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FRACTURE MECHANICS AND THERMODYNAMICS IN PILLOW LAVAS

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INTRODUCTION

Undirhlíðar quarry, found at the northeast corner of Undirhlíðar ridge, contains thousands of exposed pillow lavas. Most pillow lavas reveal a cross-sectional view with various fracture patterns. These fractures are the focus of our research, and can be studied to interpret details about this history of the pillow lavas, such as cooling rates and emplacement environments. Our primary goal is to understand the formation of fractures in pillow lavas. Our research questions include: What fracture patterns are observed in pillow lavas? How do fracture patterns change at various radii within a singular pillow lava? To what extent does pillow size affect the fracture patterns? What can fracture spacing at the edge of the pillows tell us about the cooling environments? When and where do fractures initiate on a pillow lava? How much change in temperature is required to initiate a fracture? Once a fracture is initiated in a pillow, where will it propagate and why? In order to answer these questions, we used both theoretical and physical methods of analysis to better understand the fracture mechanics that take place in pillow lavas.

METHODS

Detailed observations of hundreds of pillow lavas were made at each wall within the quarry. For each pillow lava, sketches and high-resolution photographs were recorded. In the lab, Adobe Illustrator was used to trace the fracture patterns present in the pillow lavas. Fracture tracings were completed for five pillows. The field observations, sketches, and image analysis were all used to create a classification system that organizes the various fracture types.

In order to further quantify the fractures, we used ImageJ to measure various aspects of the pillow images. First, we measured the perimeters and radii of the five pillows. We also measured the lengths between fractures in contact with the perimeter. Adobe Illustrator was used to trace the perimeters and shrink the perimeters by 10%, 10 times. At each new radius percentage (90%, 80%, 70%...), we recorded the number of fractures in contact with the 'new' perimeter. This allowed us to quantify the fractures at various radii within each pillow. We also used Adobe Illustrator to record the total fracture counts present in the various pillows.

After quantifying the fractures through field and lab analysis, we attempted to connect our physical observations to the theoretical physics behind the fractures. First, we calculated the temperature change necessary to fracture basalt. The calculations incorporated Young's Modulus, the thermal expansion equation, the tensile stress of basalt, and the thermal expansion coefficient for basalt. Then, we created a two-dimensional thermal model that simulates pillow cooling over time. In Microsoft Excel, we created an emplacement pillow by inserting the initial temperatures of ice and the lava in each cell. An emplacement pillow is simply a theoretical pillow that contains the temperatures 1200°C (Degraff and Aydin, 1993) and has been cut off of any lava flow. This means that no more lava will be added and no new pillow lavas will form off of this pillow lava. This emplacement pillow can be manipulated to have any initial conditions desired. Initial conditions include the pillow shape and what the pillow is in contact with. For example, an emplacement pillow can have more of a circular shape or it could be more of an oval shape. An emplacement pillow lava can be completely surrounded by ice, or it can be emplaced on top of or next to other pillow lavas.

Once the emplacement pillow was created, we iterated this pillow 93 times, with each pillow having a time step of 1800 seconds, to simulate cooling. Within every cell in the spreadsheet, the Heat Conduction Equation is embedded so that with each time step, the cell displays a new temperature based off of the thermal diffusion that has occurred in the time that has passed. Thermal diffusivity is a constant that describes how easily heat dissipates through a material. The Heat Conduction Equation includes the thermal diffusivities of the material α, the temperatures of the surrounding cells *T*, the time step *t* and the spatial coordinates (in our case, we used *x* and *y-coordinates*). The Heat Conduction Equation is found in Carslaw and Jaeger's (1959) book:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \quad [1]$$

where

$$\alpha = \frac{k}{\rho c_v} = \text{Thermal diffusivity} \quad [2]$$

The thermal diffusivities that we used, found in Robertson's (1998) article and Cuffey and Paterson's (2000) text, are:

$$\alpha_{basalt} = 9 * 10^{-3}\ cm^2/s$$
$$\alpha_{ice} = 1.09 * 10^{-4}\ cm^2/s$$
$$\alpha_{water} = 1.5 * 10^{-3}\ cm^2/s$$

This model allows for the manipulation of the time step, spatial values, and diffusivities if necessary. The thermal model is shown in Figure 1.

