CONSTRAINTS ON FORMATION OF COLUMNAR JOINTS IN BASALTIC LAVA

by

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Abstract

Columnar joints form as a brittle relaxation response to tensile stresses within cooling lava flows and magma bodies, and are found in lavas that vary greatly in chemistry and outcrop geometry. However, columnar joints do not form in all cooling igneous rocks, and the specific conditions under which columnar joints form are unknown. In this study, outcrops containing columns in the Cheakamus Valley basalt flows near Whistler, BC are studied, and the size, orientation, and distribution of columns is recorded. Forward numerical models using the finite element method are created with Matlab using the Partial Differential Equation Toolbox to model the outcrops in the Whistler field area, and determine the cooling rates ($\frac{\partial T}{\partial t}$) and thermal gradients ($\frac{\partial T}{\partial x}$) experienced by the lava flows during their formation. High temperature experimentation involving basalt rock samples is then used to determine the cooling rates and thermal gradients present during the cooling of these samples under a variety of naturally occurring conditions.

This study finds that noticeable differences in the distribution of columns within an outcrop occur only when there are large differences in cooling rates between the upper and lower outcrop surfaces. Modeling shows that the cooling rates must differ by approximately an order of magnitude. High temperature experiments show that extremely high cooling rates (especially in the small sample sizes used in this study) between approximately 700 to 800 °C are necessary for the formation of columnar joints.
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1. **Introduction**

Columnar joints are contractional joints that form in both extrusive and thin intrusive melt bodies, such as sills or dykes (Mallet, 1875; Budkewitsch and Robin, 1994; Grossenbacher and McDuffie, 1995; Hetényi et al., 2012). These joints intersect longitudinally to produce columns (Fig. 1.1), and are formed by the brittle release of tensile stress accumulated from a decrease in volume due to cooling (e.g., Mallet, 1875; James, 1920; Tomkeieff, 1940; Spry, 1962; Hetényi et al., 2012). Columns often have additional features, shown in Fig. 1.1, and described in Chapter 2.

Columnar joints are seen all over the world in various types of rocks, ranging from mafic to felsic, as well as both coherent and fragmental volcanic rocks, including ignimbrites (e.g., Tomkeieff, 1940; Spry, 1962; Michol et al., 2008; Wright et al., 2011). However, columnar joints are not observed in all cooled igneous bodies. The specifics as to why some cooling rock bodies form columnar joints and others do not remains unexplained. The purpose of this thesis is to explore the relationship between the geometry, orientation, and organization of columnar joints and the cooling history and environment of the lava body. Furthermore, the thermal gradients and cooling rates that produce columnar jointing are investigated. This increases the understanding of the properties of cooling lava, and thus of intrusive and extrusive emplacement events worldwide.

Proposed in this thesis is the hypothesis that there is a range of cooling rates that allows column formation at a specific column forming temperature, which is near the glass transition temperature. Outside the limits of this column forming cooling rate, columnar joints do not form.

1.1. **Approach to Studying Columnar Joints**

There are three main parts to this thesis: field work, forward modeling, and high temperature experiments. All contribute valuable information to the overall understanding of columnar joints in the context of this thesis.
Figure 1.1. An explanation of various terms used throughout this study. While chisel marks are purely surficial features, and can form slightly raised or depressed surfaces, ball and socket joints completely penetrate columns and divide them into sections vertically. Chisel marks and ball and socket joints are discussed later in the text.

Starting with an overview of the field area, four outcrops of interest are identified, and the reader is introduced to the overall structure of the flows, and the geometry of the columns therein. Columns are first described qualitatively, then quantitatively through measurement of the heights and widths of the columns. In addition, the thicknesses of the colonnades are measured where present in the outcrop.

Subsequently, this thesis uses forward modeling to examine the temperature profiles, cooling rates, and thermal gradients of modeled cooling lava flows. Different boundary conditions are used, as well as various geometries of lava flows (high and low aspect ratio, square and rectangular).

Columnar joints are synthesized using high temperature experiments, which enables textural analysis of the joints within the experiments. Thermal gradients and cooling rates are also measured within the experiments, to see what kind of thermal gradients are necessary to produce columns at the experimental scale. The gradients from the forward modeling are then compared with the gradients found in the experiments.
The field area is then revisited, and comparisons are made to the columnar joints in natural outcrops using previous knowledge gleaned from the forward modeling and the high temperature experiments. Column propagation directions and geometries are examined with attention paid to the actual and inferred boundaries of the lava flow, and how these affect the columns. The column geometries in the field are compared with the modeled column propagation directions, as well as with the synthesized columns within the high temperature experiments. All of these avenues are used to extend knowledge of the formation conditions of columnar joints.
2. Literature Review

Columns are three dimensional objects which are bounded by two dimensional columnar joint surfaces, formed during cooling of both extrusive and shallow intrusive igneous bodies. This section presents the research past workers have undertaken that includes investigations into the macroscopic organization of columns, geometric column properties, formation mechanisms of columnar joints, previous studies of columns involving field analysis, as well as analog and numerical modeling, and concludes with unresolved issues that will be elucidated.

2.1. Macroscopic Organization of Columns

Columnar joints propagate parallel to heat flow and perpendicular to temperature isotherms within the cooling body, and they self-organize into multi-sided polygonal columns, whose long axis is parallel to heat flow and perpendicular to the isotherms (e.g., James, 1920; Degraff and Aydin, 1987).

Columns within lava flows are commonly organized to form two distinct zones. Tomkeieff (1940) gives the terms colonnade and entablature to these two zones of columns. The colonnade is defined as having linear, regularly spaced, equal-sized, usually hexagonal columns. The entablature is comprised of smaller, irregular, curvilinear columns that vary in number of sides and are not always hexagonal (e.g., Tomkeieff, 1940; Spry, 1962). The colonnade is split further into two more zones, the upper and lower colonnade, with the entablature situated between these two (Fig. 2.1), though the entablature is not always present. When no entablature exists in the outcrop, the upper and lower colonnade meet at what I call the column interface (Fig. 2.2). While many flows have well organized colonnades, some flows, particularly thick ones (though there is no particular limitation on the thickness according to Hetényi et al. (2012)), have poorly organized entablatures.
Figure 2.1. Diagram of flow structures, including colonnades and entablature. Fan structures in the entablature are visible. Drawn from picture of outcrop in Columbia River Basalts. Modified from Spry (1962).

Figure 2.2. Outline drawing of columnar joints on east side of Daisy Lake outcrop. Upper and lower colonnades visible, with diffuse colonnade interface between the two (grey shading). Bottom of outcrop is brecciated flow base.
Columnar joints do not necessarily always propagate linearly throughout an outcrop. Because the joints propagate perpendicular to isotherms, if these isotherms curve within an outcrop, the joints will curve as well. This can produce curving columns, like those seen in Fig. 2.3.

Figure 2.3. Outcrop from Whistler field area, Railroad Quarry outcrop 6. See Fig. 3.2 for area map. Curving columns visible in both foreground and background. Lower columns are vertical, and curve towards horizontal as they propagate upwards. Scale accurate for foreground. Background column diameters ~80 cm.

2.2 Geometric Column Properties

Columns generally consist of between four and seven sides, with six sides both the mean and the mode. Columns can vary in diameter from millimeters up to several meters (e.g., De Graff and Aydin, 1987). In addition, columns often have interesting surficial textures. These are all detailed in this section.
The large range in column diameters exists due to the relationship between the cooling rate and the size of the columns. Lower cooling rates (smaller $\frac{\partial T}{\partial t}$, where $T$ is temperature and $t$ is time) result in columns with larger diameters, while higher cooling rates (larger $\frac{\partial T}{\partial t}$) result in columns with smaller diameters (e.g., Hetényi et al., 2012). This relationship is apparent when looking at a cross section of a solidified lava flow. Along the top and the bottom, where the cooling rate is highest, the columns can be quite narrow, on the order of ones to tens of centimeters. On the interior of the flow, where the lava cools much more slowly, the columns are larger and can have diameters of up to several meters, depending on the thickness of the flow. The thicker the flow, the longer the cooling time for the interior, and thus the wider the columns.

Triangles, squares, and hexagons are the only regular polygons that tessellate (cover a surface by repeating without any gaps). For columnar joints to form a regular repeating pattern in the cooling material, these are the only three regular shapes that are possible. According to Mallet (1875), hexagons have the smallest ratio of “resistance to splitting” over the “splitting effort.” Mallet (1875) calculated this ratio as 1.0 for triangles, 0.68 for squares, and 0.519 for hexagons. Thus hexagonal jointing patterns require the least amount of energy to form.

This explains why columns are hexagonal, but not how hexagonal columns form, or how “triple junctions” (a Y-shaped junction, with 120° between each joint) in particular develop. Spry (1962) observes that sheets of cooling lava often first form “master joints” on the surface, which are widely spaced (tens of meters apart). These then break into what he terms “mega-columns,” and after this is when hexagonal columns start to form. Gray (1986) mentions that on the surface of lava flows, joints commonly intersect at 90° angles, forming T-shaped junctions, much like those found in mudcracks, and which are also similar to those found in the drying experiments of Shorlin et al. (2000). Evolution of the joints through propagation into a lava flow allows the T-shaped junctions to slowly develop into Y-shaped junctions through a complex process which involves modification and elimination of the joints (Gray, 1986).
This agrees with the observations of Goehring et al. (2006), who report that columns evolve from four-sided towards six-sided as they grow. In early forming column systems, which are closer to the cooling surface and have experienced a higher $\frac{\partial T}{\partial t}$, columns more often comprise square cross sections than columns on the interior of the flow, where the more mature column systems have experienced a lower $\frac{\partial T}{\partial t}$, and are more often hexagonal in cross section. Greater thermal energy at the cooling surface equates to less need to conserve energy to form fractures. As the columnar joints propagate further away from the cooling surface, less thermal energy ensures hexagons are more likely to form due to the smaller effort required to produce them (Mallet, 1875).

Igneous rocks are not the only material to form evolving systems of contractional joints; joints in permafrost behave in a similar fashion. Earlier formed cracks produce four-sided polygons, while later systems produce six-sided polygons (Sletten et al., 2003).

Though columns do not start hexagonal and equally sized, Budkewitsch and Robin (1994) develop an algorithm that shows hexagonal columns of unequal size will become more equal over time, with some reasonable assumptions about the geometry of isotherms within the cooling flow. Jagla and Rojo (2002) expand on this to show that any pattern of fractures, not just six-sided columns, will evolve into a pattern of columns that are mostly six-sided and approximately equal in area.

Hetényi et al. (2012) perform shape analysis at several flows in Iceland, France, and Hungary. With over 3,000 complete columns analyzed, they find that the mean number of sides of the columns studied is 5.71, with about half having 6 sides, and about a third having 5 sides. They also find that the geometry and thickness of the emplaced magma body, as well as the chemistry of the magma, play a role in the size of columns formed. Thicker flows and less effective boundary conditions produce larger diameter columns, and given identical boundary conditions and thicknesses, felsic lavas will produce larger diameter columns than mafic lavas.
Many columnar joints have surficial features known as “chisel marks” (James, 1920; Degraff and Aydin, 1987) or “ striations” (Ryan and Sammis, 1978). These were first observed by Iddings (1886), and have been addressed by many other workers since (e.g., James, 1920; Tomkeieff, 1940; Spry, 1962; Ryan and Sammis, 1978; Degraff and Aydin, 1987; Grossenbacher and McDuffie, 1995).

Chisel marks (Figs. 1.1 and 2.4) are planar features on joint surfaces, and are thought to be a surface expression of the incremental growth of columnar joints (e.g., James, 1920; Tomkeieff, 1940; Spry, 1962; Degraff and Aydin, 1987). As the tensile stresses increase within a cooling flow, a single point eventually surpasses the tensile strength of the material, and a fracture forms, originating at this point. This fracture then propagates both vertically and laterally; laterally along the same isotherm as the original point failure, and vertically towards the interior of the flow, until the accumulated stress is no longer great enough to induce brittle failure. At this point, the incremental joint growth halts. The result of this process is a single chisel mark.

Ryan and Sammis (1978) investigate the formation of chisel marks in detail. They observe that on fresh column surfaces each chisel mark often has smooth and rough sections. They interpret that the smooth section of the chisel mark forms in the cooler, brittle portion of the flow. As the joint propagates into a warmer, less brittle area, the fracture surface starts to approach the melt interface and increases in surface roughness as the fracture stops propagating. This enables the possibility to track the propagation direction of columnar joints based on surficial features, if they are present. Plumose structures often form on chisel marks as well (Aydin and DeGraff, 1988). As an example, Degraff et al. (1989) use surficial joint features, along with petrographic methods, to infer the cooling histories of basaltic flows.

Grossenbacher and McDuffie (1995) create a conductive cooling model that finds an inverse relationship between cooling rates and column diameters, as well as between thermal gradients and chisel mark heights. They also predict that the ratio of chisel mark height to column diameter should be fairly constant, based on analytical models, and write that field observations support this statement. Despite widespread observation of chisel marks, not all columns form chisel marks, and the reasons for this are unknown.
Ball and socket joints are present in basalt flows around the world (e.g., James, 1920; Tomkeieff, 1940; Symons, 1967; Schaefer and Kattenhorn, 2004), including those at the Giant’s Causeway (Fig. 2.5, Preston (1930)), and in the Whistler field area (Fig. 3.6). Preston (1930) elucidates a model in which a thermal gradient within each column causes the formation of ball and socket joints, but his model necessitates that the convex side point towards the cooling surface. This is not supported by field observations (Tomkeieff, 1940). In Fig. 2.5, the ball and socket joints are visible, with surfaces both concave up and concave down. The ball and socket joints appear to be contractional in nature, but due to the curviplanar nature of the joints and the fact that their concavity direction does not appear to be consistent, this means their formation mechanism remains elusive.

Figure 2.4. Field photograph showing columns resulting from connected joint surfaces (arrows) and chisel marks present on the column faces. Chisel marks are planar, two-dimensional features, and represent each increment of joint growth. Box indicates visible chisel marks.
Figure 2.5. Photo of columns at Giant's Causeway. Notice some columns have pools of water, showing concave up surface, while other do not, and show a convex up surface. There is no column interface of any kind within this outcrop, so all columns experienced the same cooling history. Picture by Chmee2 (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-3.0 (http://creativecommons.org/licenses/by/3.0)], via Wikimedia Commons.

2.3. Formation Mechanisms

Columns have long been observed and studied. Articles published as early as the 17th and 18th centuries discuss the existence and formation of basaltic columns (e.g., Bulkley, 1693; Keir and Fordyce, 1776; Raspe, 1776), and high temperature experiments aimed at better understanding the formation process of columns were carried out over two centuries ago (Watt, 1804).

Early workers described columnar joints and the columns they create, and speculated as to how columns formed, but were often incorrect. Bulkley (1693) described the columns at the Giant’s Causeway in Northern Ireland as pillars, remarking that each one is a single piece bounded by joints, which are so narrow that nothing thicker than a knife will slide between them. He does not offer any method for the formation of the columns, only asserting that they are a natural phenomenon.
Keir and Fordyce (1776) discussed high temperature experiments conducted on glass, wherein glass was heated above its melting temperature and then slowly cooled and crystallized. This led them to make the connection between liquid lava and solid basalt, hypothesizing that basalt crystallizes from lava, much like the glass from their experiments crystallized into various materials. Though this seems like a very basic connection to make, Keir and Fordyce wrote this around the same time that Neptunism became a valid theory for the formation of basalt. Keir and Fordyce discussed the shape of the crystals within their crystallized glass, and drew a comparison between these crystals and columns found at the Giant’s Causeway, based on the similar prismatic shape of both. Crystals and columns do not form in similar ways, and their inferences on the formation of basalt columns are not correct.

Around the same time, Raspe (1776) published his observations on a number of lavas found in Germany, and specifically addressed basaltic columns. He was the first to propose the currently most widely accepted viewpoint for the formation of columnar joints, namely that the joints are formed by contraction due to cooling.

More early high temperature experiments were performed by Watt (1804), who melted a mass of basalt and then cooled it at two different rates. He first cooled it rapidly, producing a dark glass. In a second experiment, he cooled an irregular, wedge-shaped mass approximately 1 m by 75 cm, with a thickness ranging from 10 to 45 cm over the course of eight days. Unlike the first experiment, crystals were present in this sample. However, he was unable to form columns, likely due to the slow cooling of the sample.

Watt (1804) attempts to describe the formation of basaltic columns as arising from the contact of spheroids within the molten basalt. As these spheroids increase in size and come into contact with one another, they do not join but compress against each other, taking up all available space in a single plane until they have the cross sectional shape of hexagons. As the spheroids continue to increase in size, they propagate into the interior of the lava and form elongated columns. It is not entirely clear what the spheroids consist of, or why they would initially be spaced equidistant from each other. He also mentions that the spheroids could propagate due to loss of either heat or moisture through the top of the lava, so despite his high temperature experiments with
molten basalt, he still does not take sides in the Neptunism vs. Plutonism debate of the time.

Early work by Mallet (1875), showed that there was no agreement on whether columnar joints form from contraction during cooling, or from some type of preexisting concretion or mass of crystals. However, Mallet showed that hexagons require the least energy to create, and are thus the most common cross sectional shape of columns.

Some of the earliest explanations for the propagation of columnar joints perpendicular to the cooling surface are also addressed by Mallet (1875). He gives examples of lava flows with various geometries, and details when and in what direction the columns form. He also addresses the fact that there must be a certain “splitting-temperature” at which columnar joints form, when enough tensile stress is present within the rock to cause brittle stress release, but also when the rock is cool enough that it will not alleviate the stress through viscous flow. He estimates that this temperature is somewhere between 600° and 900°F (315° to 482°C), based on measurements from metallurgic slag. This entire range of temperatures is much too low (Peck and Minakami, 1968). At such low temperatures, most of the tensile stresses have either been accommodated for already, or are no longer present, but his study is a starting point for further investigation.

