MARTIAN VOLCANISM: FESTOON-LIKE RIDGES ON TERRESTRIAL BASALT FLOWS AND IMPLICATIONS FOR MARS

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Determination of lava flow compositions on Mars is a significant problem with major implications for the thermal history and differentiation of the planet. Silica content within a magma is one of the factors controlling rheological properties of a flow. Thus, one of the major focuses within martian volcanology has been to estimate the composition of a lava flow based on rheological properties determined from flow morphology. One method, derived by Fink and Fletcher [1] and Fink [2], which has been used is the analysis of regularly spaced, arcuate, festoon-like ridges oriented perpendicular to flow direction. Their model relates ridge height and spacing to lava rheology, thickness of the flow's thermal boundary, and applied stresses and allows the viscosity of the interior of the flow at the time of ridge formation to be estimated. Festoon ridges on martian lava flows are similar in size to those on terrestrial silicic flows and previously have been compared to rhyolitic, dacitic [2-4], and trachytic [5] flows. In this study we use the Fink and Fletcher [1] and Fink [2] model to assess and compare flow rheology for two terrestrial basalt flows and one martian flow with previous studies.

Lava flows selected for this study include the Lakagigar and Barthardalshraun flows, Iceland and a flow west of Arsia Mons on Mars, located at 3°S, 138.2°W. The Lakagigar flow [6], more commonly referred to as Laki, contains festoon ridges which occur locally but which are dominant where the flow spreads out on a coastal plain. Festoon ridges on the Barthardalshraun lava flow, Iceland are located in an area of the flow which ponded in a valley ~ 80 km from the vent [7]. On the martian flow west of Arsia Mons, festoon ridges occur across large flow lobes [4]. Values of ridge spacing and height used for this study are shown in Table 1. Statistical analyses of the data indicate that a dominant spacing exists for the flows included in the study [8]. This suggests that a strong folding instability existed, thus the model of ridge growth should be applicable to these flows.

Fink and Fletcher [1] and Fink [2] considered festoon-like ridges to be folds resulting from compression of a fluid in which viscosity decreases with depth. Regular ridge spacing indicates a folding instability which places constraints on dimensionless parameters expressing the ratio of surface to interior viscosity, the ratio of gravitational stress to compressive stress, and ridge spacing [2]. Based on these constraints, minimum interior viscosity at the time of ridge formation can be estimated from ridge height and spacing, determined either in the field or from image data [2,3,5]. The dimensionless groups used for this analysis are:

$$R = \eta_o / \eta_i \tag{1}$$

$$\ln R > 30\ h/d \tag{2}$$

$$\dot{\varepsilon}\, \eta_i > \rho g h / (0.08\ R \ln R) \tag{3}$$

where R is the ratio between the exterior viscosity (η_o) and interior viscosity (η_i), h is the thickness of the thermal boundary layer approximated by ridge height, d is the average ridge spacing, $\dot{\varepsilon}$ is the strain rate, ρ is lava density, and g is the gravitational acceleration. To estimate the minimum interior viscosity, strain rate can be approximated from finite strain and an assumption of ridge growth time.

Results are shown in Table 2 and compared with previous studies. Estimated viscosities for the Icelandic flows are high ($5x10^6$ - $8x10^{11}$ Pa s) for terrestrial basalts which typically range from 10^2 - 10^4 Pa s [9]. Higher than normal viscosity can be obtained, however, by decreasing temperature, increasing solid content in the magma, or decreasing gas content, all of which are related. In the cooled, terminal areas of basaltic flows on Mount Etna, viscosities reached 10^8 - 10^{10} Pa s as the flow halted [10]; and for a basalt flow on Mauna Loa, viscosity was estimated at 10^7 Pa s at the toe [11]. Cigolini et al. [12] determined viscosities of ~ 10^7 Pa s from both field measurements and experimental results for basaltic andesite flows on Arenal Volcano, Costa Rica. They attributed the high viscosity values to a high crystal content in the magma and low effusion temperatures. Thus the viscosities for the Icelandic flows indicated by the formation of festoon ridges are not unreasonable for mafic magmas. The dominant location of these ridges on the terminal lobes of the Laki flow and in the ponded section of the Barthardalshraun flow suggest that cooling was a significant factor in increasing the viscosity in these flows.

The minimum interior viscosity values are comparable to those for a trachyte flow on Hualalai, Hawaii ($7.6x10^8$ - $7.6x10^{10}$ Pa s), a flow on Ascraeus Mons ($1.1x10^8$ - $1.1x10^{10}$ Pa s) [5], a dacite flow in Chile (> $4.6x10^8$ Pa s), and some ridges in Arcadia Planitia (10^8 Pa s) [2]. The similarity in results (Table 2) probably reflects a requirement for lavas to have high viscosities before this size ridge will form. Because basalt may have a high viscosity under specific conditions ridge height and spacing may not represent compositional variations. Thus, caution should be used in applying this model to obtain rough estimates of composition.

Based on the morphologic similarities between the martian flows and the Icelandic flows and knowledge of the emplacement of the terrestrial flows, the flows west of Arsia Mons are considered to have been emplaced as large sheet flows from basaltic flood-style eruptions. Festoon ridges represent folding of the surface crust in the last stages of emplacement when viscosities would be high due to cooling. Alternatively, the lava may have had a high crystallinity or was erupted at low temperatures. In addition, increased compressive stress behind halted flow fronts or in ponded areas may have contributed to ridge formation.

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Table 1. Ridge Geometry Data Used in Calculations.

Study Area	Values Used in Calculations		Ridge Spacing					
	Height (m)	Spacing (m)	Range (m)	Number of Samples	Median (m)	Mean (m)	Standard Deviation	Dispersion
West Arsia Mons	12	90	30-194	120	89.0	91.7	29.7	0.3
Laki Flow								
Interior	1	10	7-23	56	13.1	12.9	4.3	0.3
	2	10						
	2	15						
Margin	2	16.5	9-37	65	16.4	16.8	5.3	0.3
Barthardalshraun Flow	5	100	–	–	–	–	–	–

Table 2. Estimates of Interior Viscosity for Martian and Terrestrial Lava Flows

Study Area	Height (m)	Spacing (m)	$\dot{\epsilon}\eta$	Interior Viscosity (Pa s) 1 Hour	1 Week
West Arsia Mons	12	90	6.5 E3	1 E8	2 E10
Laki Flow					
Interior	1	10	5.1 E3	1 E8	2 E10
	2	10	2.5 E2	5 E6	9 E8
Margin	2	16.5	4.4 E3	1 E8	2 E10
Barthardalshraun Flow	5	100	2.3 E5	5 E9	8 E11
Chao Flow (Dacite)*	30	100		5 E8	
Arcadia Planitia*	100	750		1 E8	1 E9
Hualalai (Trachyte)†	15	150		8 E8	8 E10
Ascraeus Mons†	15	120		1 E8	1 E10

* [2] †[5] "E" Indicates the exponent in powers of 10.