Columnar Jointing on Mars: Earth Analog Studies

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Introduction

The High Resolution Imaging Science Experiment (HiRISE) on the Mars Reconnaissance Orbiter (MRO) discovered multi-tiered columnar jointing on Mars [1] (Fig. 1). Since the initial discovery image, more columns, some with entablature, have been observed at multiple sites [2] on Mars. Nearly all of these sites occur in the uplifted walls of impact craters in regions with histories of flood volcanism. The local geologic history leads to the suggestion that these are columnar basalts [1]. Extension of the modeling of terrestrial columnar lavas by [3] and [4] to the martian columnar joints and entablature discussed in [1] (and seen in observation PSP 006985 2020; Fig. 1) suggests that the lavas cooled, in the presence of water, over a period of approximately 2 to 14 years, depending on the details of joint formation.

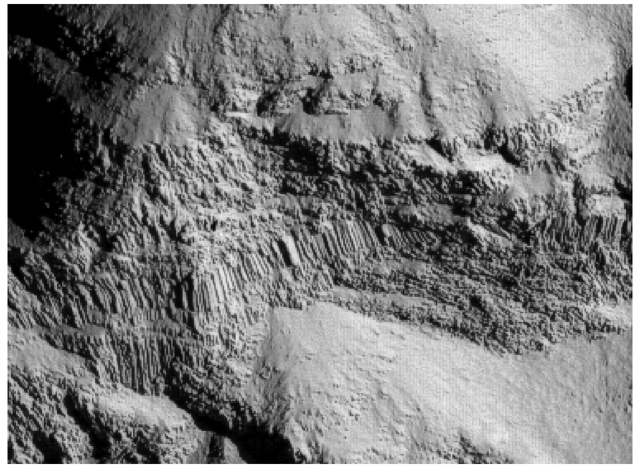

Figure 1: *Columns seen in the wall of the impact crater at the discovery site, in Marte Vallis between Elysium and Amazonis plana. Observation ID: PSP 006985 2020*

Role of Water in the Formation of Terrestrial Columnar Lavas

[3] and [4] found that in terrestrial columnar lavas a major factor controlling the width of columns (entablature or colonnade) is the cooling rate of the layer of plastic lava just beneath (for a horizontally-oriented cooling front) the solidified lava. [4] derived a solution useful for estimating the cooling rate (or alternatively the water influx) by comparing the column width with the length of an individual cracking episode (stria). They found that the ratio of the stria length to the spacing of the contraction fractures (joints), η, is dependent upon the cooling rate.

A high cooling rate, associated with significant water influx, will generate entablatures (thin, hackly colonnade) with widths a few centimeters to tens of centimeters [3]. Entablatures often form in response to irregular (i.e., non-horizontal and non-planar) cooling fronts, causing splaying, radiating, or other non-parallel jointing patterns; this is because the high rate of infiltration of water may allow it to briefly collect in irregularities within the lava flow, reorienting the cooling front from the usual horizontal orientation of colonnade.

A lower cooling rate associated with steam and water convection within the forming joints will generate more regular, parallel colonnade with approximately constant widths of tens of centimeters to meters over their length.

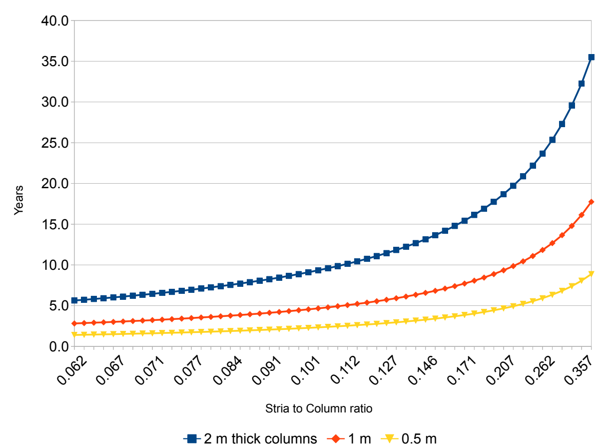

Figure 2: *Stria to joint spacing ratio vs time to form 40 meters of colonnade. The different color plots show the times required to form 2-meter, 1-meter, and 0.5-meter thick columns over the entire height of a 40-meter-thick flow. The stria to column width ratio is a proxy for the relative importance of conduction versus steam- and water-driven convective removal of heat through the joint faces; a larger ratio implies less advection/convection and more conduction.*

Role of Water in Martian Columnar Joints

Assuming that the solution found by [4] applies to the martian columnar jointing, the role that water played in their formation can be better understood. [4] suggested that the Péclet number, (Pe), relating the heat transport due to conductive and that due to advective-convective regimes can be used to characterize the system. This Péclet number can be shown to be related to the joint spacing (column width) and the fracture velocity (dependent on the distance between two isotherms: the crack initialization temperature, T_{init} and the crack termination temperature, T_{term}); in other words, the joint spacing and the stria height (which is dependent on the separation between T_{init} and T_{term}). A Pe of $\sim$0.3 is suggested by [4] as the most likely and common value to use for the Columbia River Basalt Group (CRBG), though some hysteresis and possibly composition may have an influence on the final column width and stria height.