Sosman (1916) investigates the difference between columns formed by contraction, and columns formed by convection currents in melted wax. He concludes that while columns formed via contraction are the most common, convection type columns could exist in igneous rocks, but he does not give any definitive field examples or definitely say that these types of columnar structures exist. This origin of columnar joint formation has been criticized in the past, with a detailed account of its drawbacks by Spry (1962).

James (1920) mentions that as lava cools, it contracts in all directions. The vertical contraction is accounted for by viscous flow of the still molten interior of the lava flow, but the horizontal contraction must be accommodated by cracking in the already solid portion of the flow, thus forming columnar joints.

No other formation mechanisms for columns were proposed until Guy and Le Coze (1990) and Gilman (2009) advanced the notion that columnar joints could form
from “constitutional supercooling.” This is found mostly in alloys of metal in which a hexagonal cracking pattern develops due to the compositional heterogeneity of the metal at the solidus. Gilman (2009) proposes this because he argues that basalts do not create crack patterns that are consistent with homogeneous solids. However, basalts generally do not change in composition within the outcrop (e.g., Spry, 1962).

The current most widely accepted mechanism for columnar joint formation is thermal contraction and brittle deformation, and has a large host of supporters (e.g., Raspe, 1776; Spry, 1962; Degraff and Aydin, 1987), despite the other theories that have been hypothesized over the years.

The formation mechanism for the entablature between the upper and lower colonnades of lava flows is not precisely known. Long and Wood (1986) suggest that the entablature is formed from water penetrating the top of still cooling lava flows through cracks in the lava crust. The convective heat loss from water escaping as steam would produce a variety of cooling surfaces within the interior of the flow, as well as produce smaller columns due to the increased rate of heat loss. They base this mostly on petrographic textures and phase abundances, as well as results from a simple cooling model and paleoclimate data. Degraff and Aydin (1987) and Degraff et al. (1989) agree with this interpretation, arguing that the entablature cannot be formed through conductive cooling alone, and therefore a convective cooling mechanism must be at play. In some cases the entablature is over six times as thick as the lower colonnade (Tomkeieff, 1940).

While the formation of the entablature within lava flows remains enigmatic, the currently accepted formation mechanism for columnar joints involves the accumulation of tensile stresses due to a decrease in volume, from heat loss, exceeding the viscous relaxation rate of the cooling material. These tensile stresses are relieved through brittle deformation of the cooling material, specifically through Mode I tensile jointing (Degraff and Aydin, 1987).
2.4. Previous Analysis of Columns

In addition to geometric analysis of columns and columnar joint surfaces, previous workers have used analog and numerical models to study columns, and others have carried out field observations on the active formation of columnar joints.

2.4.1. Analog Modeling of Columns

Shorlin et al. (2000) investigate cracking patterns in alumina powder and water mixtures. A thin layer of powder and water shrinks as it dries, producing tensile stresses and cracking within the layer. Curvilinear cracks form during both directional and non-directional drying. Occasionally the angle between cracks measures 120°, producing triple junctions like those seen in hexagonal columns, but 90° spacing is the most common by far, producing 4 sided polygons. Though few 6 sided polygons are formed, the authors do make interesting observations relating the thickness of their dried alumina material to the spacing of jointing. In one experiment, they found that when there was a step down in the bottom of the drying tank, and subsequently an increase in about 50% of the thickness of their dried alumina material, the spacing of the cracks approximately doubled. This clearly demonstrates that there are consistent links between crack spacing and the thickness of the material. This is true in cooling lava flows as well (e.g., Tomkeieff, 1940).

Allain and Limat (1995) studied regular cracking patterns in colloidal suspensions. They found that a series of regular cracks formed perpendicular to the drying surface, and parallel to the direction of evaporation. Shortly after these findings, Müller (1998) reintroduced the idea of analog modeling of cooling lava flows on the basis that cooling of basalt and starch desiccation are both diffusion processes, and both must obey similar diffusion equations. Previous authors using analog modeling techniques include Huxley (1881) and French (1922), as stated by Goehring and Morris (2005). Other authors to use starch desiccation as an analog for cooling lava flows include Toramaru and Matsumoto (2004) and Lodge and Lescinsky (2009), and their findings are similar to those of Goehring and Morris (2005) and Goehring et al. (2006), as detailed below.
Goehring and Morris (2005) use the drying of corn starch and water slurries as a proxy for the cooling of a lava flow. In their models, the evaporation of water from the corn starch slurry is analogous to the loss of heat from a lava flow. Just as basalt decreases in volume and increases in viscosity with a decrease in temperature, the corn starch slurry decreases in volume and increases in viscosity due to water loss until it can deform only under brittle conditions.

As the corn starch slurry solidifies and it begins to decrease in volume, the contractional stresses begin to exceed the tensile strength of the material, and it fails brittly, forming tension cracks. As the drying front propagates downward, the cracks follow, forming joints that organize into columns, much like those seen in basalts.

With this type of easily reproducible analog model, it is possible to conduct a multitude of experiments examining properties such as column cross sectional area as compared to drying time and initial thickness of corn starch slurry. Goehring and Morris (2005) find that the mean cross sectional area of columns decreases with increasing drying rates, and that it also increases with increasing model depth. These findings are similar to those found in basaltic lava flows (Goehring and Morris, 2008).

2.4.2. Numerical Modeling of Columns

Field observations and analog modeling have both helped expand the horizon of knowledge with regard to columnar joints, but numerical modeling is a very useful tool as well, and numerical modeling techniques have existed for over 50 years. Crank and Nicolson (1947) published a seminal paper on numerical solutions for partial differential equations related to heat conduction that has been used by others (e.g., Carslaw and Jaeger, 1986). Crank and Nicolson (1947) described an implicit space-centered forward model that was unconditionally stable, and faster than other models of the time.

Jaeger (1961) used numerical techniques to model the evolution of isotherms within a cooling lava flow, given a set of boundary conditions. Starting with simple cross sections of slabs, he then moves on to model more complex shapes, such as an infilled valley. Numerical models have also been used to describe the influx of water into joints, helping drive joint propagation (Lister, 1974; Long and Wood, 1986) and as
an explanation for the presence of entablature in the Columbia River flood basalts (Long and Wood, 1986).

Grossenbacher and McDuffie (1995) use numerical analysis techniques to model not only temperature profiles and thermal gradients within cooling flows, but also to investigate the relationship between chisel mark width and column diameter, finding a direct relationship between the two. They also find an inverse correlation between the cooling rate and columnar joint spacing, as well as between the thermal gradient and the chisel mark width.

Constructing a model that accounts for viscoelastic relaxation in addition to elastic stress release, Lore et al. (2000) show that relaxation by viscous flow does have an effect on elastic stress. They also find that higher cooling and strain rates correlate with higher effective glass transition temperatures. The glass transition temperature is the temperature at which strain rate exceeds the relaxation timescale, and the cooling material deforms brittlely, in addition causing the cooling material to undergo several physical parameter changes (thermal expansivity, heat capacity, etc.) (e.g., Dingwell and Webb, 1989; Dingwell and Webb, 1990; Webb et al., 1992; Webb, 1997). Faster cooling rates produce higher percentages of strain that is elastic, which then translates to stress within the system.

2.4.3 Field Studies of Active Lavas

Peck and Minakami (1968) use the cooling of the 1963 Alae lava lake, as well as the 1965 Makaopuhi lava lake, to observe the active formation of columnar joints. Several drill cores into the cooling Alae lava lake enabled an accurate temperature profile to be constructed for the top half of the lava lake throughout the entire cooling history, and for the entire lava lake after it had completely cooled below the glass transition temperature.

They were able to observe cracks forming on the surface of the cooling lava lake, which would initiate at temperatures as high as 900°C, and propagate down to temperatures up to 1000°C. Using a high-gain seismograph, Peck and Minakami (1968) could record each increment of column growth, as it would appear as a short, low amplitude vibration.
Through analog and numerical modeling, as well as field studies of both current and past systems, understanding of columnar joints has improved markedly. However, there remain several unanswered questions which are described in the next section, and which this thesis attempts to answer.

2.5.  Unresolved Issues

Though the thermal contraction hypothesis is the accepted formation mechanism for columnar joints, there are some aspects that have not been fully explained, such as curving columns and the relative thicknesses of the upper and lower colonnades.

Curving columns have been described by previous authors (e.g., Iddings, 1886; Spry, 1962), and following the theory that columnar joints propagate parallel to heat flow, joints (and therefore columns) will curve following heat flow vectors. However, curving columns have never before been described by numerical models. Using heat flow vectors as a proxy for columnar joint formation direction, and heat flow magnitude as a proxy for columnar joint spacing, models which more accurately depict curving columns within a lava flow are presented in this thesis.

Previous authors have invoked various cooling mediums, including water, to explain the apparently accelerated cooling rate of the entablature (e.g., Long and Wood, 1986; Degräff and Aydin, 1987; Degräff et al., 1989). Others, such as Tomkeieff (1940) and Swanson (1967), observe that the upper colonnade and entablature can be up to six times as thick as the lower colonnade. However, the relative amount of heat flow from one boundary as compared to the other has never been investigated in outcrops such as these. By modeling a variety of the outcrops in the Whistler field area, this thesis more accurately describes the relative amounts of heat lost through the upper, as compared to the lower, boundaries.
3. Field Examples

There are many excellent examples of columnar joints in basaltic lava flows throughout the northwest of the United States and the southwest of British Columbia, Canada. These include jointing in the Columbia River flood basalts (e.g., Long and Wood, 1986; Mangan et al., 1986) and the Cheakamus Valley basalts near Whistler, BC, which are part of the larger Garibaldi Group (Mathews, 1958; Lee, 1988; Green, 2006). The Cheakamus Valley basalts were chosen for this field study due to their proximity, ease of access, their excellent exposure due to both erosion and road cuts, and their young age. Green et al. (1988) sampled and dated two of the outcrops in this study. They place the Railroad Quarry outcrops at 34 Ka (based on radiocarbon dates from wood in lacustrine sediments of the same age), and the Daisy Lake outcrops at 50 Ka (based on K-Ar analysis). The young age ensures minimal weathering and alteration of the column surfaces. Additionally, these basalt lavas were erupted while there was ice in the valleys, or possibly while glaciers were present (Mathews, 1958). The highly variable cooling environments give the flows interesting and dynamic cooling histories that vary greatly depending on the outcrop.

Mathews (1958) observes lava flows with esker-like forms, and hypothesizes that these flows could have erupted into subglacial meltwater passages during the waning stages of the Wisconsin ice sheet. These lava flows have a much higher aspect ratio than is typical for basaltic lavas, and also contain radial columnar joints. This evidence leads him to the conclusion that there was ice in the valleys for at least some of the time during the eruption of the Cheakamus Valley basalts. However, the outcrops in this study do not have the same esker-like structural form, and thus the location and extent of the ice is not as easily determined.

This section examines four outcrops from the Whistler field area (Fig. 3.1). Columnar structures, including the column interface, are described, along with surface features. Both colonnade proportions and average diameters of columns are qualitatively analyzed.
3.1. Location and Extent of Flows

The Cheakamus Valley basalts are part of the Garibaldi Group (Mathews, 1958). The four outcrops this study focuses on are located along Highway 99 between Whistler and Squamish, BC. The outcrops are named, from north to south, Railroad Quarry, Brandywine Falls, Pinecrest, and Daisy Lake (Figs. 3.1 and 3.2).

The Railroad Quarry outcrops are approximately 10 km SW of Whistler, BC, along Highway 99 (see Table 3.1 for a list of outcrop locations). These outcrops are composed of at least two different flows, all originating from an unknown source higher in elevation (Kelman, 2005). There are areas near the highway where the contact between the underlying intrusive bedrock and the overlying basalts is visible, but this contact is only exposed in the road cut. At the road, the basalts are 5-8 m thick, but increase in thickness as the topography drops away to the east. The eastern exposure of the basalts is a large, subvertical cliff-face of both vertical and horizontal columns, at least 20 m high in coherent outcrop, and with a large talus slope at the bottom, equal or greater in vertical height, which leads down to the Cheakamus River. Though the bedrock is seen at the road cut near the top of the outcrops, it is not visible anywhere else in the area, including at the river.

There are several “islands” of basalts, which have been eroded in such a way that they are all isolated from each other currently, even if they were joined at some point in the past. These “islands” have been labeled outcrops 1 through 7 (Fig. 3.2). Though these outcrops are not the only ones in the Railroad Quarry area, they are the ones with the best exposure and most interesting geometries.

The Brandywine Falls outcrops are 5 km south of the Railroad Quarry. The flows have been exposed through erosion by Brandywine Creek. At the falls, tens of meters of subhorizontal, laterally continuous flows are visible, but there is no easy way to access the flows in this vertical cliff face, and they are not described here. There is one outcrop visible on the upper side of the falls, and it was this outcrop that was studied (Fig. 3.2). This same outcrop has been described by Mathews (1958). He refers to this outcrop as esker-like, and it will be discussed further below.
At the Pinecrest field area, 3 km south of Brandywine Falls, two extensive outcrops occur on either side of the highway, and have very different outcrop exposures. The western outcrop is approximately 20 m wide, while the eastern outcrop is approximately 150 m wide (Fig. 3.2). While the eastern outcrop is slightly taller, it still has a much lower aspect ratio than the western side. The reason for the discrepancy between the two outcrop patterns is unclear. Both western and eastern Pinecrest outcrops have a well-defined column interface.

The southernmost field area is Daisy Lake, 4 km south of Pinecrest. Here, the road cuts through two flows, with a flow breccia visible between the two. The upper surface of the upper flow has been eroded somewhat by the Fraser Glaciation (Green, 1981b), and the bottom of the lower flow is not visible. Both western and eastern Daisy Lake outcrops have a well-developed column interface, visible in the upper of the two flows.

Table 3.1. List of outcrops and their locations.

<table>
<thead>
<tr>
<th>Outcrop</th>
<th>Latitude</th>
<th>Longitude</th>
<th>UTM Zone</th>
<th>Easting</th>
<th>Northing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Railroad Quarry</td>
<td>50°04.4’N</td>
<td>123°05.5’ W</td>
<td>10</td>
<td>493441</td>
<td>5546788</td>
</tr>
<tr>
<td>Brandywine Falls</td>
<td>50°01.6’N</td>
<td>123°07.2’ W</td>
<td>10</td>
<td>491405</td>
<td>5541603</td>
</tr>
<tr>
<td>Pinecrest</td>
<td>50°00.3’N</td>
<td>123°07.9’ W</td>
<td>10</td>
<td>490565</td>
<td>5539195</td>
</tr>
<tr>
<td>Daisy Lake</td>
<td>49°59.2’N</td>
<td>123°08.7’ W</td>
<td>10</td>
<td>489605</td>
<td>5537158</td>
</tr>
</tbody>
</table>

Chemically, the Cheakamus Valley basalt is characterized by Green (1981) as an olivine basalt, containing varying amounts of olivine (7-16%), plagioclase (10-16%), and clinopyroxene (1-11%), with between 64 and 72% groundmass. The groundmass consists mostly of glass, but has minor magnetite, pyroxene, and plagioclase as well. Fig. 3.3 shows photos of an entire thin section from Railroad Quarry outcrop 1, in both plane-polarized and cross-polarized light.
Figure 3.1. Regional map of the Lower Mainland in the upper right corner, with box showing field area. Center map is of the Cheakamus Valley, with outcrops numbered as follows: Railroad Quarry (1), Brandywine Falls (2), Pinecrest (3), Daisy Lake (4). Small scale map image modified from Mathews (1951).
Figure 3.2. Schematic diagrams of the field areas in this study. The Railroad Quarry schematic shows outcrops 1 through 7, while the Brandywine Falls schematic shows the esker-like outcrop, which is part of a larger flow that is less well exposed. The eastern and western sections of the Daisy Lake and Pinecrest areas are labeled as well.
Figure 3.3. Thin sections of the Cheakamus Valley basalt. A is in plane-polarized light, and B is in cross-polarized light. Phenocrysts of brightly colored olivine and gray plagioclase are present, as seen in B. The olivine is both rounded and angular, while the plagioclase occurs mostly in elongated or angular shapes. The groundmass is composed of mostly glass, with minor magnetite, pyroxene, and plagioclase.
3.2. Columnar Structures in Outcrop

There are several types of columnar structures observed in the outcrops. In the past, authors such as Spry (1962) have identified columnar structures such as fans, chevrons, and basins (Fig. 3.4), but not all of these structures are present in the field area of this study. This is partially due to the lack of entablature in any of the outcrops studied, as Spry (1962) found many of his structures within the entablatures of his outcrops.

One of these unclassified structures is seen on the eastern side of the Railroad Quarry outcrop 6, where the basalt contacts the Cheakamus River. At this subvertical cliff face, there are large (approximately 1 m diameter), vertical columns near the bottom of the outcrop, and smaller (approximately 30 cm diameter), horizontal columns near the top. Where they meet it is possible to see the curving of the vertical columns over towards horizontal (Fig. 2.3). The columns change orientation and size quite suddenly, and the possible reasons for this are detailed below.

There is a section of Railroad Quarry outcrop 3 that shows a structure similar to, but distinct from, the fan as described by Spry (1962). Instead of columns that curve into parallelism from a more radial pattern below, they instead pinch in to a single point near the top, as viewed on the outcrop surface (Fig. 3.5). In three dimensions, the columns pinch in to a lineation on the top of the flow, rather than a single point. It is also distinct in that the lower columns are completely vertical, rather than fanning outwards.

Mathews (1958) observes an “esker-like flow” at the Brandywine Falls outcrop (Fig. 3.6). Eskers are long, winding ridges composed of sediment deposited from englacial and subglacial water flow (Ritter et al., 2002). They are essentially the depositional remnant of glacial rivers. When Mathews (1958) refers to the flow as esker-like in form, he means that the flow has a high aspect ratio (for basaltic flows) similar to that of an esker, and that its geographic form is narrow and sinuous, also similar to an esker. Based on these observations, along with the presence of radial columnar jointing as well as sideromelane, he makes the conclusion that the flow may have erupted or flowed subglacially.
(Green et al., 1988), it is likely that there were glaciers or valley ice present during the eruption of the Cheakamus Valley basalts (Armstrong et al., 1965; Clague et al., 1989), as shown by this outcrop.

