INTRODUCTION:

The purpose of this project is to determine what characteristics an active volcanic system should exhibit in order to be considered ‘open-vent.’ As we have debated there seems to a broad spectrum of definitions describing the degree of openness. In one definition open-vent can simply mean that the magma within the system is exposed to the open atmosphere. This, of course, could lead to the classification of any volcano with some level of activity as an open-vent system—an obvious over-simplification of the problem. Throughout the course of the semester many aspects of an active volcanic system were discussed, including magma composition, degassing rates, eruptive activity (including effusion and degassing), cyclical eruption patterns, seismic characteristics, as well as models for magma degassing and recycling.

In an attempt to make a qualitative guideline for what makes a system open-vent, six volcanoes and several characteristics were chosen for comparison. These volcanoes are Semeru, Erebus, Arenal, Popocatepetl, Villarrica, and Karymsky. They are located all over the globe and demonstrate a range of characteristics, including size, magmatic compositions and tectonic settings (see table 1). The characteristics chosen for discussion are as follows: timescales of activity, gas flux, magma input rates, heat flux, seismicity, and deformation patterns.
Table 1. Comparison of characteristics of studied open-vent systems.

<table>
<thead>
<tr>
<th>Location/Country</th>
<th>Tectonic Setting</th>
<th>Type</th>
<th>Height</th>
<th>Volume</th>
<th>Composition</th>
<th>Effusion Rate</th>
<th>Hazards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arenal</td>
<td>Costa Rica</td>
<td>Subduction Zone</td>
<td>Stratovolcano</td>
<td>1670 m.</td>
<td>15 km$^3$</td>
<td>Basaltic-andesite</td>
<td>0.3 - 0.6 m$^2$/sec</td>
</tr>
<tr>
<td>Erebus</td>
<td>Antarctica</td>
<td>Rift</td>
<td>Stratovolcano</td>
<td>3794 m.</td>
<td>1670-2000 km$^3$</td>
<td>Phonolite</td>
<td>N.A.</td>
</tr>
<tr>
<td>Karymsky</td>
<td>Kamchatka, Russia</td>
<td>Subduction Zone</td>
<td>Stratovolcano</td>
<td>1550 m.</td>
<td>N.A.</td>
<td>Andesite-dacite</td>
<td>N.A.</td>
</tr>
<tr>
<td>Popocatepetl</td>
<td>Mexico</td>
<td>Subduction Zone</td>
<td>Stratovolcano</td>
<td>5464 m.</td>
<td>N.A.</td>
<td>Andesite-dacite</td>
<td>1-3 m$^2$/sec</td>
</tr>
<tr>
<td>Semeru</td>
<td>Java, Indonesia</td>
<td>Subduction Zone</td>
<td>Stratovolcano</td>
<td>3676 m.</td>
<td>60 km$^3$</td>
<td>Andesite</td>
<td>Low</td>
</tr>
<tr>
<td>Villarrica</td>
<td>Chile</td>
<td>Subduction Zone</td>
<td>Stratovolcano</td>
<td>2847 m.</td>
<td>327 km$^3$</td>
<td>Basaltic-andesite</td>
<td>0 m$^2$/sec</td>
</tr>
</tbody>
</table>
ERUPTIVE TIME SCALES

In this section we compare the similarities in eruptive time scales of the six study volcanoes. By looking at the eruptive history of each volcano we present a qualitative argument for the “openness” of the volcanic systems based on similarities in short term eruptive cycles. Unfortunately, a complete analysis of current eruptive timescales and cycles is not available for all volcanoes included in this paper; therefore, we simply summarize the available information, primarily that provided by the Smithsonian’s “Global Volcanism Program.”

Arenal

It has been estimated that the first eruption of Arenal occurred approximately 7000 years before present and it has demonstrated an eruptive cycle of roughly every 800 years (Ryder et al 2006), and the last eruptive phase happening roughly 500 years ago in 1525, with central vent and radial fissure eruptions and lava flows (Melson and Saenz, 1973).

The current eruptive phase began in 1968 and has continued to present day with mild explosions followed by lava flows from the crater. In 1975 a small explosive eruption evacuated the lake within the cone and formed a new crater. Blocky lava flows persisted sporadically through 1979. Two years of tilt data indicated deflation correlating to lava effusion at stations closest to the volcano. This suggested a shallow magma chamber ~ 2 km below the surface. Lava extrusion and vigorous degassing continued through 1983. In July 1984, lava flows decreased and a new, explosive phase began.

The new phase was marked with frequent small, Strombolian eruptions that occurred every 10-30 minutes with weak explosions and gas pulsing every 10-50 seconds. Seismic signals preceded eruption columns by approximately two seconds. By July 1985 Strombolian eruptions and seismicity had declined in frequency but tephra emissions and lava flows continued. In 1987 Strombolian activity renewed and continued – occasionally fluctuating – with lava flows, pyroclastic flows and degassing through 1994 when explosive eruptions became more sporadic. In 1999 eruptions increased in volume and frequency and produced pyroclastic flows. Today eruptive activity is persistent producing mild explosive, effusive eruptions and block-and-ash flows every several weeks. The last decade of continuous activity can be seen throughout the MODIS data, however some gaps are present most likely due to tropical weather conditions that are not ideal for thermal imaging.