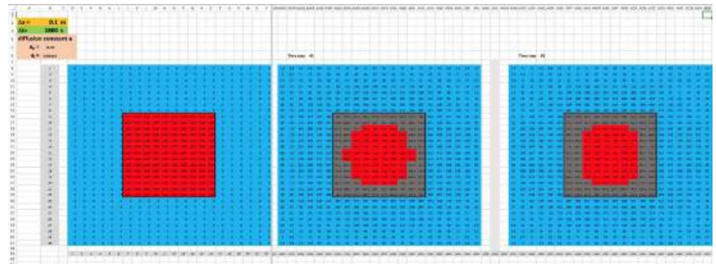

Figure 1. Screenshot of the two-dimensional thermal model in Microsoft Excel. Top left corner displays our 'tool box,' which contains values for the time step Δt, the space that each cell represents Δx, and the thermal diffusivities of basalt and ice. The emplacement pillow is shown on the left side where t=0 s. Red cells represent liquid lava. Blue cells represent ice. Grey cells represent solidified basalt. The middle and right side of the photo shows the pillow at time steps 41 and 42, having cooled for 73,800 s and 75,600 s respectively.

RESULTS

Physical Observations

The field observations and image analysis yielded seven fracture categories: short (<5 cm) fractures at the outer edge of a pillow, fractures within pillow cores, fractures between the core and the edge of a pillow, long fractures (up to 40 cm) that go through the entire pillow, 'web'-like fractures, fractures that branch from other fractures, and curvilinear fractures that cut through bands of vesicles (Fig. 2). Most pillows that were analyzed in the field and in the lab have a pillow core (roughly 75%). A pillow core is present where there is a distinct difference in fracture patterns within a pillow lava. It is usually outlined by a circular/ovular fracture (shown in green in Fig. 2 and 3). Short fractures at the outer edge of a pillow are <5 cm and come in contact with the pillow's edge. They do not come in contact with the core of the pillow. Fractures categorized within the pillow cores do not exist outside of the cores. Fractures between the core and the edge of the pillow do not come in contact with both the pillow core or edge. Long fractures go through the entire pillow and are approximately 40 cm in length. They start at the edge of a pillow and propagate through the pillow core. 'Web'-like fractures are unique in that they form hexagonal patterns within a pillow (Fig. 3 brown). They can occur anywhere within a pillow and are unique in that they do not follow the typical radial fracture pattern found in most pillow lavas. Fractures that branch from other fractures are shorter fractures. They tend to look as though they formed as secondary fractures off of the presumed pre-existing long fractures described above. Curvilinear fractures are fractures that cut through bands of vesicles. Sometimes, these fractures form shelves of basalt that are highly vesiculated (Fig. 2 yellow).

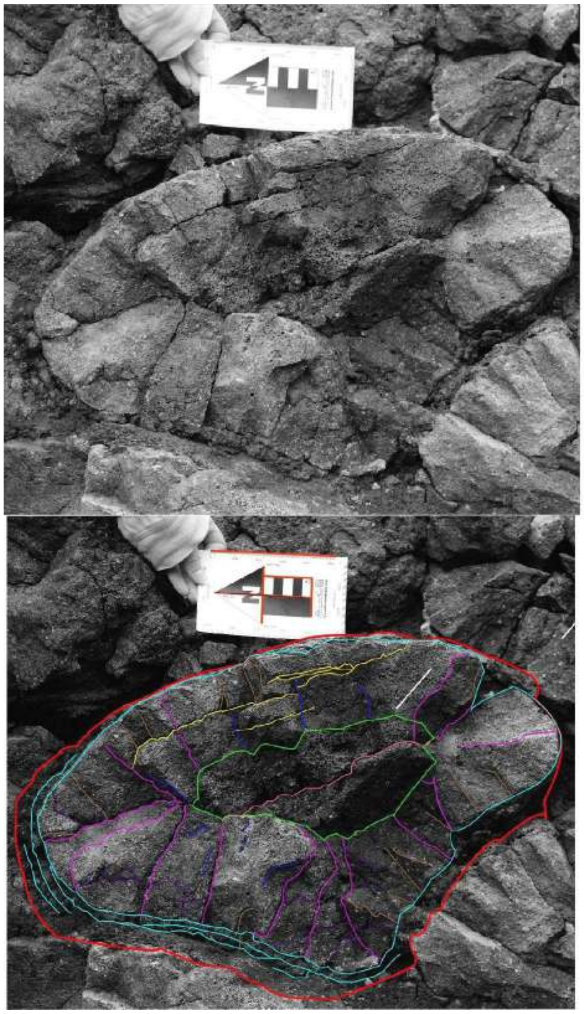

Figure 2. Photo of Pillow 1 and Pillow 1 tracings. Green: core outline, Magenta: long fractures, Brown: short fractures, Blue: fractures between edge and core. Yellow: curvilinear fractures, Pink: fractures within core, Purple: fractures stemming from other fractures.