![Chevron](image1)
![Fan](image2)
![Basin](image3)

Figure 3.4. Three structures of columns found in outcrops, as discussed by Spry (1962). The chevron and basin structures are not seen in the Whistler Field area, but outcrops similar to the fan structure are seen, particularly in Railroad Quarry outcrop 3 (Fig. 3.5). These differing column structures result from outcrops with a variety of geometries. Figure modified from Spry (1962).
Figure 3.5. Vertical columns pinching upwards at Railroad Quarry outcrop 3. Lower columns are vertical, then pinch towards each other near the top. On the right side, coalescing columns are visible. The column structure seen in this outcrop is similar to, but still distinct from, the fan structure in Fig. 3.4. Hammer for scale.
3.3. **Field Observations**

3.3.1. **Lower Colonnade**

Most of the lower colonnades in outcrops in the Whistler field area are composed of columns with diameters between 50 cm and 1 m, and are generally equant in cross-section, subvertical in orientation, and are composed of either 5 or 6 sides. Many of the columns have well-developed chisel marks on their surfaces (Fig. 3.7), but show no plumose structure. Some of the columns have planar or curviplanar cross joints as well (Fig. 3.8), known as *ball and socket* joints (e.g., James, 1920; Preston, 1930; Symons, 1967), but they are not found in all outcrops.

3.3.2. **Upper Colonnade**

Generally the columns in the upper colonnades of observed outcrops are far less organized than those of the lower colonnades. Individual columns are not as well defined, and appear to break into blocky rubble more easily. They also have a smaller mean diameter, as shown by the statistical data for the eastern Pinecrest outcrop in
Section 3.4.2. Chisel marks are not nearly as prevalent, and there are no outcrops with ball and socket joints.

3.3.3. Colonnade Interface

The interface between the upper and lower colonnade is prominent on several outcrops in the field area, including the Daisy Lake outcrops, Pinecrest outcrops, and the western side of Railroad Quarry outcrop 1. The interface looks different depending on the scale at which it is viewed (Fig. 3.9). From a distance, the interface appears to be quite sharp, a definitive boundary between the smaller columns of the upper colonnade and the larger columns of the lower colonnade. However, when viewed up close, the interface is much more gradual and indeterminate.

As shown in Fig. 3.9, the interface between colonnades is not a sharp boundary but rather a zone of blocky, equant, somewhat rubble-like columns. Joints do not seamlessly grade into one another across the interface, nor do they stop completely. The joints from the upper colonnade will often angle away from vertical to intersect another joint, and create a column with a tapered end. In some cases the joints in the upper colonnade appear to simply stop propagating downwards, however the vertical joint often terminates in a perpendicular cross-cutting joint. There are also many cracks that are smaller than the column-forming joints, and are often curvilinear. These cracks often subdivide the larger lower colonnade columns as they approach the interface, but they are clearly not part of the upper colonnade. They are visible in the lower right side of the bottom image in Fig. 3.9. These cracks abound at the interface, preventing the clear delineation between upper and lower colonnade.
Figure 3.7. Surficial chisel marks on the columns in the lower colonnade of the eastern Daisy Lake outcrop. No plumose structures are visible on the joint surfaces.
Figure 3.8. Ball and socket joints in outcrop 7 of the Railroad Quarry field site. Convexity of cross joints points in both ways and does not indicate the direction of column formation. Cross joints do not appear to be continuous across columns, and so formed after columnar joints. Hammer is 90 cm in length.
Figure 3.9. Set of images from the eastern face of the Daisy Lake field area. A shows the column interface as a clearly visible and definite line. In B the column interface is still quite obvious, but more diffuse. In C, the column interface very gradual and not well defined.
3.4. Colonnade Proportions and Measurements

3.4.1. Colonnade Thickness

The upper and lower colonnades are not always of equal thickness (e.g., Iddings, 1886; Swanson, 1967; Schaefer and Kattenhorn, 2004). Fig. 3.10 shows information gathered from three outcrops in the Whistler field area, along with information gathered from diagrams and photos of outcrops from three other studies (Iddings, 1886; Swanson, 1967; Schaefer and Kattenhorn, 2004). The measurements for the Snake River Plain outcrops (Schaefer and Kattenhorn, 2004), as well as for the Watchung Group (Iddings, 1886), were taken from photos of the outcrops, with several measurements taken to show the range within the outcrop. The Yakima Group measurements were taken from schematic diagrams of flows from Swanson (1967).

Because the diameter of the columns is inversely proportional to the cooling rate, the upper colonnade should be thicker than the lower colonnade, assuming the columns in the upper colonnade are smaller in diameter. Faster cooling rates are a product of higher heat flow; if more heat is released through the top of the lava flow than through the bottom, then logically the upper colonnade will compose a higher proportion of the flow, as the columnar joints will propagate more quickly from the upper boundary. This model only works for a static lava flow that is not perturbed during cooling. If the cooling conditions of the flow are changed, such as through inundation of water into the already formed cracks in the upper surface, this will upset the stable cooling regime and change the expected proportions of the upper and lower colonnade.

The hypotheses of entablature formation (such as water infiltration into cracks) posit that the presence of entablature indicates that the lava was not subject to a stable cooling regime, but rather a transient one. Because the cooling history of outcrops with entablature cannot be easily quantified, these outcrops are not used in determining the physicality of column size and colonnade proportions.

The Yakima Group outcrops (Fig. 3.10) all have thicker lower colonnades than upper colonnades, when entablature is present. This can be explained by the fact that these outcrops have extremely thick entablatures. Assuming either of the two
entablature formation mechanisms described above are correct, the entablature forms from increased heat loss through the upper boundary, not the lower boundary. This results the entablature consisting only of what would have been upper colonnade, had the entablature not formed. Because the thickness of the lower colonnade remains the same, and the upper colonnade decreases in thickness due to the presence of entablature, it is possible for the lower colonnade to be thicker than the upper colonnade in outcrops with large proportions of entablature, such as the Yakima Group.

Fig. 3.10 shows that almost all outcrops (without entablature) measured have greater than 50% upper colonnade. The only outcrop in the Whistler Field area that is proportionally greater than 50% lower colonnade is outcrop 1 at the Railroad Quarry site (Fig. 3.11). There are a couple possible explanations for this. First, the lower boundary of the lava flow is very irregular, but the thickness of the upper colonnade is constant, and the colonnade interface boundary is horizontal. This means that the lower colonnade varies in thickness, and in some places is thinner than the upper colonnade. This irregularity in the lower boundary may have created more surface area, increasing heat flow. A second possible explanation is that the entire Whistler area has been glaciated since these flows were emplaced (Green 1981b), and this could have eroded some of the upper colonnade away. However, there is no reason for there to be more erosion here than elsewhere.
Figure 3.10. Basaltic flow colonnade proportions from this and previous studies. Most outcrops have a larger percentage of upper colonnade compared to lower colonnade. The two blue lines demarcate three different zones in the figure, A, B, and C. A includes outcrops with high ratios of upper to lower colonnade. These outcrops likely experienced extreme cooling on the upper colonnade, possibly due to subglacial emplacement or extreme inundation of water (flooding). B includes outcrops with more than half upper colonnade, but not extreme amounts. These likely experienced high rates of convection on the upper surface, or possibly heavy rain. The B-C boundary line is the 1:1 ratio line, and below this the outcrops have more lower than upper colonnade. This could be due to emplacement on a wet ground surface, enhancing cooling via the lower boundary. Outcrops that plot off the 0% entablature line have some component of entablature in addition to the colonnades, regardless of whether the upper or lower colonnade is thicker.
Figure 3.11. Western face of Outcrop 1 of the Railroad Quarry area. Line 1 shows upper surface of flow, and line 3 shows the lower surface of the flow. Below line 3 is a flow-base breccia and bedrock. The column interface is represented by line 2, situated between the upper and lower surfaces. On average, the upper and lower colonnades are nearly equal in thickness, and the arrows show three locations in particular where the colonnades are equal in thickness. The non-planar upper and lower surfaces of the outcrop may contribute to the thicker than average lower colonnaade.

3.4.2. Column Width Variation

Looking at outcrops with both lower and upper colonnades, the most prominent difference is the sizes of columns; the columns of the upper colonnaade are usually noticeably narrower than those of the lower colonnaade. This is due to the difference in the heat transfer coefficients of the different boundaries. Air is a more efficient medium for transferring heat than the ground material, partly because the air can cool via convection, and partly because the underlying rock is a very poor heat conductor (Touloukian et al., 1989).

Though the size difference is qualitatively noticeable, a quantitative approach was deemed necessary to assess the numerical difference in column widths between the lower and upper colonnades of a typical lava flow in the Whistler field area.

Field photos were taken of the eastern face of the Pinecrest outcrop, because it has a clear upper and lower colonnaade with different widths of columns in each colonnaade. The individual columns are also readily visible to make measurements easy as well as accurate. These were then traced in Adobe Illustrator CS5 (Fig. 3.12), and the outlines were imported into Image]. A best fit ellipsoid was fit to the columns, and the long and short axes of the ellipses were computed. In order to account for columns whose exposure was greater in width than in length (and thus Image] computed the
Figure 3.12. A section of the eastern face of the Pinecrest outcrop. A is the original, while B shows the columns after they have been traced in Adobe Illustrator CS5, and these outlines were imported into ImageJ for analysis. Line 1 outlines the upper boundary, while line 2 traces the column interface, and line 3 shows the flow-base breccia and lower boundary. A separate lava flow lies beneath line 3.
Figure 3.13. Histograms of the northern end of the upper colonnade (A), and the entire lower colonnade (B), of the eastern Pinecrest outcrop. The x-axis shows the range of widths of each column, with "<30" representing the range from 0 to 30 cm, "<60" representing the range from 30 to 60, etc. The y-axis shows the number of columns within each size range. The histogram of the upper colonnade is more similar to a normal distribution due to the larger sample size. There is a difference of approximately 80 cm in average and median size between the upper and lower colonnades.
width as the long axis instead of the short axis), for any ellipse with an angle of greater than 45° from horizontal, the long axis was used for the width instead of the short axis.

Histograms show the relative widths of the columns in the upper and lower colonnades (Fig. 3.13). Both upper and lower colonnades show a somewhat normal distribution of widths (the upper colonnade shows a more regular normal distribution. The columns in the upper colonnade range in width from less than 30 cm up to approximately 360 cm, with an average of 143 cm. Columns in the lower colonnade range from 35 cm up to approximately 420 cm in width, with an average width of 225 cm.
4. **A Forward Model**

Many workers have employed forward numerical modeling in their research of cooling igneous bodies, both extrusive and intrusive (e.g., Jaeger, 1961; Lister, 1974; Long and Wood, 1986; Grossenbacher and McDuffie, 1995). Because of the nature of lava flows and inaccessibility of intrusions, numerical models are an excellent proxy for direct measurements. There have been some cases where measurement of large cooling extrusive igneous bodies has been possible, such as Hawaiian lava lakes (Peck and Minakami, 1968), but this is not common.

Past authors, such as Grossenbacher and McDuffie (1995), have used numerical models to evaluate temperature profiles within simple one-dimensional cooling bodies. This thesis expands on these past authors’ work and examines two-dimensional flows, which are directly comparable to outcrops found in the field.

The question this thesis addresses focuses on the propagation of columnar joints within a cooling lava flow. The models help constrain the rate at which they propagate, and how the boundary conditions affect the direction of propagation at various times and locations within the flow. The models also address the sizes of the columns, and how the size of the columns changes with respect to the boundary conditions. The boundary conditions change for each model, but all are within the range of natural materials that could exist on various boundaries, such as rock, ice, and water.

Modeling the physics of crack propagation is a difficult process, and beyond the scope of this thesis. However, joint formation is closely related to heat flow and thus the models use heat flow as a proxy for modeling the propagation of columnar joints. Multiple models with both identical and edge-dependent boundary conditions are computed, and the results are compared to each other and to results from actual cooling rock bodies.

The aim of the modeling is 1) to show the transient temperature distribution and how it changes with various boundary conditions; 2) to show the magnitude and direction of the heat flow, and from that, to infer the propagation direction and relative size of columns within a lava flow; 3) to show where columns must change direction.
and interact with one another, based on the direction of heat flow; 4) to show the temperature gradients and heat flow at a specified column formation temperature, which can be directly related to the high temperature experiments discussed Chapter 5.

4.1. Methodology

4.1.1. Finite Element Method

The Partial Differential Equations Toolbox, an add-on to Matlab, is used to model an instantaneously emplaced cooling basalt flow. This add-on allows the user access to many high-level Matlab functions employing partial differential equations. These functions, and the associated graphical user interface (GUI), let the user model elliptic, parabolic, and hyperbolic equations for the purposes of modeling wave and heat equations.

The models presented below use the parabolic equation to model conductive heat diffusion through a solid bounded by Neumann boundary conditions, which give the boundary a fixed heat transfer coefficient, rather than a fixed temperature or fixed amount of heat flow. This coefficient can be tweaked to accurately model each boundary between the flow and the cooling environment. To accomplish this, the PDE Toolbox employs a finite element method to solve the equation numerically. Depending on the size of the model, the spacing between each element node along the boundaries ranges from 0.0125 m to 0.125 m, and the models range in size from 1 m$^2$ to 30 m$^2$.

4.1.2. Equations

The parabolic partial differential equation is used (terms defined in Table 4.1):

$$\rho \cdot C_p \cdot \frac{\partial u}{\partial t} = c \cdot \nabla^2 u$$

or expanded and rearranged (in two dimensions)

$$\frac{\partial u}{\partial t} = \frac{c}{\rho C_p} \cdot \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right)$$

For a complete list of variables used in these equations, see Table 4.1.
The equation for the generalized Neumann boundary condition is

$$\vec{n} \cdot (c \nabla u) + qu = g$$

where $n$ is the vector normal to the boundary, $c$ is a constant equal to the thermal conductivity of the material, $\text{grad}(u)$ is the temperature gradient, $q$ is the heat source amount, and $g$ is the total heat flux through the boundary. If $q$ is defined such that

$$q = h$$

and

$$g = hu_{\infty}$$

where $h$ is the heat transfer coefficient (higher for quicker transfer, lower for slower transfer) and $u_{\infty}$ is the external temperature, then the equation can be rearranged such that

$$\vec{n} \cdot (c \nabla u) = h(u - u_{\infty})$$

This form of the equation facilitates entering the $h$ and $u_{\infty}$ values into Matlab.

### 4.1.3. Constants Used

Table 4.1. Physical parameters and variables used in the numerical modeling. Value ranges and units are shown. See text for more detail and conditions in which the variables below are used.

<table>
<thead>
<tr>
<th>Physical Parameter or Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>$c$</td>
<td>2 W m$^{-1}$ °C$^{-1}$</td>
<td>Touloukian et al. (1989)</td>
</tr>
<tr>
<td>Heat transfer coefficient</td>
<td>$h$</td>
<td>1-6000 W m$^{-2}$ °C$^{-1}$</td>
<td>Recktenwald (2006), Keszthelyi and Denlinger (1996)</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>$C_p$</td>
<td>850 J kg$^{-1}$ °C$^{-1}$</td>
<td>Bouhifd et al. (2007)</td>
</tr>
<tr>
<td>Density</td>
<td>$\rho$</td>
<td>2900 kg m$^{-3}$</td>
<td>wet/dry measurements</td>
</tr>
<tr>
<td>Boundary temperature</td>
<td>$u_{\infty}$</td>
<td>1-25 °C</td>
<td></td>
</tr>
<tr>
<td>Emplacement temperature</td>
<td>$u_i$</td>
<td>1100 °C</td>
<td></td>
</tr>
<tr>
<td>Boundary normal vector</td>
<td>$\vec{n}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>$u$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature gradient</td>
<td>$\nabla u$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume</td>
<td>$V$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat</td>
<td>$Q$</td>
<td></td>
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<tr>
<td>Length</td>
<td>$L$</td>
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<td></td>
</tr>
<tr>
<td>Time</td>
<td>$t$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The density of field samples is around 2810 kg m\(^{-3}\), though the value used in the calculations is 2900 kg m\(^{-3}\), for the sake of simplicity. The variable \( u_\infty \) changes depending on the boundary considered, but ranges between 1°C for the ice-contact edge and 25°C for the air-contact edge. The variable \( h \) also changes, and ranges from 1 to 6,000 W m\(^{-2}\) °C\(^{-1}\). Recktenwald (2006) uses 6,000 W m\(^{-2}\) °C\(^{-1}\) as the \( h \) value for cooling of a metal sphere in 50°C water, and this value was initially deemed appropriate for the most extreme examples of ice-lava contact. After running several model trials (Appendix A), it was shown that there is a negligible difference in temperature distribution or magnitude between \( h \) values of 6,000 and 100. Because of this, the highest \( h \) value used in the models is 100 W m\(^{-2}\) °C\(^{-1}\). Keszthelyi and Denlinger (1996) use 70 W m\(^{-2}\) °C\(^{-1}\) for the \( h \) value between a pahoehoe flow and the convective atmosphere above it, based on field experiments. The wind speed measured in their experiments ranges between 3 and 4 m s\(^{-1}\). They find that the \( h_{\text{forced}} \) value (the \( h \) value due to forced convection of atmospheric wind) did not change significantly with temperature, but hypothesized that it would change with wind speed. The atmospheric conditions present during these measurements are considered acceptable for the models in this thesis. An \( h \) value of between 1 and 10 W m\(^{-2}\) °C\(^{-1}\) is used for the ground-lava interface, because the ground-lava interface is not a convective boundary, but the equation used models a convective boundary. Thus a very low \( h \) value is used to mitigate the effect of the modeled convective cooling. There are no published experimental values on what this \( h \) value is, so these are estimated values.

The range of \( h \) is so large because of the difference in ability to transfer heat between the various substances against which lava cools. While the ability to transfer heat between lava and the ground is very low, the heat transfer between lava and air or especially melted ice is much higher, and the range in \( h \) reflects that.