Erebus

Mt.Erebus is estimated to have been active for approximately 1.3 million years (MEV0). Since 1973—with the exception of 1984 when activity increased and 2001-2004 when activity decreased in frequency and intensity — the eruptive activity is primarily Strombolian with roughly six eruptions per day and cyclic turnover, or pulsatory behavior around every 10 minutes, in the constantly convecting lava lake (Sweeney et al., 2008; Oppenheimer et al., 2009.
**Karymsky**

Karymsky Volcano has been active off and on for about the last 500 years after more than 2000 years quiescence. For the last 100 years Karymsky has shown a cycle of activity ranging from 4 years to 15 years interspaced with periods of quite ranging from 3 to 14 years. This activity has been primarily small explosive events (VEI 2) and occasional lava flows.

After almost 11 years of minor thermal and fumarolic activity, this eruption cycle was invigorated in January 1996 with an ash column that reached roughly 1.5 km above the summit, as well as an increased in seismicity. Since then the volcano has been quite active producing explosions, ash plumes, strombolian eruptions, dome building and pyroclastic flows. The explosions contained mainly steam with minor ash. By December 1996 elevated seismicity suggested that up to 300 explosions were occurring per day. In February 1997 AVO reported a persistent hot spot at the summit and occasional low level ash plumes. By January 1998, an explosion was occurring about every 30 minutes and producing an ash plume which rose about 300-300 m. In May 1998 lava effusion was detected and in June KVERT detected explosive events that were accompanied by harmonic tremors. Low level strombolian eruptions and ash plumes continued through November 1999 then briefly stopped in December.

Low to moderate level eruptive activity resumed in May 2000 producing ash and gas explosions with an increase in seismicity. Three new lava flows were reported in September 2002 while ash explosions and dome growth continued through 2008. In August 2009 a new explosion crater was formed and KVERT continues to report seismicity, thermal anomalies and small ash columns.

**Popocatepetl**

Popocatepetl shows evidence of a Plinian type eruption about every 2000 years. Based on ice-core samples the last large major eruption occurred in 823 AD (GVP; CENEPRED). Since then it has exhibited a continuous cycle of minor explosive activity interspaced with anywhere from two to 70 years of inactivity. The last eruptive cycle occurred in 1920 and lasted seven years (Delgado-Granados, 2001; GVP). Current eruptive activity began in 1994 and continues today.

The volcano re-awoke in December 1994 with a strong phreatic explosion that cleared the vent and opened the conduit. This activity continued through January 1995. During the next year-and-a-half sporadic explosions opened four new vents at the crater. March 1996 through 2003 saw a period of effusive and explosive activity with dome creation and destruction, large gas flux, lava flows, phreatic eruptions and lahars. Activity since 2004 through today exhibits continued central vent explosions, about 7-13 per day, and continued lava dome extrusion.

**Semeru**
Volcano Semeru seems to experience a low activity eruption cycle and produce a small (VEI 2) eruption every 2-5 years. This has been happening continuously since 1818 with a possible 25 year quietus between 1915 through 1940. Eruption characteristics are minor explosive, Vulcanian, with lava effusion and occasional pyroclastic flows.

The current eruptive style demonstrates eruptive intervals of 5-60 minutes. It is reported that there are 40-90 small eruptions per day with ash columns that reach 300-900 m above the vent, while every 1-6 months an ash column will reach .95-3.3 km and every 2-5 years, Semeru may produce a column that reaches 3-7 km. During the eruptive phase from 1998-2003 the average column was 2.45 -3.95 km. Currently Semeru is in a state of perpetual, low level eruptive activity.

Villarrica

Since 1558 Villarrica has erupted over 59 times producing both effusive and mildly explosive eruptions. Eruptions in 1948-49, 1963-64, and 1971-72 produced fatal lahars while the eruption of 1984-1985 produced a small scoria cone at the summit of the crater as well as large volume of lava. Eruptive activity since then consists primarily of passive degassing and occasional minor strombolian eruptions from the persistent lava lake within the crater. The lava lake surface has also been observed to rise and fall several meters over several weeks to months. This type of activity dominated until roughly 1992 when phreatomagmatic explosions and intense fumarolic activity began to increase.

Seismic activity increased in 1996 as did Strombolian explosions and lava fluctuations. In February 2002, a small strombolian eruption ejected incandescent ballistics out of the vent. Activity continues today similar to this.

Discussion

Prior to the current eruptive phase all volcanoes except Erebus and Semeru exhibit cyclical behavior in terms of dormancy, quiescence and activity. The common eruptive characteristic demonstrated by all six volcanoes, during their “open vent” phase is the persistent pulse of minor activity.