Any given pillow may have any combinations of these fracture types; however, there are some common trends. As stated above, most pillow lavas have a core (about 75%). Almost all of the fracture patterns analyzed showed radial fractures. The exception to this would be the presence of 'web-like' fractures (Fig. 3). Most pillow lavas had more fractures outside of the pillow core compared to the inside of the core, although this was not that case in 100% of the pillows. There also seemed to be a trend of more fractures (fractures spaced closer together) in the bottom half of the pillow lavas and less fractures (fractures spaced further apart) in the upper half of the pillow lavas. Fracture patterns also seemed to be related to surrounding pillows. When pillow lavas come in contact with other pillow lavas, the shape of the pillows can be deformed. With the deformation of pillow shape also comes the deformation of the fractures within a pillow.

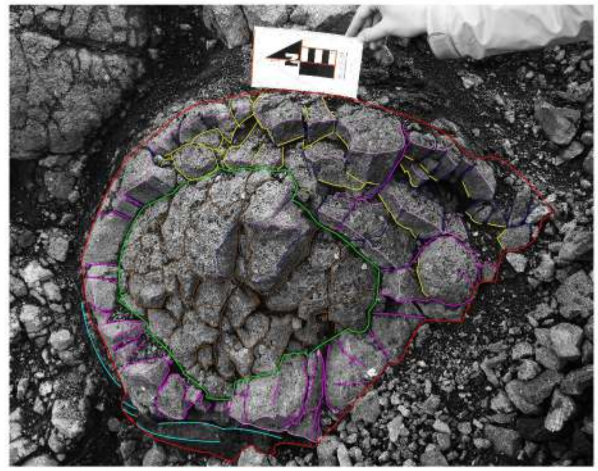

Figure 3. Pillow 3 shows 'web-like' fractures (brown tracings) within a pillow core (green tracing).

The measurements found through ImageJ and Adobe Illustrator are shown in Figure 4. A linear relationship is found between the perimeter length and the number of fractures in contact with the perimeter with a slope of 0.258 (R^2 0.975; Fig. 4A). We also see a linear relationship between the fracture count as a function of radius percentage, where larger radii intersect more fractures and smaller radii intersect fewer fractures (Fig. 4B). It is important to note that the data with the smallest slope (Pillow 5) is our largest pillow, having a diameter of 163 cm. A linear relationship is also found for the total fracture count as a function of radius, where pillows with larger radii have more total fractures and pillows with smaller radii have fewer total fractures (Fig. 4C).

Theoretical Model

To calculate the change in temperature necessary to create a fracture, we used the equations for tensile stress and Young's Modulus given Shultz's article. Both Young's modulus and the tensile strength are