According to Griffiths and Fink (1992) radiative cooling accounts for very little of the heat lost from the lava, and so it is neglected and believed to have no influence on the outcomes of this model, especially over the long time scales on which this model runs.
4.1.4. Double Checking Integrity of the Code

Although the Partial Differential Equations Toolbox for Matlab is a professionally constructed GUI, it was prudent to check that there were no “holes” in the model; nowhere that heat was escaping or being created that was not accounted for by the physical elements of the model.

To do this, the total heat loss of the lava flow was calculated in two independent ways. First, the heat loss was calculated simply by the difference in temperature from the beginning of the model to the end. This was done using the following equation:

$$\Delta Q_{\text{total}} = C_p \cdot \rho \cdot V \cdot \Delta u$$

This simply gives the total heat lost from the lava flow in Joules.

The second and independent way to calculate the heat loss was to measure the heat flow through the boundaries exclusively, and add the heat flow per time for the entire run time of the model. To do this, the temperature was first calculated at a node point $i$, and subtracted from the external temperature $T_\infty$. This was then multiplied by the heat transfer coefficient $h$, the change in time between node points, the thickness of the lava flow, and the length between node points along the boundary. $Q_{\text{boundary}}$ has units of Joules.

$$Q_{\text{boundary}} i = \Delta L \cdot z \cdot \Delta t \cdot h(u_i - u_\infty)$$

This gives a matrix of heat flow through the area between two adjacent node points for each time interval. Summing the entire matrix gives the total heat flow through the boundaries over the time length of the model.

$$\sum_{i=1}^{n} Q_{\text{boundary}} i = \text{Total heat through boundary}$$

This is equivalent to the total heat lost from the modeled lava flow, and provides a check against the total heat loss calculated earlier from simple temperature change.

The code was checked using both identical and edge-dependent boundary conditions, and the results are discussed after each section below.
4.2. Model Testing

The following models are examples of sections of lava flows that can be found in the field. Rather than trying to tackle the entire lava flow all at once, sections of the flow are analyzed in increasing complexity, with various boundary conditions. The emplacement temperature for all models is 1100°C. This temperature was chosen because it is below the calculated liquidus of 1213°C for the Cheakamus Basalts, based on data from Green (1981) and calculated using the program rhyolite-MELTS (Gualda et al., 2012), and it is likely that these flows were erupted slightly sub-liquidus.

The models are all shown with symbology from Matlab’s Partial Differential Equation Toolbox. The color maps range from cool to warm colors, with warmer colors representing higher temperatures. The thin dark lines within the models represent isotherms. Matlab takes the entire temperature range in the model at any one time, creates 20 equal bins, and draws the isotherms at those specified temperatures.

The arrows in some of the models show the formation direction and size of columns. The arrow vectors quantitatively represent the heat flow direction and magnitude at specific points in time. To construct these arrows, the temperature gradients are first calculated at every time step throughout the model. The heat flow vector is then calculated at specific points. While columnar joints form parallel to the direction of heat flow, joints propagate towards the higher temperatures, and so the arrows point in the opposite direction of the heat flow. Column size is also inversely proportional to the magnitude of heat flow; large columns are formed by low heat flows, while small columns are formed by high heat flows. Thus the direction and magnitude of the arrows is calculated quantitatively from the thermal gradients, and they are used in the models to qualitatively show the direction of column formation, and the relative sizes of the columns (large arrows indicate small columns, and vice versa).

In some of the models isograds are used instead of (or in conjunction with) arrows to represent the thermal gradient (Figs. 4.10 & 4.11). The gradient is calculated in the same way, but the contours show lines of equal heat flow. Columnar joints form perpendicular to these isograds, and these isograds show the same data in a different
form. Closely spaced isograds show high thermal gradients, while widely spaced isograds show low thermal gradients. The difference in spacing between the isograds is also often easier to see than the difference in size between the arrows, and so provides a better representation of the magnitude of heat flow and thermal gradients.

While the temperature profile shown in the models is the temperature at the time given (the end of the model run), the arrows represent column formation, and because column formation is a transient process, the arrow vectors are not all calculated at the same time. A column formation temperature, close to the glass transition temperature of the basalt (in this case $T_{column}$ is 800°C), is used, and the heat flow direction and magnitude is calculated when each modeled cell cools to that temperature. Thus the arrows represent the correct size and orientation of the columns as they formed in discrete time steps. The same is true for the heat flow isograds. The gradient is calculated at $T_{column}$, and therefore the spacing of the contours represents the transient thermal gradient at the time of column formation.

4.3. Identical Boundary Conditions

These models all have boundaries with equal boundary conditions, with the exception of boundaries that are treated as perfect insulators so as to isolate sections of possible flows for simpler analysis. These models serve as an introduction to the modeling section, introducing several ideas, such as the column interface, before adding additional variables to the models. These models all have $h$ factor values of 100 W m$^{-2}$ °C$^{-1}$ on the boundaries that transmit heat.

4.3.1. Semi-Infinite Slab

This model has two cooling surfaces, one on the top and bottom of the modeled lava flow (Fig. 4.1). In this way a semi-infinite slab is modeled, so that any side boundaries are arbitrarily far away and have no effect on the cooling history of the model. This is accomplished by making the side boundaries of the model perfect insulators.

Because the boundary conditions of the two cooling surfaces are equal, any joints that form will nucleate on the boundary and propagate inwards. In the exact
middle of the flow, these joints will meet at the *column interface*. Though simple in these models, this interface is rather complex in natural rocks, and has been covered in Chapter 3.

The arrows indicate that the columns that form on the exterior of the flow will be much narrower than those that form on the interior of the flow, since the heat flow magnitude is much larger on the edge.

Though this is a simple model, basalt flows have such low viscosities that outcrops often do have geometries such as this in the middle, with only the top and bottom boundaries influencing the cooling history of the lava. In most cases the top and bottom boundaries are not equal, and the outcrop is more like the semi-infinite slab model with edge-dependent boundary conditions.

### 4.3.2. Slab Corner

This model also has two cooling surfaces, but they are adjacent surfaces, not opposite surfaces as in the previous model. In this way the model represents the corner of a cooling lava flow, where two cooling surfaces come into contact (Fig. 4.2).

The main difference between the *slab corner* model and the *semi-infinite slab* model is that there is no column interface present. The isotherms do not repeat within the model, but rather curve around from one boundary to the adjacent one. Because the isotherms curve, the columns formed by columnar joints will curve as well, since columnar joints form perpendicular to isotherms. Due to this nonlinearity, the columnar joints will meet and likely coalesce, because as the joints propagate inward, there is less space (and less total thermal stress) for the same number of joints, and they will decrease in number. There is still melt for the joints to propagate into, but the joints will not meet straight on as in the *semi-infinite slab* model.

### 4.3.3. Slab Side

This model is the most complex of the three identical boundary models detailed (Fig. 4.3). It contains both curving columns as well as a column interface. Unlike the *semi-infinite slab* model, the column interface does not extend across the entire outcrop, but rather stops as it approaches the lateral boundary. As seen in Fig. 4.3, columnar
joints propagating from the lateral boundary interfere with the column interface. Fig. 4.3 also shows the density distribution of columnar joints within an outcrop as it relates to heat flow. Heat flow arrows show large magnitudes of heat flow near the edge of the flow, while the heat flow decreases rapidly on the interior of the flow. This is represented in the distribution of the joints – there is a higher joint density near the boundaries, and a lower density further from the boundaries. The cessation of a columnar joint results in the two adjacent columns coalescing.

4.3.4. Identical Boundary Code Integrity

Several models were run with the total change in heat compared to the heat lost through the boundaries. In these cases, all the boundaries for each model had equal $T_\infty$ values and equal $h$ factor values, though they change in value for different models. The results are summarized in Table 4.2 and Fig. 4.4. The main point is that there is very little difference between the two heat measurements, and this difference is small enough to be considered insignificant.
Figure 4.1. Semi-infinite slab model with identical boundary conditions on top and bottom surface. Sides are perfect insulators. Color represents temperature, with warmer colors representing higher temperatures. Thin lines within the model are isotherms. Arrows represent column formation direction and size. The arrows near the center of the flow are very small, and may appear as dots, rather than arrows. Midpoint of flow and column interface is shown by dashed line. Model ran for 72000 s. See text for further explanation.
Figure 4.2. Slab corner model. In this model, there is no column interface. Instead, the curving temperature isotherms produce curving columns. Because of the space issue associated with all the columns propagating towards a common point in the upper right corner, the propagation of some joints ceases, causing columns to coalesce. Model ran for 180000 s. Symbology same as previous figure.
Figure 4.3. Slab side model. A shows the slab side model with heat flow arrows, and the dashed line shows to where the column interface extends. It is not continuous across the flow because the lateral cooling boundary creates coalescing columns. B shows hypothetical joints drawn perpendicular to the isotherms, and column diameters are relative to heat flow gradients at the column formation temperature. Models ran for 72000 s. Other symbology same as previous figure.
Table 4.2. A summary of numerical models 1 through 9 with identical boundary conditions, with the various dimensions of the models and $h$ factor values listed. The two values compared for each model are the $Q_1$-$Q_{end}$ value and the $Q$ through boundaries value, both of which have units of Joules.

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<th>Boundary 2 (Right)</th>
<th>Boundary 3 (Bottom)</th>
<th>Boundary 4 (Left)</th>
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<td>$T_\infty$ (°C)</td>
<td>h factor</td>
<td>$T_\infty$ (°C)</td>
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<table>
<thead>
<tr>
<th>Trial</th>
<th>time step (s)</th>
<th>total time (s)</th>
<th>x size (m)</th>
<th>y size (m)</th>
<th>total area (m$^2$)</th>
<th>$Q_1$-$Q_{end}$ (J)</th>
<th>Q through boundaries (J)</th>
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<td>36</td>
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<td>5.54E+10</td>
</tr>
</tbody>
</table>
Identical Boundary Condition Heat Change

Figure 4.4. Comparison of the total heat through boundaries vs. the total heat change of the system between the beginning and end of the model. The dashed line shows parity between the two independent measurements of total heat change within the system, and all the models tested fall almost exactly on the dashed line.

4.4. Edge-Dependent Boundary Conditions

Identical boundary conditions are the simplest to model, but very rarely in nature are boundary conditions identical on all sides of a cooling lava flow. Edge-dependent boundary conditions (models with different boundary conditions on each side of the modeled flow) are a more accurate depiction of the processes occurring in the natural world. This also enables a more direct comparison of models and field outcrops, which makes understanding the thermal history of these outcrops easier and increases the accuracy of the comparisons as well.

4.4.1. Semi-Infinite Slab

In this model (Fig. 4.5) the upper boundary has been given an \( h \) factor value of 70 W m\(^{-2}\) °C\(^{-1}\), while the lower boundary \( h \) value is 10 W m\(^{-2}\) °C\(^{-1}\). Convecting air is more efficient at heat dissipation than the soil or rock that typically underlies most lava flows.
The column interface is not in the middle of the flow, but shifted downwards, closer to the lower boundary. This is due to higher heat flow through the upper boundary, causing quicker propagation of joints. This shift in the position of the column interface is observed often in the field area of this study as well.

4.4.2. Slab Corner

This model (Fig. 4.6) shows similar temperature distributions as the slab corner with identical boundary conditions, but both boundaries do not cool to the same temperature. This changes the geometry of the isotherms within the model from the identical boundary model, but not drastically. The left boundary has an $h$ factor value of 70, while the bottom has a value of 10.

4.4.3. Slab Side

Fig. 4.7 shows both the first two models combined, and all three non-insulating boundaries have different heat transfer coefficients. This changes both the location of the column interface and the isotherms near the sides of the flow, as described below. The upper and lower boundaries have $h$ factor values of 70 and 10 respectively, while the left boundary has a value of 100.

Fig. 4.7 also shows representative columnar joints drawn in, similar to those in Fig. 4.3. In Fig. 4.7 the distribution of the joints is more complex, due to the edge-dependent boundary conditions. With higher heat flow magnitudes on the upper boundary than on the lower boundary, the joints are more closely spaced on the upper boundary.

4.4.4. Finite Slab

This last model (Fig. 4.8) represents an actual, finite lava flow with different boundary conditions on the top, bottom, and sides. The sides have identical boundary conditions of $100 \text{ W m}^{-2} \text{ °C}^{-1}$, because it is likely that most actual lava flows were bounded on both sides by similar mediums, whether they were confined by ice or a valley. If they were confined only by air, the aspect ratio of the flow would be much lower, but the boundaries would be very similar, and the inferences made the same.
The top has an $h$ factor of 70, and thus can transfer heat away from the boundary at a higher rate. This, along with the smaller $h$ factor value of 10 on the bottom boundary, causes the column interface to be located below the midpoint of the flow, similar to many outcrops seen in the Whistler field area. The higher $h$ factor value of 100 on the side boundaries creates more cross-sectional area in which the isotherms curve between the top and bottom boundaries and the side boundaries, which affects the direction of propagation of the columnar joints.

4.4.5. Edge-Dependent Boundary Conditions Integrity

Several models were run with the total change in heat compared to the heat lost through the boundaries. In these cases, the boundaries had unequal $T_\infty$ values and in some cases unequal $h$ factor values. The results are summarized in Table 4.3 and Fig. 4.9 below. The two models with the highest heat output (Trials 16 and 17) had the most difference between the two heat change measurements, but this difference is not large. Again, the main point is that there is very little difference between the two heat measurements, and this difference is small enough to be considered insignificant.
Figure 4.5. Semi-infinite slab model with edge-dependent boundary conditions on top and bottom surface. Sides are perfect insulators. Color represents temperature, with warmer colors representing higher temperatures. Thin lines within the model are isotherms. Arrows represent column formation direction and magnitude of heat flow at the time of column formation. Column interface is shown by dashed line, and is below the midpoint of the flow. Model ran for 90000 s. See text for further explanation.
Figure 4.6. Slab corner model. In this model, similar to Fig. 4.2, there is no column interface. The unequal boundary conditions produce curving temperature isotherms. These in turn produce curving columns of varying diameters propagating from the lower and left lateral boundaries. Because of the space issue associated with all the columns propagating towards a common point in the upper right corner, the propagation of some joints ceases, causing columns to coalesce. Model ran for 216000 s. Symbology same as previous figures.
Figure 4.7. Slab side model. A shows the slab side model with heat flow arrows, and the dashed line shows where the column interface extends to. It is not continuous across the flow because the lateral cooling boundary creates coalescing columns. B shows hypothetical joints drawn perpendicular to the isotherms, and column diameters are relative to heat flow gradients at the column formation temperature. Joint density is less on the bottom because of the lower relative heat flow through the lower boundary. Models ran for 90000 s. Other symbology same as previous figures.
Figure 4.8. Finite slab model. Column interface occurs below middle of flow due to unequal boundary conditions. As in Fig. 4.7, the column interface does not extend to the lateral boundaries, but rather is confined within the center of the flow. Model ran for 108000 s. Symbology same as previous figures.
Table 4.3. A summary of numerical models 10 through 19 with edge-dependent boundary conditions, with the various dimensions of the models and $h$ factor values listed. The two values compared for each model are the $Q_1$-$Q_{end}$ value and the $Q$ through boundaries value, both of which have units of Joules.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Boundary 1 (Top)</th>
<th>Boundary 2 (Right)</th>
<th>Boundary 3 (Bottom)</th>
<th>Boundary 4 (Left)</th>
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<td>$T_\infty$ (°C)</td>
<td>$h$ factor</td>
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<table>
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<tr>
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<th>total time (s)</th>
<th>x size (m)</th>
<th>y size (m)</th>
<th>total area (m$^2$)</th>
<th>$Q_1$-$Q_{end}$ (J)</th>
<th>Q through boundaries (J)</th>
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<td>1800000</td>
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<td>6</td>
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<td>900000</td>
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<td>7920000</td>
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<td>3600000</td>
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<td>1.07E+11</td>
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<td>64</td>
<td>9.89E+10</td>
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60
Figure 4.9. Comparison of the total heat through boundaries vs. the total heat change of the system between the beginning and end of the model. The dashed line shows parity between the two independent measurements of total heat change within the system, and all the models tested fall almost exactly on the dashed line. The two models with the most heat loss are very slightly off the dashed line, but the difference is insignificant.

4.5. **Modeling Results**

4.5.1. **Temperature Profiles**

All of the above models assume instantaneous emplacement of the flow into the cooling environment. As the model starts its first time step, the difference in temperatures between the environment and the lava flow, as well as the high $h$ factor values used for some of the boundaries, creates a very large heat flow and very high thermal gradient at the edge of the flow. Because both lava and solid basalt have such high heat capacities and low thermal diffusivities, a large temperature difference between the interior and exterior of the flow is maintained for the majority of the cooling history.
As the model progresses, the temperature differences between the boundaries and interior of the flow decrease. However, while parts of the flow are above $T_{\text{column}}$, there is always a large temperature difference present. The greatest difference occurs immediately after emplacement when the edges of the flow have cooled to near $T_{\infty}$, and when the center of the flow has not yet lost any heat. The exact amount of time the center stays above $T_{\text{column}}$ depends completely on the size of the flow, but in the two-dimensional models that measure 1 m by 3 m, the interior can stay above $T_{\text{column}}$ for over 24 hours.

The finite slab model shown has edge-dependent boundary conditions on all four sides of the model, and most accurately depicts the temperature profile present within an actual lava flow. The unequal boundaries have two distinct effects on the temperature profile of the model. First, they cause the column interface between the upper and lower colonnade to be located below the midpoint of the flow cross section. Second, they cause much higher heat flows near the sides of the model where the $h$ factor is highest, with a value of 100. Not only is this visible in the heat flow arrow magnitudes, but also in the temperature profile contours. The temperature $n$ meters in from the edge of the side of the flow is significantly less than the temperature $n$ meters in from the top or bottom of the flow.