Because the column widths on Mars are very near the limit of detectability by HiRISE and many of the columns are covered in dust, it is obviously impossible to measure the stria heights on martian colonnade [5]. We have performed a parameter search assuming that the model of [4] is applicable to the martian colonnade. (Figs. 2, 3) show the results of the model run with Pe from 0.1 to 0.63 (corresponding to a stria to column width ratio (η) of 0.39 to 0.0624, respectively). For the values of Pe=0.3$\pm$0.05, η ranges from 0.112 to 0.16 (the x-axis on Figs. 2, 3).

If the columnar basalts in the CRBG are an analog for the columnar jointing on Mars (which have similar column widths), the martian columnar basalts would have formed in the presence of many tens of cubic meters of water vaporized per second over the course of two to fourteen years. The total volume of water vaporized is between 2×10^9 and 8×10^9-m^3 over 200-km^2, depending on the column widths (more water would be necessary for smaller-diameter columns). This volume, if all of the water were vaporized once and then lost to the system, corresponds to a water depth of between 10- and 40-meters vaporized over the course of two to fourteen years (70- to 2,000-cm yr^{-1} in equivalent rainfall). However, a complication with this estimate is that much of this water vaporized was probably recycled, so the upper range of volume estimates are likely to be too high. The mechanism for drawing water into the joints is probably capillary action, and after a time, the top of the lava flow will have cooled enough that the recently vaporized, advecting water vapor may encounter low enough temperature to re-condense before escaping [4, 6].

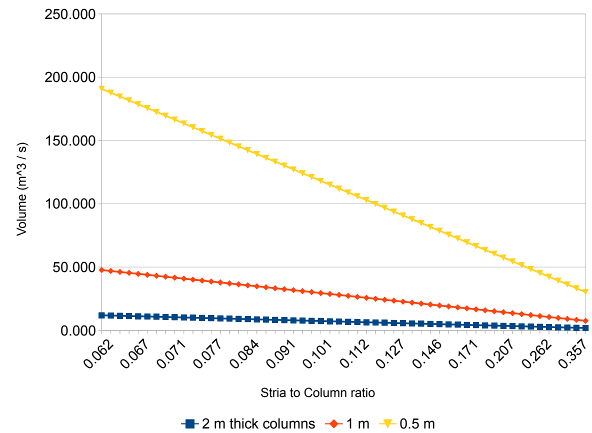

Figure 3: *The amount of water vaporized is dependent on the total joint surface area; a smaller column diameter implies more joints for the same volume lava flow. The water volume vaporization rate calculations here are based on a 200-km^2 by 40-meter thick flow. Note that this rate does not imply one can integrate over the time period of joint formation to calculate a total water volume required to form the joints, because some, and possibly a significant amount, of the water may be vaporized multiple times.*

Conclusions

The columnar jointing on Mars is generally found in geological settings which suggest the columns formed in lavas. If these lavas have terrestrial analogs such as the CRBG, then modeling of the formation of columnar lavas on Mars is likely to be similarly illuminating as modeling columnar basalt formation on the Earth. Extension of the results of terrestrial modeling of columnar basalt formation suggests that the columnar jointing on Mars may have formed in the persistent presence of liquid water over a time period of several to tens of years.

References

[1] Milazzo, MP, Keszthelyi, LP, Jaeger, WL, et al. *Geology*, 37:171–174 (2009). [2] Milazzo, MP, Keszthelyi, LP, Jaeger, WL, et al. *LPSC*, vol. 40, p. 2159 (2009). [3] Long, P and Wood, B. *Geol Soc Am Bull*, 97:1144–1155 (1986). [4] Goehring, L, Mahadevan, L, and Morris, S. *PNAS*, 106:387 (2009). [5] Weiss, DK, Jackson, B, Milazzo, MP, et al. P33B-1769. AGU (2011). [6] H.C. Hardee. *Tectonophysics*, 84:179 – 195 (1982). doi:10.1016/0040-1951(82)90159-7.