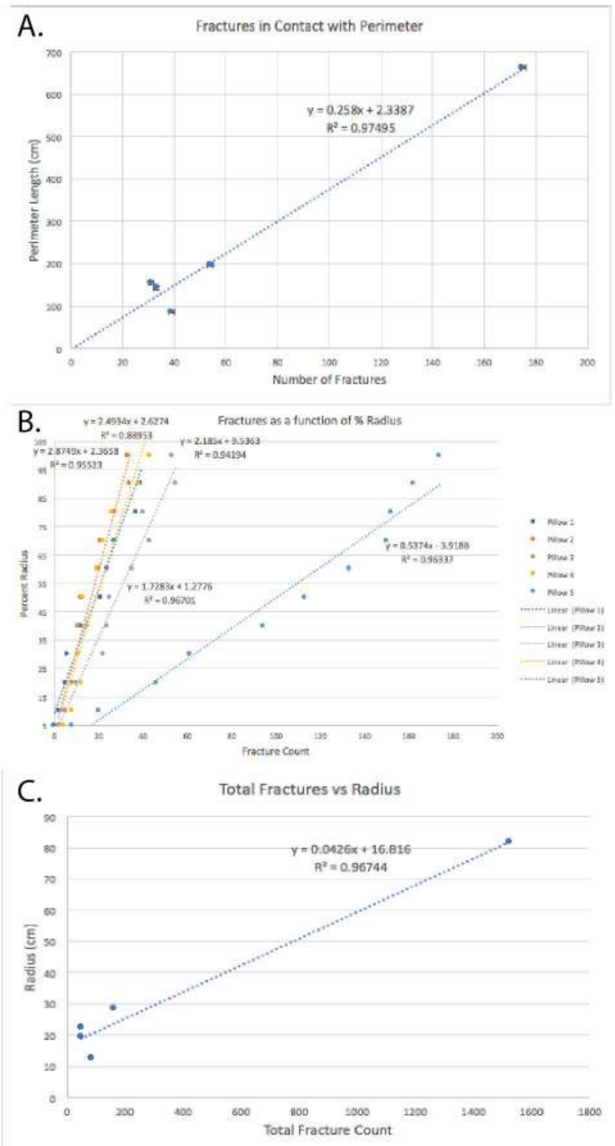

Figure 4. Perimeter length as a function of fractures in contact with edge of pillow. A linear relationship is found with small error. B. Fracture counts were recorded at various radii within each pillow. We see that more fractures are found at larger radii and fewer at smaller radii. This is consistent for pillows of various sizes. C. Radius size as a function of total fracture count. Larger pillows contain more fractures.

values of strength parameters of intact basalt. The average values for Young's Modulus and tensile stress of basalt are E_{basalt}=73 *GPa at 20°C* and $\sigma(\varepsilon)_{basalt}= -14$ *MPa*. These values are not specific to the composition of basalt at our field site and are general values for basalt. We then manipulated the thermal expansion equation found in Schroeder's article to find how much change in temperature is required to fracture a pillow lava. The thermal expansion equation is:

$$\Delta L = \alpha_{lin} L_o \Delta T \qquad [3]$$

Solving for : ΔT

$$\Delta T = \frac{\Delta L}{\alpha_{lin} L\, a_o} \qquad [4]$$

The equation for Young's Modulus is:

$$E = \frac{\sigma(\varepsilon)}{\varepsilon} = \frac{F L_o}{A_o \Delta L} = \frac{tensile\ stress}{strain} \qquad [5]$$

Assuming that $L_o = 1m$, we calculated $\Delta L = -0.245 * 10^{-3}\ m$. Figure 5 shows these variables in a model cylinder. Plugging this value back into our thermal expansion equation (Equation 4), and knowing $a_{lin} = 0.53 * 10^{-5}\ \frac{1}{°c}$, we found $\Delta T = -46$°C. This means that, for a basaltic pillow lava that has solidified at approximately 900°C (Shultz, 1993) when it cools to approximately 854°C, there has been enough thermal shrinkage to cause a fracture to initiate. These temperature values are used to constrain our two-dimensional thermal model in Microsoft Excel.

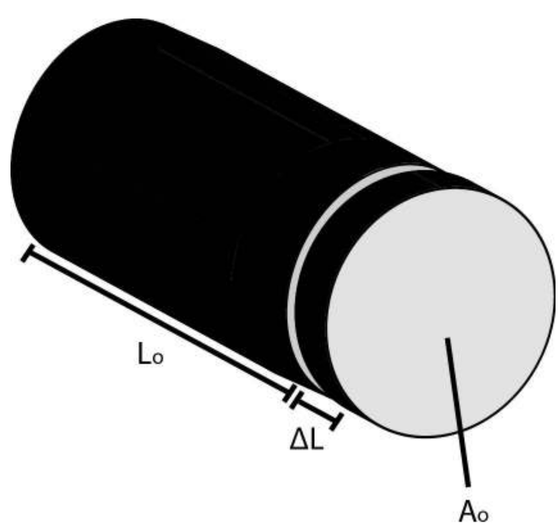

Figure 5. Cylinder showing thermal expansion variables. L_0 is the initial length. ΔL is the change in length produced by a change in temperature. Ao is the cross-sectional area of the cylinder.

The two-dimensional thermal model is an iterated visualization of the heat diffusion that occurs while a pillow lava cools in time. It is merely an approximation of temperatures at various time steps. We use this model to identify where $\Delta T = -46°C$ occurs in the pillow and at what time step. At any point in the two-dimensional thermal model where a particular cell has experienced a $\Delta T = -46°C$ from the previous time step, a theoretical fracture is initiated within that cell. This allows us to determine where a fracture is initiated and where it will propagate once it is initiated.

We simulated the cooling of a square basaltic pillow lava that was 1m x 1.4m and emplaced in ice. In general, the model shows that, due to the temperature gradient, fractures will propagate from the outside of a pillow inwards towards the core when surrounded by ice or other pillow lavas (Fig. 1). This model only gives us information about long fractures that extend from the edge through the core.