**4.5.2. Heat Flow Gradients at $T_{\text{column}}$**

As mentioned above, the large heat capacity of both molten lava and solid basalt, along with the small thermal diffusivity values allow large temperature differences between the interior and exterior of a cooling lava flow. The modeled lava flows are also instantaneously emplaced, placing 1100°C lava against material that ranges from 1-25°C. This large temperature difference creates very large thermal gradients on the edge of the modeled flows, with the gradients decreasing as the critical column formation temperature propagates inward. Fig. 4.10 shows thermal gradients for one of the models with identical boundary conditions.

The spacing of the heat flow isograds represents the gradient when the model is at a specific temperature: the column formation temperature ($T_{\text{column}}$). The
resulting gradient is transient from emplacement until the entire flow is below $T_{\text{column}}$. The closer the contours are together, the greater the heat flow at $T_{\text{column}}$.

The range of boundary conditions used in the forward models creates a large range of cooling rates and thermal gradients at the column formation temperature. Where two boundaries interact, the heat flow isograds curve in response. Based on previous assumptions that columns follow the direction of heat flow, the columns will curve within the flow. The magnitude of heat flow changes dramatically from the outside of the flow to the inside as well, and again based on previous assumptions, the size of the columns produced will vary. As the section of the flow in question is at the column formation temperature, smaller columns form where the heat flow is greatest, and larger columns where the heat flow is least. Because the magnitude of heat flow is directly proportional to the $h$ factor value at a particular boundary, boundaries with large $h$ factor values will have columns with smaller diameters propagating away from them, while boundaries with small $h$ factor values will create large diameter columns.

The models show that the geometry of the columns, including the size and distribution, is dependent upon the boundary conditions. Because the diameter of the columns is inversely proportional to the cooling rate, the more effective at cooling a boundary is, the smaller the diameter of the columns that will be formed.

The models predict that high heat flow and cooling rates are present at boundaries with high $h$ factors, while lower heat flow and smaller thermal gradients are present at boundaries with low $h$ factors. Any boundary with a low $h$ factor will necessarily have larger diameter columns propagating away from it than will a boundary with a high $h$ factor. The models also dictate that as the columnar joints propagate inwards, the cooling rate and thermal gradient will decrease as well. This leads to a decrease in the formation of tensile stresses, and thus a decrease in the number of columnar joints per square meter. Reduction in the number of joints per square meter is accomplished by the termination of some columnar joints, and thus an increase in average column diameter, in addition to the differences in column diameter already present from the various boundary conditions.
Near the corners of a lava flow, there will necessarily be curving columnar joints. Joints propagate parallel to heat flow, which is perpendicular to the thermal gradient isograds in Fig. 4.10. If one were to trace a line perpendicular to the isograds that originates from somewhere near one of the corners of the lava flow (as shown in Fig. 4.12), that line (joint) will necessarily have to curve to maintain orthogonality to the isograds. This is assuming that the lava flow in question has a high enough aspect ratio at the lateral boundaries of the flow, and that these are affected by the side boundaries. Curving columns are visible in outcrop setting in Figs. 3.5 and 6.3.

The location of the column interface is also dependent on the boundary conditions. The more effective at cooling a boundary is, the further from it the colonnade interface will be. This is because the cooling rate is higher at that boundary, and the columnar joints propagate further in the same amount of time. This is visible in Figs. 4.8 and 4.11.

The models accurately predict the amount of relative heat flow and relative sizes of cooling gradients within cooling lava masses, as well as accurately predict the direction and relative sizes of columns within the outcrop. With this determined, the models can be used in conjunction with the high temperature experiments outlined in Chapter 5 to later reconstruct the cooling history of lava flows in the field based on the geometry of the columns in outcrop.

4.5.3. Predictions

Larger diameter columns are observed in the field most often in lower colonnades and especially near the center of flows (Grossenbacher and McDuffie, 1995), where the models show the cooling rates are the lowest. For the experiments in Chapter 5, we know that lower cooling rates produce larger diameter columns, and higher cooling rates produce smaller diameter columns. From this, we can predict that there will be a certain cooling rate, at the column formation temperature, that produces columnar joints. We can also predict that if the cooling rate is too low for the physical dimensions of the experimental sample, (i.e. if the cooling rate is lower and the sample is small) columns will not form. It is
also important that this cooling rate is present at the column formation temperature ($T_{column}$). If it is present at some other temperature, columnar joints may not form.
Figure 4.10. Heat flow contour map. All edges have $h$ factor values of 60. The heat flow isogrids are symmetric about all the boundary surfaces. The isogrids show lines of equal magnitude of heat flow at $T_{column}$. The spacing of the isogrids is proportional to the thermal gradient. The isogrids are close together near the edge of the flow, and show high gradients at $T_{column}$ while the isogrids become more spaced out in the interior, showing lower gradients at $T_{column}$ Midpoint of flow is shown by dashed line. Gradient units are in °C / ΔL, where ΔL is the node spacing. These units are directly proportional to heat flow. Arrows show heat flow as well, and arrows in the center of the model may appear as dots due to small size. Model was run until below $T_{column}$, approximately 800000 s.

Figure 4.11. Heat flow contour map. This model has edge-dependent boundary conditions. The bottom boundary has the lowest $h$ factor, with a value of 8, while the side boundaries have high $h$ factors, with values of 100, and the top boundary has an $h$ factor value of 60. Column interface location is shown by the dashed line. Note that it is below the midpoint of the flow. Model was run until below $T_{column}$, approximately 800000 s. Other symbology same as Fig. 4.10.
Figure 4.12. Line drawing of hypothetical columnar joints superimposed upon model with heat flow isogrdas. Joints propagate normal to isogrdas, and column diameter is inversely proportional to cooling rate. Both curving and coalescing columns are shown, as is the column interface. Other symbology same as previous figures.
5. **High Temperature Experiments**

High temperature experiments are used extensively in petrological studies. However, they are not commonly used for heat flow, melt, and brittle deformation studies and have not been used to study column formation. Only analog experiments, as well as some field experiments, have been conducted with the aim of increasing understanding of the mechanisms of formation and the geometrical expression of columnar joints.

Ryan and Sammis (1981) infer the glass transition temperature of basalt to be 725°C, based on dilatometry, stress relaxation, and acoustic spectroscopy measurements of basalts at various temperatures. Taking this as the approximate “columnar formation temperature,” the rate of cooling through this temperature is what determines the spacing of the joints, and thus the diameter of the columns formed.

Peck and Minakami (1968) observed the cooling of Kilauean lava lakes and the formation of jointing in those lavas. They recorded jointing starting at temperatures as high at 900°C, and propagating down to temperatures up to 1000°C. Based on the work of both Ryan and Sammis (1981) and Peck and Minakami (1968), the “column formation temperature” ranges from 725-900°C.

The experiments outlined below were carried out using powdered basalt, a high temperature furnace, and various cooling mediums. The purpose is to 1) see if columnar joints can be synthesized in a laboratory setting to document joint morphology and texture; 2) to determine the thermal gradients and cooling rates that are required to form columnar joints in these samples.

The powdered basalt used in these experiments is from the Cheakamus Valley basalts, which are fairly typical olivine basalts. The chemistry and petrology of the basalts is described briefly in Section 3.1, and for an in-depth chemical and mineralogical analysis, see Green (1981).
5.1. Methodology

5.1.1. Designing the Experiments

Lithium metaborate flux was added to the powdered basalt prior to melting, in order to lower both the liquidus and the viscosity of the melt. For these experiments, a lower liquidus is desired to prevent undue wear and tear on the Nabertherm high temperature furnace. Lithium metaborate fluxes are typically used in the fusion of samples for x-ray fluorescence, often with flux to sample ratios of 5:1 or higher. The flux is only needed to ensure glass formation, and there are no good data describing the effects of much smaller flux to sample ratios, such as those used in this study, which are near 1:5, rather than 5:1. Mastin et al. (2009) mention that the 5 wt. % dilithium tetraborate flux they used in their experiments decreased the viscosity by several times, and also decreased the liquidus to below their experimental temperature of 1200°C. However, they performed no quantitative measurements on the viscosity and liquidus of the fluxed melt.

The way in which the flux would alter the ideal starting temperature for the experiments was another unknown. The exact mineralogy of the crystals present in the experiments was not a concern, but the amount of crystals present in the melt was, since this will affect the tensile strength and the heterogeneity of the samples, as well as the volume change available due to the phase changes in the crystallizing samples.

Initially, 1000°C was picked as the starting temperature for the experiments. However, upon removing the samples from the furnace and cooling either by partial or complete submersion in water, or even simply by free air convection, the cooling material would simply become glass. An additional observation was that the material would accommodate any volume loss due to a decrease in temperature via viscous flow, but only in the center of the sample. Where the sample met the crucible on the perimeter, the material would solidify extremely quickly and be unable to flow. Thus, with all the viscous deformation occurring in the center of the samples, a “cone of depression” was formed (Fig. 6.9). If thermocouples were to be used in these experiments, this “cone of depression” may expose the thermocouples
to the atmosphere and interfere with the readings. Between the viscous flow and complete glassification of the samples, it was obvious that a lower starting temperature was needed, so the cooling material would have a higher viscosity, and be less able to accommodate volume loss through viscous flow.

To decide a starting temperature for the main experiments, a set of preliminary experiments was carried out. Two crucibles were filled with a basalt-flux mixture, one with 10 wt. % flux, and the other with 15 wt. % flux. It was necessary to lower the liquidus below the 1000°C starting temperature to ensure a homogenous starting melt, but it was also undesirable for the flux to influence the experiments to a large degree. Unsure of what exact weight percentage of flux to use, the preliminary experiments were carried out with two different percentages of flux. The thermocouples were inserted into the middle of each crucible, and were attached to a computer program that recorded the temperature once every second.

For these and subsequent experiments, a Nabertherm high-temperature chamber furnace with SiC rod heating was used, model HTC 08/15. The Nabertherm furnace was set at 1000°C, and when the thermocouples reported that the center of the samples was at equilibrium with the furnace, a small aliquot of melt was sampled with a glass rod and immediately quenched. The furnace was then set to 900°C, and when the sample was at equilibrium, another aliquot of melt was taken and quenched. Below 900°C, the 10 weight percent flux melt became too viscous to sample without disturbing the crucible. The 15 wt. % flux melt was also sampled at 800°C and 750°C. The aliquots of melt were then analyzed and the crystal fraction of the various samples was determined (Fig. 5.1).

The purpose of these preliminary experiments was two-fold. First, by measuring the time it takes the samples to reach equilibrium temperature with the furnace, the dwell time was determined to ensure homogeneous temperature distribution within the samples. Second, taking aliquots of the melt at various temperatures enabled plotting of the change in crystal fraction against the change in temperature and finding an ideal starting temperature for the main experiments (Fig. 5.1). The purpose of two different flux concentrations was to ascertain that at 1000°C, the quenched aliquot is entirely glass. A homogenous starting material is
required before cooling the samples down to the starting temperature, to ensure that they are in equilibrium. It was not clear if 10 or 15 wt. % flux was needed to reach liquidus at 1000°C, so both were used in the preliminary experiments.

Starting temperatures ranging from 800-700°C were chosen because the large percentage of crystals within the samples ensures little viscous flow will accommodate volume change during cooling, but the samples are not yet entirely solid, and there is still a difference in crystal fraction between experiments.

As shown in Fig. 5.2, the experimental setup for the forced air convection experiments consisted of a cut rock slab cooling surface and a household fan. The samples were placed on the rock slab, and the fan was turned on to the highest setting. The air temperature was approximately 20 °C for all experiments. For the water cooled experiments, convecting water was necessary to prevent the samples from heating the nearby water, and possibly reducing heat transfer to the cooling material. This was accomplished by placing a large beaker filled with 1 L of water at approximately 3 °C on a magnetic stirrer. The stirrer was adjusted so that the water was circulating quite quickly, but was slow enough that the insertion of the sample into the water did not cause undue disturbance of the circulation. The samples were placed midway between the center and edge of the beaker, since the circulation of the water would be minimal in the center of the beaker.
Figure 5.1. Four aliquots of sample were taken from a single experiment of 15 wt. % flux, one each at 1000, 900, 800, and 750°C, as represented by the stars. These samples were smear mounted and crystal percentages were estimated visually using a percent abundance estimation chart, in conjunction with analysis from X-ray diffraction and subsequent Rietveld refinement, to determine percent crystallinity. The dashed line shows the inferred crystal percentage between samples. The box on the right side of the chart outlines the temperature range chosen as starting temperatures for the experiments. These temperatures were chosen because the large proportion of crystals ensures little viscous flow during cooling, but differences in crystal percentages still remain between experiments.
5.1.2. Textural Experimental Grid

All of the experiments, both textural and gradient focused, are performed using cylindrical alumina crucibles, with a radius and height of 25 mm, and an approximate volume of 10 mL.

Starting at three initial temperatures (700°C, 750°C, and 800°C), an experimental grid was created (Table 5.1), using different cooling mechanisms, producing a variety of thermal gradients. While liquid nitrogen was originally thought to produce the highest gradient, it in fact does not, most likely due to the Leidenfrost effect. The Leidenfrost effect occurs when a liquid and a much hotter solid come into contact with each other. The liquid immediately boils and forms a layer of gas between the liquid and the solid. The thermal conductivity of the gas is so low that it actually acts as an insulator, preventing the solid from cooling quickly (Gottfried et al., 1966; Leidenfrost, 1966). Thus the fastest cooling rates occurred when the samples were cooled in water. The slowest cooling occurred while cooling in the oven, at a temperature decrease of 5°C per minute.

Table 5.1. Experimental grid for textural experiments. The numbers 2012-XX represent a single experiment. For some experimental conditions, no experiments were performed. Two experiments per temperature value were performed for the partially submerged, water cooled experiments.

<table>
<thead>
<tr>
<th>Cooling Medium</th>
<th>Temperature (°C)</th>
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<th>750</th>
<th>700</th>
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</thead>
<tbody>
<tr>
<td>Oven (5°C per minute)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock Slab (with forced air convection)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Liquid Nitrogen (3 sides)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water (partially submerged)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Water (fully submerged)</td>
<td></td>
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</tr>
</tbody>
</table>

5.1.3. Gradient Experimental Grid

To measure the thermal gradients and cooling rates, samples were subjected to the same cooling conditions as the textural experiments, but had two thermocouples in the samples (Fig. 5.2). These experiments are separate from the
textural experiments, because the presence of thermocouples in the sample would obscure any textures created by the cooling.

For each experiment, the samples were heated to 1000°C to ensure homogeneous melting, and then the thermocouples were inserted. The thermocouples were spaced 9.5 mm apart from each other, and they were inserted so one of the ends touched the bottom of the crucible. Because the crucibles measure 25 mm tall, and the crucibles were not completely filled, 9.5 mm spacing between crucibles was determined to produce a substantial difference in cooling rate, and return accurate results.

Two experiments were conducted for each set of cooling conditions, with either a starting temperature of 800°C or 700°C, or as close as was possible to these temperatures. Because the thermocouples could not be in the sample while it was in the high temperature furnace, for all the experiments where the sample was cooled outside of the oven, the thermocouples had to be inserted in the samples while they were outside the furnace. This was done when the samples were at higher temperatures (around 1000°C) since they would be too viscous at 800°C or 700°C. Once the thermocouples were inserted into the samples, the samples were slowly cooled outside the furnace with the help of a blowtorch to prevent any significant temperature gradient from forming prematurely in the sample as it cools to the starting temperature for the experiment. Due to the error associated with this method, small temperature differences of approximately 20-25 °C did develop. The largest starting temperature difference occurred in experiment 2012-20, with a difference of 40 °C between the thermocouples. Once the samples were cooled to approximately the correct starting conditions, and the difference in temperature between thermocouples was at a minimum, the samples were exposed to the specified cooling conditions. Table 5.2 shows the experimental grid for the thermal gradient experiments. Figs. 5.7 through 5.10 show the thermocouple readings of the thermal gradient experiments.
Table 5.2. Thermal gradient experiments with cooling medium and starting temperature shown. Though no thermal gradient experiments were carried out using 750°C as a starting temperature, the column is present because textural experiments were conducted starting at this temperature.

<table>
<thead>
<tr>
<th>Cooling Medium</th>
<th>Temperature (˚C)</th>
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<tr>
<td>Rock Slab (with forced air convection)</td>
<td>2012-23</td>
</tr>
<tr>
<td>Water (partially submerged)</td>
<td>2012-19</td>
</tr>
<tr>
<td>Water (fully submerged)</td>
<td>2012-25</td>
</tr>
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</table>
Figure 5.2. A shows the experimental setup for samples cooled via forced air convection. The sample sits on a room temperature rock slab and has air blown across it by a household-style fan, set on its highest setting. B shows the experimental setup for samples cooled via partial submersion in water. The container holding the water is much larger than pictured in this figure, and contains ice as well, so the temperature of the water does not change by an appreciable amount. For samples completely submerged in water, the setup is the same, but the sample is cooled on all sides by water, including the upper surface.
5.2. Results

5.2.1. Internal Structures and Textures

Joints are found within some of the experimental products, but not all samples contain joints. Overall, experiments cooled via either partial or complete submersion in water developed jointing, while experiments cooled in the oven or via forced air convection did not form joints. The specific textures found in the experiments vary from sample to sample, but this division holds true for all the experiments.

Some of the samples are not jointed, but do have fractured surfaces, such as experiments 2012-21 and 2012-03 (Figs. 5.3 and 5.4). Fracture surfaces form only where the sample was broken to expose the interior for observation, and they are not present elsewhere within the sample. If cooling joints are present within the sample, they will be visible as joints intersecting the main broken surface (Figs. 5.5 and 5.6).

Fig. 5.3 shows experiment 2012-21, which was cooled in the furnace from 700°C down to 400°C (well below the solidus and glass transition) at 5°C per minute. This sample cooled slowly enough to form small crystals, visible in the lower right of Fig. 5.3. As is evident from the photo, experiment 2012-21 does not have any joints bisecting it, though fracture surfaces are visible. This is true for both oven-cooled samples.

Experiment 2012-03 was cooled via forced air convection from a temperature of 750 °C (Fig. 5.4). No joints exist within the sample, though texturally it is distinct from experiment 2012-21 (Fig. 5.3). The air cooled experiment is rougher in surface texture, and did not form many of the fracture surfaces that are present in experiment 2012-21. Experiment 2012-03 did not form any visible crystals.

