4] Hamilton C. W. (2015) *EOS, 96.*

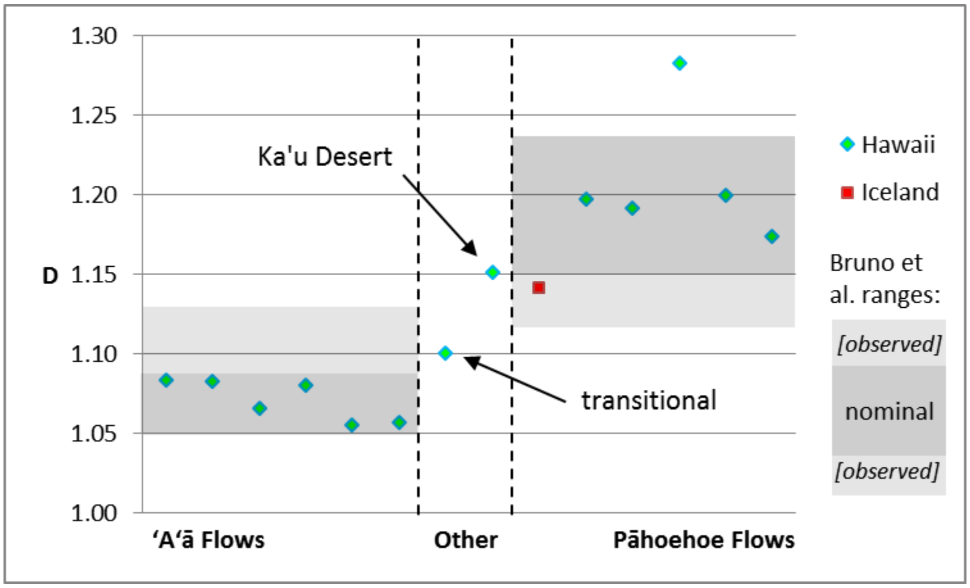

Fig. 2: Plot shows fractal dimension *D* values calculated for each of 14 lava margin traverses in Hawaii and Iceland. The gray shaded region spans between the maximum and minimum *D* observed by [1] for each lava flow type (x-axis), with the darker sub-region representing the nominal range [1]. The two other flows are a transitional slabby pāhoehoe/‘a‘ā (left) and sand embayed (right) flow, respectively.