DISCUSSION

Our goal was to understand the formation of fractures in pillow lavas by connecting the theoretical physics of fracturing to observations of natural fracture patterns. In categorizing the fracture types, we attempted to organize a complex phenomenon found in nature. We are the first to classify fractures by their length, orientation relative to the pillow, and relationship to other fractures to this extent. We identified seven fracture categories and the frequent occurrence of a fracture core. The presence of a fracture core, the existence of multiple fracture types, and the variations in fracture patterns suggest that the physics of fracturing may depend on more than simple cooling. However, the correlation between total number of fractures and pillow size metrics (Fig. 4) suggests that thermal cooling may play a dominant role in controlling fracture formation.

Our two-dimensional thermal model tests the hypothesis that cooling controls fracture formation. The model produces one of the fracture types observed in the pillow lavas: long fractures that propagate from the pillow's edge through the core. We learned that these fractures initiate at the outer edge of the pillow and propagate inwards. A fracture is initiated once solidified basalt has experienced a $\Delta T = -46°C$. This occurs around time step 3, or about 5,400 seconds (1.5 hours) for a pillow that is 1m x 1.4m. We have not yet used the thermal model to test the change in fractures due to a change in pillow size. We have, however, manipulated the initial shape of the emplacement pillow. Using an emplacement pillow with a more circular shape produces radial theoretical fractures that look more accurate to those found in nature.

At this time, our model does not provide any insight into the formation of short fractures at the outer edge, fractures within the core, fractures between the core and the edge, 'web-like' fractures, fractures that branch off other fractures, or curvilinear fractures. We hypothesize that a pillow core is produced due to a different history of lava flow. Our thermal model has been theoretically cut off, with no additional lava flow entering or leaving the pillow. A pillow core may be created when additional lava is pushed through a pillow that has already experienced cooling. The fact that our model cannot produce a pillow core eliminates its ability to produce short fractures, fractures within a core, or fracture between a core and the edge.

Our thermal model also does not depict local changes in vesicularity or in local strength. We hypothesize that curvilinear fractures that cut through bands of vesicles are produced when changes in vesicularity or strength occur. We also assumed the composition of basalt to be homogeneous, and that the formation of different crystal sizes is not present. This may explain why we do not see secondary fractures (fractures that branch off of long fractures) present in our thermal model. 'Web-like' fractures are reminiscent of columnar joints and sheet-like lava flows. These types of lava flows have been studied in great depth. The resembled hexagonal geometry found in the pillow lavas can be produced due to a change in cooling orientation. It is possible that when we look at the cross-section of a pillow lava in the quarry walls, that we are not looking at the z-axis of a pillow lava but rather a different cooling axis. This could explain the presence of 'web-like' cooling. Due to the simplicity of our thermal model, we are unable to account for the natural complications that may be controlling many of the fracture types.

The discretized thermal model is a good starting point but clearly shows that not all natural fractures can be created by simple cooling in a static pillow lava. The next model will attempt to simulate natural conditions by taking into account phase changes of ice and lava, which alter the thermal diffusivities during cooling.

An even more accurate approximation of cooling as a function of time and radius apart from a more advanced thermal model will be to solve the Heat Conduction Equation in cylindrical coordinates. We have identified the Heat Conduction Equation in cylindrical coordinates, found in Crank's text, to be:

$$\frac{\partial T_{(r,t)}}{\partial t} = \alpha \frac{1}{r} \frac{\partial}{\partial r}\left(r \frac{\partial}{\partial r} T(r,t) \right) \quad [6]$$

We are planning on solving this equation, using Bessel functions, which will give us a numerical solution of temperature as a function of time and radius. A numerical solution will allow us to move past the setbacks and approximations that were involved in the thermal model.

CONCLUSIONS

Cross-sections of pillow lavas exposed in the walls of Undirhlíðar quarry have allowed us to investigate the connection between natural fracture patterns and the theoretical physics behind fracturing. We have been successful in identifying a fracture core and defining seven categories of fracture types. The number of fractures in a pillow is dependent on pillow size, suggesting that cooling is a primary control on fracture formation. We have calculated that the change in temperature required to initiate a fracture in a given pillow lava is $\Delta T = -46°C$ and have developed a two-dimensional thermal model to provide a visualization of a static pillow lava cooling over time. Our model produces one fracture type but fails to recreate the others. The frequent occurrence of a fracture core and the variety of natural fracture patterns suggest that additional factors must be considered, such as change in vesiculation, local changes in tensile and compressional strength, or the presence of additional lava flow after cooling. More work can be done to refine the thermal model in a software program such as Igor Pro or MATLAB. An advanced model may be able to reproduce some of the other fracture patterns observed in this study. Additionally, finding a solution to the Heat Conduction Equation in cylindrical coordinates will allow us to obtain a numerical solution for the temperature at any radii at any time.

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