In Figs. 5.5 and 5.6, jointing can be seen throughout the samples. Much of this jointing is perpendicular to the cooling surfaces, though cross joints are seen as well. Both these samples were cooled in convecting water, with experiment 2012-12 (Fig. 5.5) fully submerged in water, while experiment 2012-15 (Fig. 5.6) was
partially submerged (cooled by water on the bottom and the sides, with the top open to the atmosphere).

The joints formed in these two samples are not well organized or ordered like those found in outcrops. However, well organized joints were not expected to be found, owing to the rapid cooling and small size (approximately 10 mL) of the samples. Regardless, the presence of joints within these samples sets them apart from experiments with slower cooling rates, such as experiment 2012-21 (Fig. 5.3).

The difference in textures and presence of joints between the experiments shows that the cooling rate does have a direct impact on the presence or absence of cooling joints within the samples. See Appendix C for photos of all the experiments.
This sample was cooled from 700°C down to 400°C in the Nabertherm furnace at 5°C per minute. It cooled slowly enough that small white crystals formed during the process, visible in the lower right corner of the sample. The planar surfaces facing the viewer are not joints, but rather the fracture surfaces formed when the crucible was broken off the sample. The sample does not have any joints in its interior, and so the sample fractured near the crucible, rather than through the center. These fractures are all parallel to the crucible walls, rather than perpendicular to those cooling surfaces. The sample extends towards the viewer in this photo by approximately 8 mm. The fractures are not considered cooling joints, but rather a sample preparation artifact. They do not propagate into the interior of the sample, and this experiment cooled as one mass. This is in contrast to experiments 2012-12 and 2012-15, which cooled much more quickly than this sample, and are extensively jointed.
Figure 5.4. Photo of experiment 2012-03. This sample was cooled from 750°C via forced air convection. There is much more variability in the texture of the sample than in the oven cooled experiment (Fig. 5.3), however cooling joints are not present. There are one or two planar surfaces that could be considered fracture surfaces, but these are only present on the large broken face created to view the cross section of the sample. There are no joints present that are not associated with and created by the breaking of the sample after cooling.
A shows experiment 2012-12. This sample was fully submerged in water and cooled by forced convection. B shows a schematic drawing of the above sample. Dark lines outline joints in sample. In some cases these have organized to form columns within the sample. Timing relationships can be determined by joint geometry. Later joints perpendicularly intersect earlier, continuous joints. Almost all the joints have formed perpendicular to the cooling surfaces.
Figure 5.6. A shows experiment 2012-15. Sample was cooled on the sides and lower boundary in water by forced convection, while the upper surface was cooled by freely convecting air. In B, dark lines outline joints within sample. Joints form subperpendicular to cooling surface, and later joints perpendicularly intersect earlier joints.
Each cooling method produced a distinct set of cooling rates and thermal gradients, which are reported here. The results are outlined in Figs. 5.7 through 5.10. Fig. 5.11 shows the maximum difference in temperatures between the two thermocouples during the experiments. The maximum difference happened at different times for each of the experiments, but as a general rule, the maximum difference occurred very early for the quickly cooled experiments, such as the water cooled ones, and somewhat further into the experiment for the slowly cooled experiments, such as those cooled in the oven.

There is one outlier within the experimental results – experiment 2012-19. The maximum temperature difference is far greater for this experiment than for the rest of the experiments. It is not entirely clear why this is the case, since the cooling rate for experiment 2012-19 is very similar to the other partially submerged experiment, 2012-20 (Table 5.5, Fig. 5.12). It is possible that the middle thermocouple happened to be located in the exact center of the sample, where it was most insulated, whereas in the other experiments the middle thermocouple was slightly off-center, but this is merely speculation. The cooling rates for this experiment are still valid, and it is those data that are analyzed below.

The oven cooled experiments had very low thermal gradients, as judged by the maximum temperature difference, and that is to be expected. The samples took over an hour to cool from either 700 or 800°C down to 400°C, so the variation in temperature within the sample was minimal, and generally fairly constant for the duration of the experiment. As shown by Fig. 5.3, the slow cooling rate and negligible thermal gradient does not produce columnar joints within the sample.

The air conduction cooled experiment gave comparatively intermediate values for the maximum temperature difference. Though the atmosphere was much cooler than the sample at the time of the experiment, air does not the ability to absorb large amounts of heat effectively, and so was not the most effective refrigerant. Fig. 5.4 shows that the air cooled experiments did not form cooling joints.
Excepting experiment 2012-19, all the water cooled experiments had similar maximum differences in temperature. Surprisingly, the experiment with a starting temperature of 700°C (2012-25) had a larger temperature difference than the experiment with a starting temperature of 800°C (2012-26). This could be from some small difference between the experiments, such as an enhanced surface crack network in the 700°C sample. Regardless, both samples that were completely submerged had higher temperature differences than the sample that was cooled from only the bottom and sides.

Table 5.3. Shows the maximum temperature difference between the two thermocouples, and converts this into the maximum thermal gradient experienced by the sample based on the 9.5 mm distance between the thermocouples.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Cooling Mechanism</th>
<th>Max Temp Difference (˚C)</th>
<th>Thermal Gradient (˚C/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012-21</td>
<td>oven</td>
<td>6.32</td>
<td>0.66</td>
</tr>
<tr>
<td>2012-22</td>
<td>oven</td>
<td>6.16</td>
<td>0.65</td>
</tr>
<tr>
<td>2012-23</td>
<td>air</td>
<td>26.83</td>
<td>2.82</td>
</tr>
<tr>
<td>2012-19</td>
<td>partial sub. in water</td>
<td>206.46</td>
<td>21.68</td>
</tr>
<tr>
<td>2012-20</td>
<td>partial sub. in water</td>
<td>58.53</td>
<td>6.14</td>
</tr>
<tr>
<td>2012-25</td>
<td>full sub. in water</td>
<td>66.06</td>
<td>6.94</td>
</tr>
<tr>
<td>2012-26</td>
<td>full sub. in water</td>
<td>61.41</td>
<td>6.45</td>
</tr>
</tbody>
</table>
Table 5.4. This table shows each experiment, the thermocouple that made the reading, and the maximum averaged heat flow. This number was calculated by finding the maximum change in temperature per second in each thermocouple, averaging that value with the previous and next change in temperature values, and then accounting for heat capacity and mass to arrive at the J s⁻¹, or heat flow, of the experiments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Thermocouple</th>
<th>Cooling Mechanism</th>
<th>Maximum Averaged °C s⁻¹ ((\frac{\partial T}{\partial t}) Cooling Rate)</th>
<th>Maximum Averaged J s⁻¹ (Heat Flow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012-21</td>
<td>1</td>
<td>oven</td>
<td>-0.08</td>
<td>-0.83</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>oven</td>
<td>-0.08</td>
<td>-0.81</td>
</tr>
<tr>
<td>2012-22</td>
<td>1</td>
<td>oven</td>
<td>-0.61</td>
<td>-6.11</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>oven</td>
<td>-0.08</td>
<td>-0.80</td>
</tr>
<tr>
<td>2012-23</td>
<td>1</td>
<td>air</td>
<td>-2.6</td>
<td>-26.54</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>air</td>
<td>-2.4</td>
<td>-24.70</td>
</tr>
<tr>
<td>2012-24</td>
<td>2</td>
<td>air</td>
<td>-6.2</td>
<td>-62.52</td>
</tr>
<tr>
<td>2012-19</td>
<td>1</td>
<td>partial sub.</td>
<td>-14.5</td>
<td>-145.51</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>partial sub.</td>
<td>-12.9</td>
<td>-129.84</td>
</tr>
<tr>
<td>2012-20</td>
<td>1</td>
<td>partial sub.</td>
<td>-15.3</td>
<td>-154.78</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>partial sub.</td>
<td>-20.5</td>
<td>-207.05</td>
</tr>
<tr>
<td>2012-25</td>
<td>1</td>
<td>full sub.</td>
<td>-18.0</td>
<td>-181.21</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>full sub.</td>
<td>-24.3</td>
<td>-245.25</td>
</tr>
<tr>
<td>2012-26</td>
<td>1</td>
<td>full sub.</td>
<td>-17.3</td>
<td>-172.64</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>full sub.</td>
<td>-32.8</td>
<td>-327.83</td>
</tr>
</tbody>
</table>
Figure 5.7. A shows experiment 2012-21, with a starting temperature of 700°C. B shows experiment 2012-22, with a starting temperature of 800°C. Both samples were cooled at a rate of approximately 5°C per minute down to 400°C. The cooling rate was not perfectly constant, as shown by the small inflection points in both graphs, but was close enough for the purposes of these experiments. The maximum cooling rate is shown for each thermocouple, with the numbers 1 and 2 labeling each thermocouple, and showing approximately where the maximum cooling rate occurred during the experiment. As shown by these two experiments, with a sufficiently slow cooling rate, the temperature difference between the center and edge of the samples is negligible. Neither of these experiments produced columnar joints. Inset shows location of thermocouples.
Figure 5.8. A shows experiment 2012-23, with a starting temperature of 700°C. B shows experiment 2012-24, with a starting temperature of 800°C. Both samples were cooled via forced air convection, with a household fan on its highest setting blowing air past the sample as it sits on a cut rock slab. The numbers 1 and 2 label each thermocouple, and show approximately where the maximum cooling rate occurred during the experiment. A shows that the cooling did not start from exactly 700°C, but was close enough that the results are still valid. In B, Thermocouple 1 was exposed to the atmosphere and did not produce viable results, so was excluded. Inset shows location of thermocouples.
Figure 5.9. A shows experiment 2012-19, with a starting temperature of approximately 700°C. B shows experiment 2012-20, with a starting temperature of approximately 800°C. Neither of these samples started at exactly the specified temperature, but the difference in both cases is negligible. Both samples were cooled via partial submersion in convecting water with a temperature of approximately 3°C. The numbers 1 and 2 label each thermocouple, and show approximately where the maximum cooling rate occurred during the experiment. Inset shows location of thermocouples. Thermocouple 1 was closer to the edge of the sample in experiment 2012-19, but this thermocouple broke after the experiment, and as it was replaced the relative locations of the thermocouples changed, which is why thermocouple 2 experienced a higher cooling rate in experiment 2012-20.
Figure 5.10. A shows experiment 2012-25, with a starting temperature of 700°C. B shows experiment 2012-26, with a starting temperature of 800°C. Both samples were cooled via complete submersion in convecting water with a temperature of approximately 3°C. The numbers 1 and 2 label each thermocouple, and show approximately where the maximum cooling rate occurred during the experiment. Inset shows location of thermocouples. Thermocouple 2 was closer to the edge of the sample, and experienced a higher cooling rate in both experiments.

Subtracting each temperature reading from the previous temperature reading, a crude derivative of the temperature can be taken. The thermocouples take temperature readings once per second, so this produces the change in temperature per second. There was a large difference in the change in temperature
values from reading to reading. Because of this, the maximum °C s⁻¹ values were averaged with the previous and next value. Once the heat capacity and mass of each sample (the heat capacity and mass of the crucible is ignored) is taken into account, the resulting units are in J s⁻¹, also called heat flux (Table 5.4).

According to the thermocouple readings, the forced air convection cooled experiments all had approximately 25 times higher heat flow than the furnace cooled experiments. The water cooled experiments, both partially and fully submerged, had heat flows between 6 and 13 times as large as the forced air experiments.

![Maximum Temperature Difference](image)

**Figure 5.11.** Maximum difference in temperature between two thermocouples within the samples during cooling. Legend shows the different means by which the samples were cooled. With the exception of Experiment 2012-19, which experienced an anomalously large temperature difference between the two thermocouples for reasons unknown, there is a correlation between cooling medium and maximum temperature difference. Oven and air cooled experiments had lower temperature differences, while water cooled experiments had higher temperature differences.
Figure 5.12. Maximum averaged cooling rate. The chart shows the change in temperature in seconds of each experiment. Colors match those in previous figures, with blue representing thermocouple 1 and green thermocouple 2. Oven cooled samples experienced the least temperature change per second, with partially and fully submerged samples experiencing the greatest. There is less difference between the partially and fully submerged samples as there is between the other samples, but there is still a slight increase from partially to fully submerged. Dashed line shows general increase in rate of temperature loss for the different cooling methods.

5.3. Discussion

5.3.1. Joint Formation

The major findings of these experiments are first, that it is possible to synthesize columnar joints, and second, to narrow down the possible conditions under which joints form. Experiments like these, on this small scale, have never been attempted before, and the results are promising. Though perfectly formed hexagonal columns are not produced from the experiments, the formation of columnar joints is an excellent starting point for further experiments.

Many of the joints formed, propagate perpendicular to the cooling surface (the crucible wall). This matches with what others have hypothesized about the formation of columnar joints, and matches with numerous field observations as well. Not all joints propagate in this way, and this is most likely due to two reasons. The effects of the small size of the samples and the high thermal gradients and
cooling rates within the samples are one possibility. With gradients on the order of 7 °C mm⁻¹ and cooling rates up to approximately 32.8 °C s⁻¹ in the water cooled samples, it is expected that the joints are not perfectly organized. The other possibility is that because joints propagate such that they commonly intersect free surfaces perpendicularly (e.g., Dyer, 1988; Rawnsley et al., 1992; Gross, 1993), later joints are influenced by earlier joints, and may cause the later joints to curve during propagation and intersect the earlier joints.

Columnar joints do not form in all of the experiments. This is because joints only form within a certain range of cooling conditions and thermal gradients. In the textural experiments conducted, joints only form within the water cooled experiments (in both partially and fully submerged samples). From the gradient experiments, this is equivalent to a thermal gradient of between approximately 6 and 7 °C mm⁻¹ and cooling rates of between approximately 12.9 to 32.8 °C s⁻¹. When exposed to these cooling conditions, columnar joints are able to nucleate and propagate. When the cooling rate is below approximately 12 °C s⁻¹ (Fig. 5.13), or when these cooling rates do not occur through the column formation temperature, joints do not form.

With regard to an upper limit on the thermal gradient or cooling rate, the data from these experiments are inconclusive. As mentioned above, preliminary experiments in which samples cooled immediately from 1000°C to room temperature turned completely to glass and did not create any joints. However, it is not clear whether this was because the thermal gradient and cooling rate of these experiments was too high, or simply because the synthetic basalt was still too low in viscosity, and the appropriate amount of tensile stress was not generated. It is also possible that some degree of heterogeneity, achieved through crystallization, was required to nucleate jointing. However, because of the “cone of depression” that formed in these samples (Fig. 6.9) it is likely due to the lack of tensile stress, rather than too high cooling rates or lack of crystals, that the samples did not form joints. Because of this, these experiments cannot define an upper limit of thermal gradients or cooling rates that produce columnar joints. However, they do show that for samples of this size (cylinders 25 mm high with 25 mm diameter), the lower
boundaries for columnar joint formation are between 3 and 6 °C mm⁻¹ for thermal gradients, and between approximately 25 and 130 J s⁻¹.

![Graph showing joint formation conditions](image_url)

Figure 5.13. Joint formation conditions. All experiments plotted in cooling rate vs. thermal gradient space. Experiments are split into two groups, joint forming and non-joint forming. The exact contact between the joint forming and non-joint forming conditions cannot be exactly specified, because there is a range of parameters that the experiments did not investigate, due to limitations of the experimental setup. Thus there is a section where joint formation is possible, but the exact conditions defining the boundary are unknown. It is also unknown exactly how the thermal gradient and cooling rate relate to each other, and how the thermal gradient relates to joint formation, so the boundaries between the groups are drawn only with respect to the cooling rate.

### 5.3.2. Comparison of Experimental and Modeled Temperature Profiles

The small sample size of the experiments makes direct comparison of the models and experiments difficult, but some comparisons can still be made.

The experiments do not show many curving columnar joints, and the ones present do not extend continuously very far. This is again a limitation due to the small sample size. Since the crucibles are only 25 mm in diameter, the joints do not have enough time during cooling to be influenced by more than one boundary.
Despite these limitations, the thermal gradients of the experiments can still be compared to those of the forward models. By finding the temperatures on the edge and in the center of a model that is 19 mm high by 25 mm wide (the average cross sectional dimensions of the experiments), thermal gradients can be calculated and compared to those experimentally determined.

Two different $h$ factor values were used for the models. 70 W m$^{-2}$ °C$^{-1}$ (from Keszthelyi and Denlinger (1996)) and 1000 W m$^{-2}$ °C$^{-1}$ (modified from Recktenwald (2006)) were used to represent cooling via forced air convection and complete submersion in water, respectively. Each of these models was evaluated at 15, 30, and 60 seconds after emplacement for the temperature at the edge of the cooling surface and in the middle of the model. These temperature differences were then divided by the distance between the two points to calculate the thermal gradient. Table 5.5 shows the results of the models.

The modeled thermal gradients are much higher than those measured in the experiments. The only experiment that comes remotely close to any of the models is experiment 2012-25, a fully submerged sample, with a thermal gradient of 6.94 °C mm$^{-1}$. However this model was supposed to represent the forced air convection experiments, so none of the models can be validly compared to the experiments.

There are two definite and several possible reasons for the differences between the experimental thermal gradients and the modeled thermal gradients. The models use the exact center and the extreme edge temperatures to create the gradients, while the thermocouples use the bottom edge (which is still bounded by the crucible) and a point 9.5 mm away from that edge, which should be in the center of the sample, but it is not guaranteed to be in the exact center. Both of these issues cause the experimental gradients to be lower than the modeled gradients. Other possible reasons include various operator errors due to the small sample size, and enhanced heat dissipation due to cracking or a permeability network within the experimental samples that homogenizes the temperature profile of the samples.

Table 5.6 shows the thermal gradients calculated from an outcrop-sized flow, 3 meters thick. Again, the temperatures at the edge and the center of the flow were
taken at two different times during the cooling history. One is from the early history of the flow, while the second is after the entire flow is below the column formation temperature. Though no experiments of comparable size were undertaken in this study, the furnace cooled experiments have similar thermal gradients, at .66 and .65 °C mm⁻¹, to two of the modeled thermal gradients from the 180,000 second mark, .69 and .71 °C mm⁻¹.

Though no conclusive interpretations can be made using the comparison of experimental versus modeled thermal gradients, better techniques in the future may enable better agreement between models and experiments.

Table 5.5. Two forward models were evaluated at three different times throughout the cooling process. The two models had two different $h$ factor values, 70 W m⁻² °C⁻¹ and 1000 W m⁻² °C⁻¹, representing cooling by forced air convection and complete submersion in water, respectively. The difference in temperature between the edge and the center of the models was then divided by the distance between the points to solve the thermal gradient at that time.

<table>
<thead>
<tr>
<th>$h$ factor (W m⁻² °C⁻¹)</th>
<th>$T_\infty$ (°C)</th>
<th>Time (s)</th>
<th>Gradient (°C mm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>25</td>
<td>15</td>
<td>9.58</td>
</tr>
<tr>
<td>70</td>
<td>25</td>
<td>30</td>
<td>10.95</td>
</tr>
<tr>
<td>70</td>
<td>25</td>
<td>60</td>
<td>10.74</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
<td>15</td>
<td>56.00</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
<td>30</td>
<td>48.21</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
<td>60</td>
<td>30.63</td>
</tr>
</tbody>
</table>

Table 5.6. Two forward models of outcrop-sized flows were evaluated at two times during the cooling period, one close to the beginning of the cooling, and one after the entire flow had cooled past the column formation temperature, specified as 800 °C for these models.

<table>
<thead>
<tr>
<th>$h$ factor (W m⁻² °C⁻¹)</th>
<th>$T_\infty$ (°C)</th>
<th>Time (s)</th>
<th>Gradient (°C mm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>25</td>
<td>180,000</td>
<td>0.69</td>
</tr>
<tr>
<td>70</td>
<td>25</td>
<td>900,000</td>
<td>0.41</td>
</tr>
<tr>
<td>1000</td>
<td>25</td>
<td>180,000</td>
<td>0.71</td>
</tr>
<tr>
<td>1000</td>
<td>25</td>
<td>900,000</td>
<td>0.41</td>
</tr>
</tbody>
</table>

5.3.3. Limitations of Experimental Setup

Though the high temperature experiments display excellent examples of Mode I tension cracks within synthesized basalts, there are some limitations to the setup. One of these limitations is the size of the samples. The small size of the
samples necessitated small columns. High cooling rates were necessary to form the small columns. With such high cooling rates, the cooling mediums available were limited. In the future, using larger crucibles and different cooling mediums to explore a larger range of thermal gradients and cooling rates could lead to new insights into the formation of columnar joints.
6. Discussion & Conclusion

6.1. Fit of Models to Outcrops

The comparison of the forward models with the observations gathered from the four outcrop areas provides insights into the mechanisms for heat dissipation and the unique cooling histories of the outcrops.

Immediately after emplacement of the lava flow, the difference in temperature between the flow and the surrounding environment creates extremely high cooling rates and thermal gradients. The large cooling rates cause the lava to cool past the glass transition temperature extremely quickly, too quickly for any crystallization to occur.

The transition from liquid to glass is a second-order phase transition, and there is no volume change associated (Turnbull and Cohen, 1961). Physical properties change during the liquid to glass transition, including the thermal expansion and specific heat values (Turnbull and Cohen, 1961), but there is no volume change associated with the phase transition itself. The only volume change that occurs is due to the specific volume-temperature relationship; a decrease in temperature causes a decrease in volume, as is true with most materials. Because of this second-order phase transition, quenching of the exterior shell of the lava flow produces glass, but no tensile stresses due to phase transition.

Once glass forms on the exterior of the flow, the interior slowly crystallizes and decreases in temperature, both of which cause the volume to decrease. Lacking a viscous, free surface on the upper boundary of the lava flow to help accommodate viscous flow and volume decrease, tensile stress builds up, eventually exceeding the tensile strength of the material, at which point columnar joints form in response. Since the cooling flow is a mixture of both crystals and melt, the formation of the columnar joints is still contingent upon the stresses from the volume decrease of the material exceeding the viscous relaxation timescale of the cooling melt. Only through this mechanism will tensile stresses increase until the tensile strength of the material is exceeded.
This explanation is supported by earlier high temperature experiments. The rapid cooling of high temperature lava does not form columnar joints, but simply forms glass. As described by other workers (e.g., Peck and Minakami, 1968; Long and Wood, 1986), cooling basaltic flows often form a glassy carapace on the outer edge of the flow. Columnar jointing, though sometimes present on the surface, is not organized into columns until further into the interior of the flow (Peck and Minakami, 1968).

The outcrops studied clearly show that columns are affected by the boundary conditions present during the emplacement and cooling of the flow. The characteristics most affected are the location of the column interface, the width of the columns, and the direction of column propagation.

Macroscopic structures, including the column interface, as well as curving and coalescing columns, predicted by the numerical models are observed in the Whistler field area outcrops. The column interface is present in several outcrops, including Railroad Quarry outcrop 1 (Fig. 6.1) as well as the western Daisy Lake outcrop (Fig. 6.2). The outcrops, unlike the numerical models, are not perfectly rectangular in cross section, so the interface is not completely horizontal along the entire outcrop, but it is roughly parallel to the upper and lower boundaries in both outcrops.

The same western Daisy Lake outcrop and Railroad Quarry outcrop 1 show a difference in column diameter due to cooling rate, also in agreement with the models. In both outcrops, the columns in the upper colonnade have a smaller diameter than those in the lower colonnade. This stems from the different boundary conditions on the top and bottom of the flows. With lower heat flow and a lower cooling rate, the lower colonnade produced columns with larger diameters. High heat flow and a higher cooling rate on the upper boundary produced narrower columns in the upper colonnade.

Curving and coalescing columns are seen particularly well on the eastern side of Railroad Quarry outcrop 6 (Fig. 6.3). The columns change from vertical to nearly horizontal within a short distance. This is predicted in the models, and the changing geometry of the columns is depicted in Figs. 4.3 and 4.7. Also predicted in
the models, and depicted schematically in the same figures, is the coalescing of columns. Not all columnar joints are continuous from the edge of the flow to the center, and cessation of some of these joints causes multiple columns to merge together. This is visible in the foreground of Fig. 6.3.

Figure 6.1. Western face of outcrop 1 of the Railroad Quarry area. The non-planar upper and lower surfaces of the outcrop are visible, and may contribute to the thicker than average lower colonnade.

Figure 6.2. Daisy Lake West outcrop showing upper and lower colonnade, along with column interface zone (bounded by dashed lines).
All the columnar structures that involve curving columns are due to the interaction of more than one boundary condition. A completely linear column is influenced only by a single boundary. This is seen in outcrops modeled as an infinite slab near the center – the lateral edges have no effect on the columns, and all the jointing is due only to either the top or bottom boundaries. Whenever more than one boundary influences the formation of a column, that column will curve. Any curved column within an outcrop is due to the interaction of multiple boundaries during the formation of that column.

An important point related to reconstructing the boundary conditions is that columns can coalesce, but they can never diverge. As the cooling rate decreases on
the interior of the flow, tensile stresses decrease and columnar joints cease propagation. In order for divergence to occur, the interior of the flow would have to suddenly cool without changing the direction of heat flow, which is impossible. Thus, the direction of column coalescence will always be towards the interior of the flow, and is the same as the propagation direction.

Using the above characteristics and rules, it is possible to qualitatively reconstruct the boundary locations and cooling conditions at those boundaries from the column geometries. Relative rates of cooling and general locations of boundaries can be inferred on an outcrop scale, increasing the understanding of the flow in question.

Many of the outcrops have thicker upper colonnades compared to their lower colonnades. Cooling starts through both boundaries simultaneously, as does columnar jointing. If heat flow is higher through one boundary than the other, this causes the jointing front to propagate more rapidly towards the center of the flow. When both jointing fronts (one propagating up from the lower boundary, one down from the upper boundary) meet at the column interface, the vertical location of the interface within the flow (assuming an infinite or semi-infinite slab geometry) indicates the relative heat flow through the two boundaries.

However, since the temperatures within the flow are constantly in flux, and basalt (and all rocks in general) has a fairly high heat capacity of 850 J kg\(^{-1}\) °C\(^{-1}\) (Bouhifd et al., 2007), and a low thermal conductivity of 2 W m\(^{-1}\) °C\(^{-1}\) (Touloukian et al., 1989), the relationship between heat flow and location of column interface is not linear. Changing the boundary conditions on the forward models shows that in order to have the upper colonnade twice as thick as the lower, the upper boundary must have 25 times more effective heat loss than the lower boundary. As seen in Fig. 3.12, the upper colonnade of the eastern face of the Pinecrest outcrop is, on average, twice as thick as the lower colonnade. The numerical model in Fig. 6.4 has a convective heat transfer coefficient on the upper surface that is 25 times as great as that of the lower surface, and it matches well with the Pinecrest outcrop. The model cannot predict the exact $h$ factor value for the outcrop, only the relative values of the two boundaries. But even without the model, looking at the relative
diameters of the columns in the upper and lower colonnades it is obvious that there was a great discrepancy in cooling rates.

In other outcrops, such as the western face of the Daisy Lake outcrop (Fig. 6.5), the column interface is 40% up from the lower boundary (it would be 50% for equal amounts of heat flow). The semi-infinite slab model in Fig. 6.5 shows an example of this type of outcrop, with two different $h$ factor values. The value for the lower boundary is 3, while the value for the upper boundary is 25, which is 8.3 times that of the lower boundary. The column interface for this model is located 42% up from the lower boundary. This shows that the amount of heat lost through the upper boundary of a flow must be significantly greater, approximately 8 to 9 times greater, than the heat lost through the lower boundary in order to have a significant effect on the location of the column interface.

Another influence of this non-linear relationship between heat and change in flow structure is seen in the relationship between the planarity of the flow base and the column interface. The western face of the Railroad Quarry outcrop 1 shows a very planar column interface despite an undulating flow bottom, with one particularly high amplitude change in the flow bottom geometry (Fig. 6.6). However, this change in flow bottom geometry does not have an effect on the location of the column interface within the outcrop. A model of similar geometry to this outcrop (Fig. 6.6) shows that a modeled change in flow bottom geometry also has very little effect on the location of the column interface. This is partially due to averaging effects of the overall lower boundary, but also likely due to the large heat capacity and low thermal conductivity of rock. Any deviations from a planar surface have minimal impact on the column interface, simply because the effects are quickly reduced by the surrounding material. This reduces the effect that small wavelength changes in the boundaries have on the column interface, even if these changes are quite large in amplitude. This further shows that the models accurately represent the cooling lava flows.

There is a limit to the effective amount of heat that a flow can lose during a given time. Beyond a certain $h$ factor value, there is no additional cooling effect on the flow. This is because the thermal diffusivity of the flow is the limiting factor,
rather than the cooling efficiency of the bounding medium. Fig. 6.7 shows that for $h$ factors of 6000 and 1000, there is no appreciable change in lava temperature. Fig. 6.8 shows that below an $h$ factor of 70 is when changing $h$ factor values start to affect the internal temperature of the flow over a given time of 900,000 seconds, or 10.4 days. The difference is slight, but measureable. See Appendix A for comparison of all $h$ factor values for a single model with identical boundary conditions.

One possibility for the large disparity between the heat flow from the top and bottom colonnades could be due to a “permeability network” on the top surface. As the surface cools and forms cracks within the upper surface, fluids are able to penetrate the sub-millimeter vacancies and accelerate cooling via convection. Even with only air present the cooling will be accelerated, but if water is present, the cooling of the flow will increase dramatically. As the flow continues to cool and the cracks propagate further, the fluids also extend deeper into the flow and continue to accelerate cooling. This produces a positive feedback loop, which continues until the quickly cooling upper colonnade intersects the lower colonnade. Thus the top surface is able to release a much greater amount of heat than the lower surface, partly due to the boundary conditions, but also due to the convective cooling through this permeability network.

6.1.1 Paleoenvironmental Conditions Based on Column Geometries

The difference in column diameters in the upper and lower colonnade, as well as the unequal proportions of upper and lower colonnades in many of the outcrops, definitively show that the boundary conditions are not identical for all sides of the outcrops. However, they do not define exactly what the boundary conditions are. The relative size and orientation of columns within the outcrops give clues to the boundary and paleoenvironmental conditions into which these flows erupted.

For both the eastern Pinecrest outcrop (Fig. 3.10) and the western face of the Daisy Lake outcrop (Fig. 6.2), the upper colonnade is much thicker, up to twice as thick, as the lower colonnade. Based on numerical modeling, the heat flow through the upper boundary may have to be as high as 25 times the heat flow through the
lower boundary in order to create such differences in colonnade thicknesses. While lower differences in heat flow may be explained simply by convective atmospheric cooling on the upper boundary, a difference of 25 times is more likely due to additional factors, such as water infiltration along joint surfaces. This implies that either there was ice that was melted and flowed along the top, but not the bottom, of the lava flow, or that the flow was precipitated upon.

Railroad Quarry outcrop 6 is unique among the outcrops in this study, in that it forms a cliff tens of meters high, and while the lower section of the outcrop is composed of large, vertical columns, the upper section is composed of narrow, horizontal columns (Fig. 6.3). No colonnade interface is seen in this outcrop, as the lower columns simply seem to change propagation direction from vertical to horizontal. The most likely explanation for the formation of this outcrop is that the flow was impounded against ice in the valley. This could give extremely high cooling rates on the lateral flow boundary, due to meltwater, while conceivably the lower boundary of the flow experienced more typical slow, conductive cooling into the ground surface. If the original contact with the valley ice eroded away (which it likely would, since most rapidly cooled flow boundaries are brittle, glassy, and fragile), this could leave an outcrop where the columns propagating upwards from the lower boundary meet columns propagating inwards from the lateral boundary, similar to a section of the slab corner forward model (Figs. 4.2 & 4.6). The curving columns are certainly due to the interaction of two boundaries, but the difference in diameter of the columns involved points to boundaries with vastly different cooling rates.

### 6.1.2 Rules for Columns

All these observations lead to a set of “rules” for column formation. These are a set list of principles that, based on the above evidence and previous work, columnar joints “follow.”
1. **Columns form parallel to heat flow**

As lava flows cool, they decrease in volume. In an infinite slab model, the vertical aspect of this volume change can be accommodated by viscous flow of the still warm interior. However, the horizontal aspect of the volume change cannot be accommodated by viscous flow, since all the surrounding material is brittle as well. Thus tensile joints form, and as the cooling front propagates into the interior of the flow, so do the columnar joints. Thus columnar joints propagate parallel to heat flow. This rule is often misstated as “columns form perpendicular to the cooling surface.” While this is often true near the boundaries of flows, the presence of curving columns within both the models and outcrops, which form parallel to heat flow and *not* perpendicular to the cooling surface, shows that this statement is not true.

2. **Column diameter is inversely proportional to cooling rate**

As covered in Chapter 2, quicker cooling creates columns with smaller diameters. Though quantitative data are not available for prescribing an exact cooling environment based on a specific column diameter, columns under 10 cm in diameter generally indicate extremely rapid cooling, perhaps by water, while columns over a meter in diameter generally indicate slow cooling, possibly through a non-convective boundary, such as underlying rock.

3. **Extremely rapid cooling forms poorly-organized columns**

During high rates of cooling, abundant thermal stresses keep columns from becoming well-organized. With high thermal stresses, the joints propagate so quickly that there is no need to conserve energy, and the joints remain four-sided and somewhat chaotic. This was evident in the high temperature experiments in Chapter 5, and the lack of organized columns. With slower cooling rates and slightly less thermal stress, there is more time between increments of joint formation, and the system finds the most energetically effective direction in which to fracture. Because hexagons necessitate the least amount of energy to form, slower cooling rates form hexagonal columns.
4. **Columns form in discrete time steps**

   It is important to remember that columnar joints do not all form simultaneously; they form over a period of time. This gives the environment time to change during the formation of the columns. An example of this would be if a flow starts cooling and forming columnar joints, and at some later time, the surface of the flow is inundated with water, which travels down already formed joints. This would cause a drastic change in both the cooling rate and cooling boundaries of the flow, forming a set of columns with different diameter and trends in the interior of the flow. The only way to explain this is through the transient nature of columnar jointing.

5. **Columns only coalesce, never bifurcate**

   Column diameter is inversely proportional to the cooling rate, as mentioned above, and a consequence of this rule is that columns can only coalesce. As the cooling rate decreases within the interior of a flow, columns begin to increase in diameter, and thus joints will terminate, and cause columns to coalesce. In order to have columns that bifurcate, the cooling rate would need to increase on the interior of the flow, without changing the cooling boundaries. This is not possible, so the idea of bifurcating columns can be ruled out. The cooling rate can be increased in an already cooling flow, but this necessarily changes the cooling boundaries. For example, water influx can occur along already formed columnar joints and increase the cooling rate of the interior of the lava flow, but this causes the cooling boundary to change from the top of the flow to the columnar joint surfaces. This would cause new joints to form, and though they would be smaller in diameter, they would be completely different joints. The older joints still would not bifurcate.

6. **Columns curve only when affected by multiple boundaries**

   If only one boundary defines the cooling history for a given set of columns, those columns will all have perfectly linear geometries. This is because the heat flow will be perpendicular to the cooling boundary, and with no other boundaries affecting the direction of the heat flow, the columns will not curve.
If more than one boundary is present, this will cause the thermal gradient isograds to curve. Since the heat flow is perpendicular to the isograds, this causes the heat flow vectors to curve, and thus the columns will curve as well. Curving columns are visible in outcrops such as the western face of Railroad Quarry outcrop 1, the southeastern face of Railroad Quarry outcrop 3, and the eastern face of Railroad Quarry outcrop 6. These outcrops all indicate multiple cooling boundaries affecting the column formation geometry.

![Diagram](image.png)

Figure 6.4. The upper boundary of this model has an $h$ factor value of 25, while the lower boundary has an $h$ factor value of 1. With a convective heat transfer value 25 times greater on top, this enables the upper colonnade to be more than twice as thick as the lower colonnade. Model run time is 1260000 s.
Figure 6.5. The upper photo is of the western face of the Daisy Lake outcrop. It shows a section of that face where the upper colonnade is approximately 60% of the thickness of the flow. This locates the column interface 40% of the way up from the flow bottom, indicated by the dashed line. The forward model is based on this outcrop, and has differing boundary conditions on the top and bottom that cause the column interface to occur 42% of the way up from the lower boundary. The $h$ factor value for the upper boundary is 25, and the $h$ factor value for the lower boundary is 3. Model run time is 900000 s.
Figure 6.6. Top image is a panorama of the western face of Railroad Quarry outcrop 1. Dashed lines show the bottom flow boundary and the column interface. The black arrow shows a high amplitude change in the flow base boundary geometry, but there is no change in the column interface geometry above that location. The bottom image is a model of the same outcrop, with a dashed line showing the location of the column interface. Despite the large change in flow bottom geometry, the location of the column interface does not change significantly. The boundary conditions for the model were h=20, T=25°C on top; h=60, T=1°C on the sides; h=3, T=25°C on bottom. The arrows in this model do not accurately depict the heat flow at the column formation temperature, so the size of the arrows should be disregarded, but they do still show the column formation direction. Model run time is 720000 s.
Figure 6.7. The top model has an $h$ factor value of 6000, while the bottom model has an $h$ factor value of 1000. These models were run for identical times (900,000 seconds, or 10.4 days), and there is no difference in temperature profiles between the two (arrows), despite the large difference in $h$ factor values. The cooling rate is limited by the thermal diffusivity of the flow itself.
Figure 6.8. Top forward model has $h$ values of 70 on all sides, whereas the bottom forward model has $h$ values of 25 on all sides. The models were run for identical amounts of time (900,000 seconds, or 10.4 days), and there is a small, but measureable difference in the maximum temperature of the models, as shown by the location of the 600 °C marker on the temperature scale on the right of the models (arrows). Comparing models with $h$ values above approximately 100, there does not seem to be a difference between temperature profiles in the models.
6.2. **Summary of Experiments**

The textural experiments in this thesis demonstrate that it is possible to synthesize joints within laboratory settings. These joints are interpreted as thermal contraction joints, directly comparable to the columnar joints found in flows and intrusions of various compositions around the world.

The joints in the experiments generally form perpendicular to the cooling surfaces, but the joints are not as well organized as those usually found in nature. The best explanation for this is that, due to the small size of the samples, and the necessity of extremely high cooling rates in order to produce the required thermal gradients, the heat flow vectors within the samples were never organized into a regular geometry. Rapid temperature changes did not allow the samples to settle into organized temperature profiles like those shown in the forward models. Instead, the thermal stresses inside the samples were so large and poorly organized that the cooling material simply jointed in the direction that would relieve the most stress, even if the joint did not break parallel to the heat flow direction at that point.

Despite the lack of well-organized joints, both the textural and thermal gradient experiments allow some interesting conclusions to be made. As shown by the textural experiments, not all cooling conditions produce columnar joints. In general, high cooling rates produce joints, while low cooling rates do not, especially in the small sample sizes used in this study (approximately 10 mL). This is corroborated by the thermal gradient experiments. The experiments that experienced the lowest cooling rates, the oven and air cooled experiments, did not produce columnar joints, while the water cooled experiments, with the highest cooling rates, did produce columnar joints.

According to the thermocouple experiments, the experiments that generally formed columnar joints (those fully and partially submerged in water) had internal thermal gradients of between 6.14 and 6.94°C mm⁻¹, and cooling rates of between 12.9 and 32.8 °C s⁻¹. The air-convection and oven cooled experiments had much lower thermal gradients and cooling rates, on the order of less than 1 up to 3°C mm⁻¹, and cooling rates ranging from .08 to 2.6 °C s⁻¹. Thus, of the experiments
carried out in this study, only experiments with thermal gradients between 6 and 7°C mm⁻¹ and cooling rates between 12.9 to 32.8 °C s⁻¹ were able to form columnar joints. This link between columnar joint formation and both the thermal gradient and cooling rate is obviously dependant on the size of the sample, since jointed flows found in nature must have experienced less extreme thermal gradients.

Though the experiments show that a certain thermal gradient is required during cooling to produce columnar joints, just as important as the magnitude of the gradient is the temperature at which it occurs. As mentioned in Chapter 4, early experiments that were removed from the furnace at 1000°C and immediately quenched did not produce columnar joints, but rather turned completely to glass, and accommodated change in temperature by viscous flow, forming a “cone of depression” (Fig. 6.9). Without measurements, the thermal gradients in these early experiments cannot be quantified, but it is safe to assume that because the conditions of cooling were the same, the gradients are similar to those of the water-cooled thermal gradient experiments. So despite the fact that the cooling conditions were the same, because the starting temperature was dissimilar, columnar joints did not form.

The starting temperature for the experiments had to be at a subliquidus temperature, due to the nature of the relationship between the rate of cooling and the relaxation timescale. High temperature lavas, even when cooled very quickly, remain above the column formation temperature (or glass transition temperature – they are similar) for long enough, while the timescale of relaxation is still short enough, that most of the volume loss is accommodated through viscous flow, and no joints form. Also, since it is a second-order phase transition, there is no volume loss associated with the transition from melt to glass.

Even though at lower starting temperatures some volume loss has already occurred, when the melt and crystal mixture is cooled quickly from the lower temperatures, the relaxation timescale is somewhat longer. As the sample cools, there is no low viscosity free surface to accommodate viscous flow, and the relaxation rate is longer than the cooling rate. Thus, tensile stress accumulates, and columnar joints form in response.
Another reason for the lower starting temperature for the experiments is to have a non-zero percentage of crystals mixed in with the melt. Crystals have much higher thermal expansion values than glass does, so while glass may not change much in volume with a decrease in temperature, the crystals within the cooling material will. According to Austin (1952), quartz has a thermal expansion coefficient of approximately $83 \times 10^{-6} \, ^\circ C^{-1}$ between 0 and 600°C, while Arndt and Häberle (1973) show that synthetic glasses with plagioclase-like compositions have thermal expansion coefficients of between 6 and $7 \times 10^{-6} \, ^\circ C^{-1}$ given temperatures from 20 to 600°C. These measurements are below the glass transition temperature, and there is a discontinuous change in thermal expansion at the glass transition temperature. Though quartz is not found in abundance in the synthetic basalts in this study, these values show that minerals can contract greater than 10 times as much as the non-crystal matrix of the material. This could have a large effect on the tensile stress buildup in the experiments, and in natural lava flows in the field.

The best explanation for this temperature dependency is that column formation is not only dependent on the thermal gradient and cooling rate of the material at the column formation temperature, but is also dependent on the viscosity of the material when the required thermal gradient is present. If, in these experiments, the required 6-7°C mm$^{-1}$ thermal gradient occurs while the temperature is too high, around 1000°C, the cooling material still have a very low viscosity, and be able to accommodate much of the change in volume by viscous flow. If the thermal gradient remains the same down to the column formation temperature, the thermal stresses required may not be present, since much of the stress has already been reduced by viscous flow.

The conclusion reached from the experiments is that a specific thermal gradient and cooling rate is required for columnar joints to form, and in the case of these samples the required gradient was found to be between 6 and 7°C mm$^{-1}$, and the required cooling rate to be between 12.9 and 32.8 °C s$^{-1}$. However, this gradient also needs to occur within a specific temperature range for the joints to form, which was approximately between 700 and 800°C. Below the required thermal gradient, or outside the correct temperature range, columnar joints will not form.
Figure 6.9. The photograph on the right shows experiment 2012-26 with the so called "cone of depression," while the schematic on the left shows a cross sectional view of the sample. The glassy surface of the sample makes informative photos difficult to obtain. The surface of the sample slopes down towards the center, where it comes to a blunted point. The schematic is drawn to scale, and there is no vertical exaggeration of the slope of the cone in the figure. Experiment 2012-26 was quenched specifically for this photograph, and did not have this form during the actual thermal gradient experiments.

6.3. Further Work

This thesis has an experimental program that shows what thermal gradients and cooling rates form columnar joints in a certain sample size, but this can be improved upon with further work. An expanded experimental grid, containing a range of larger sample sizes, would allow slower cooling rates to be used, since the columns would not need to be created on such a small scale. In addition, a larger range of starting temperatures would better define the upper and lower limits on the column formation temperature. This would give a better indication of what conditions columnar joints form under.

The forward modeling could also be improved, taking more variables into account, such as the heat of crystallization and tensile stresses in the cooling flow. It could also be modified to model a three-dimensional flow. However, any of these additions would require an enormous amount of coding and a high degree of skill, and is beyond the scope of this thesis.
Though the Whistler field area has a range of well-preserved columns with a large variety of flow boundary geometries, a different field area may give more insights. A larger number of outcrops, with perhaps simpler geometries, could allow comparison of small differences within the outcrops, and perhaps tease out smaller scale effects of boundary conditions on columnar joint formation.
References


Raspe, R.E., 1776. An account of some German volcanos, and their productions. With a new hypothesis of the prismatic basaltes; established upon facts. Being an essay of physical geography for philosophers and miners. Published as supplementary to Sir William Hamilton’s observations on the Italian volcanos. Lockyer Davis, London.


Appendix A – Forward Models

This appendix has a number of forward models with various $h$ factors on the boundaries. They show the effects the different $h$ factor values have on the temperature profiles. Each model in this section was run for 900,000 seconds, and the size of the flow and all physical properties remain the same for all models.

Figure A.1. Model has $h$ factor value of 6000.
Figure A.2. Model has $h$ factor value of 1000.

Figure A.3. Model has $h$ factor value of 100.
Figure A.4. Model has $h$ factor value of 70.

Figure A.5. Model has $h$ factor value of 25.
Figure A.6. Model has $h$ factor value of 10.

Figure A.7. Model has $h$ factor value of 1.
Appendix B – MATLAB Code

Most of the forward models used a Matlab Toolbox add-on, called the Partial Differential Equation Toolbox. This is a GUI interface in which the user can create shapes, set boundary conditions and PDE coefficients and parameters, and solve for a given amount of time. The entirety of this code will not be presented here, but the specifics used for the majority of the forward models, along with other MATLAB codes used, are presented.

B.1. Finite Slab

This code, when used in conjunction with the PDE Toolbox, creates and solves the finite slab forward model, with unique boundary conditions for the top, bottom, and lateral boundaries. For the semi-infinite slab, slab corner, and slab side models, one or more of the boundary conditions is changed so no heat escapes from that boundary.

```matlab
function pdemodel
[pde_fig,ax]=pdeinit;
pdetooll('appl_cb',9);
set(ax,'DataAspectRatio',[1 1 1]);
set(ax,'PlotBoxAspectRatio',[3 2 1]);
set(ax,'XLimMode','auto');
set(ax,'YLimMode','auto');
set(ax,'XTickMode','auto');
set(ax,'YTickMode','auto');

% Geometry description:
pderect([-5 5 1.5 -1.5],'R1');
set(findobj(get(pde_fig,'Children'),'Tag','PDEEval'),
'String','R1')

% Boundary conditions:
pdetooll('changemode',0)
pdesetbd(4,...
'neu',...
'100',...
'100*1')
pdesetbd(3,...
'neu',...
'3',....
'3*25')
pdesetbd(2,...
```

B.2. Thermal Gradient

To show the thermal gradient isograds, in addition to the heat flow arrows at the time of column formation, this code was used.
% Finds flowdata nearest to column formation temperature

% STEP 1
% SELECT 'EXPORT MESH' FROM 'MESH' MENU
%
% STEP 2
% SELECT 'EXPORT SOLUTION' FROM 'SOLVE' MENU

col=800;
% column formation temperature

ut=pdeintrp(p,t,u);
% turns node data u into triangle data ut for creating utx and uty vectors

flow=abs(col-ut);
flow(1,:) = NaN;
% sets emplacement temp space to NaN, otherwise find function gets confused

searchvector=zeros(size(flow,2),1);
% sets the searchvector size

for i=1:size(flow,2)
    searchvector(i)=find(min(flow(:,i))==flow,1,'first');
end
% Finds the point in space and time at which flow temperature is closest to
% column formation temperature and puts it into searchvector
% If more than one point is returned, it only places first point into
% searchvector

[ux,uy]=pdegrad(p,t,u(:,1));
% makes gradient of emplacement temperature (no gradient, only to find size
% of ux and uy)

ux(2:size(u,2),:) = 0;
uy(2:size(u,2),:) = 0;
% creates gradient matrix, filling rows 2:end with zeros

for i=2:size(u,2)
    [ux(i,:),uy(i,:)]=pdegrad(p,t,u(:,i));
end
% fills in rest of gradients through time

utx=zeros(size(searchvector,1),1);
uty=zeros(size(searchvector,1),1);

for i=1:size(searchvector,1)
    utx(i,1)=ux(searchvector(i));
    uty(i,1)=uy(searchvector(i));
end
flowdata=[utx,uty];
flowdata=flowdata';

% fills vectors utx and uty with heat flow direction at time of column
% formation

% CONTOURING HEAT FLOW GRADIENT

% convert triangle data to node data
if size(flowdata,2)==size(t,2)
    flowdata=pdeprtni(p,t,flowdata);
end

% Determine xy-grid from geometry:
xmin=min(p(1,t)); xmax=max(p(1,t));
ymin=min(p(2,t)); ymax=max(p(2,t));

% Set up gradient matrices, make sure that x and y directions match
% with
% the width and height of the flow - need (xmax-xmin)*na to create
% different delta lengths in x and y direction
na=(size(flowdata,1)/50);
x=linspace(xmin,xmax,(xmax-xmin)*na);
y=linspace(ymin,ymax,(ymax-ymin)*na);

uhat=tri2grid(p,t,flowdata(:,1),x,y);
vhat=tri2grid(p,t,flowdata(:,2),x,y);

fhat=intgrad2(uhat,vhat);

% Now set up like above but for arrows - use far large cell sizes, fewer
% cells
naquiver=5;
xquiver=linspace(xmin,xmax,(xmax-xmin)*naquiver+1);
yquiver=linspace(ymin,ymax,(ymax-ymin)*naquiver+1);

uhatquiver=tri2grid(p,t,flowdata(:,1),xquiver,yquiver);
vhatquiver=tri2grid(p,t,flowdata(:,2),xquiver,yquiver);

% % PLOTS!
% pdeplot(p,e,t,'xydata',u(:,end-1))
hold on
contour(x,y,fhat,8)
colormap jet
quiver(xquiver,yquiver,uhatquiver,vhatquiver)
axis equal
hold off
Appendix C – Experiment Photographs

This appendix contains photographs of all the textural experiments conducted. Because most samples were broken in half, there are two photographs for most of the experiments, each photo showing one half of the sample. However, some samples did not break cleanly down the middle, so there may be more than two photos for these samples. In some cases, the sample had so few joints in it that the weakest surface was the interface between the synthetic basalt and the crucible. For these experiments, the entire sample can be seen in a single photo, except for the other half of the crucible, which only has a thin selvage of synthetic basalt on it.
Figure C.1. Experiment 2012-05. Starting temperature of 800°C, cooled via forced air convection. The sample did not break cleanly across its middle, and instead broke near the crucible wall for much of the sample. The sample extends towards the viewer approximately 8 mm in A.

Figure C.2. Experiment 2012-03. Starting temperature of 750°C, cooled via forced air convection. No cooling joints intersecting the viewing surface are present.
Figure C.3. Experiment 2012-04. Starting temperature of 800°C, cooled via partial submersion in water. Sample broke into several pieces, the largest of which are shown. B and C show individual chunks of sample that broke off after cooling.

Figure C.4. Experiment 2012-16. Starting temperature of 800°C, cooled via partial submersion in water. Sample broke into many pieces, the largest of which are shown. A shows the largest intact sample piece, while B and C show the same fragment from two different angles. Organization of joints into crude columns is visible in these photos, especially in the upper left corner of C. In the background of B are millimeter marks on a ruler for additional scale.
Figure C.5. Experiment 2012-06. Starting temperature of 800°C, cooled via partial submersion in liquid nitrogen. No cooling joints are present within the sample.

Figure C.6. Experiment 2012-07. Starting temperature of 750°C, cooled via partial submersion in liquid nitrogen. No cooling joints are present within the sample.
Figure C.7. Experiment 2012-21. Starting temperature of 800°C, cooled at 5°C per minute in the high temperature furnace. No cooling joints are present in the sample, though some fracture surfaces are visible. In A, the sample extends towards the viewer approximately 8 mm.

Figure C.8. Experiment 2012-22. Starting temperature of 700°C, cooled at 5°C per minute in the high temperature furnace. No cooling joints are present in this sample.
Figure C.9. Experiment 2012-15. Starting temperature of 750°C, cooled via partial submersion in water. Cooling joints are visible in both A and B, particularly around the edges of the sample.

Figure C.10. Experiment 2012-17. Starting temperature of 750°C, cooled via partial submersion in water. Cooling joints visible, particularly on the right half of the sample in A, as well as in the upper left corner of A.
Figure C.11. Experiment 2012-13. Starting temperature of 750°C, cooled via partial submersion in water. Cooling joints are visible in both A and B, particularly near the upper surface of the samples, and along the left edge of the sample in B.

Figure C.12. Experiment 2012-18. Starting temperature of 750°C, cooled via partial submersion in water. Sample broke into many pieces, the largest of which are shown. Columns visible on edges of samples in both A and C, with B exhibiting columnar joints as well.
Figure C.13. Experiment 2012-11. Starting temperature of 800°C, cooled via complete submersion in water. Cooling joints are visible, especially in B, both along the edges and in the center.

Figure C.14. Experiment 2012-12. Starting temperature of 750°C, cooled via complete submersion in water. Cooling joints are visible in both A and B, particularly near the upper surface of the samples.

Figure C.15. Experiment 2012-14. Starting temperature of 700°C, cooled via complete submersion in water. Cooling joints are visible in both A and B, particularly near the upper surface of the samples.