On a daily scale all six volcanoes show gas emission, while Erebus, Popocatepetl, Semeru and Villarrica exhibit magma convection, Strombolian and/or Vulcanian eruptions on a daily basis. While on a weekly to monthly scale all six volcanoes demonstrate some type of eruptive activity. Arenal continues to produce sporadic Strombolian eruptions and block-ash-flows on a monthly basis while Karymsky produces a weak ash explosions several times a month.

Based on the above observations we suggest that all six volcanoes in this study maintain a varying degree of “openness” of the vent. This is argued using the current eruptive phase and the
short term – monthly, weekly and daily - cyclic behavior and persistent activity as a qualitative parameter for openness.

**EFFUSION RATE AND OPEN-VENTNESS CORRELATION**

It is important to note that values used for effusion rates for these comparative observations are averages, so often times, there are great fluctuations in values during transition episodes of varying eruptive behavior.

In two of our studied volcanoes (Villarrica and Erebus), persistent lava lakes exist, which suggests little or no net effusion. At both of these volcanoes there is small-scale spattering, but on average, this is probably nominal. Also, for Popocatepetl, there is little to no current extrusion. Drawing comparisons for the three remaining volcanoes is very difficult given such a small sample set, nor should we make generalizations about ranges of extrusion rates and the likelihood that this factor alone has a bearing on whether a volcano achieves our definition of “open-ventedness”. Obviously, some volcanoes can very well be defined as open-vent yet do not actively extrude lava.

However, other observations can be made. Relatively low effusion rates are seen at Arenal, Popocatepetl and others that are not included in this study (Stromboli, Etna, Pacaya, Fuego, Santiaguito, etc.) might provide some insight. All of these volcanoes show compositions that range from basalts to andesite-dacite. It seems intuitive that the lower viscosity magmas would have an easier time achieving open-vent balances than would a higher viscosity dacite or rhyolite. This is probably a fairly clear-cut observation, though perhaps not the rule. Chaiten in Chile continues to extrude a rhyolitic obsidian dome, which given our class discussions, would probably fall within our definition of open-vent status.

Interestingly, all of our volcanoes are stratovolcanoes. One might assume that lower viscosity magmas, like those often present at shield volcanoes, would more easily be able to consistently maintain open-vent equilibrium through magma convection and cycling within a conduit. One representative case would be Kilauea. However, for this study, it’s clear that “open-vent” conditions can also be achieved at stratovolcanoes around the world. Similarly, in our comparison a volcano’s height nor its volume seem to be constraints limiting its ability to be open-vent, nor does the literature acknowledge these characteristics as being determining factors in a volcano’s ability to remain “open.”
HEAT FLUX

Figure 1. Data sets from 2005-10 of MODVOLC thermal alerts.

In order for the upper surface of the volcanic conduit to remain open, the system requires a heat flux that can keep the conduit from solidifying and permitting the nearly constant degassing to
the atmosphere. The heat flux required to keep a system open is highly dependent on the conduit dimensions, magma composition, and both dissolved gas and bubbles. Using the long time scales permitted through the last decade of satellite remote sensing, we have reported the heat flux from band 21 of the MODIS instruments on Aqua and Terra in spectral radiance. By deriving our data from MODVOLC, which uses a normalized thermal index threshold to determine global hotspots [Wright et al., 2004], we plotted only the averaged pixels with values exceeding the threshold of -0.8 from 2003 through the present (Figure 1). There are some major limitations with the use of MODVOLC alerts, but by using only night-time images free from solar contribution (to avoid algorithm bias), the heat flux of all six volcanoes over nearly a decade can be observed.

By looking briefly at figure 1, some major trends become obvious immediately. The most abrupt pattern is seen in Erebus, and actually is not volcanic in nature at all. This cyclic pattern is revealing a data gap during the austral summer, where there are no night time radiances due to the constant daylight on Antarctica. In addition, one other problem arises due to the low elevation of Arenal, which greatly reduces the number of detections due to cloudy conditions obscuring the relevant band difference between bands 21 and 32. Apart from the limitations of the MODVOLC algorithm, all six volcanoes exhibit a spectral radiance usually greater than 0.5 W m^-2 sr^-1 um^-1, but there is a large variation between volcanoes. For example, Erebus and Villarrica, the extreme end members of open-vent activity with persistent lava lakes, only rarely exceed 3.0 W m^-2 sr^-1 um^-1, while Semeru and Karymsky exceed this value much more frequently. An explanation for this may be due to Erebus and Villarrica not producing any significant lava outside of lava lake, hence only contributing a small part of a pixel (1 km^2) of heat flux, while lava flows may each cover greater than one pixel in area. Popocatepetl, Erebus, and Arenal display heat fluxes with little to no variation with time, while Semeru, Karymsky, and Villarrica experience broad fluctuations and spikes in spectral radiance.

In general, all six of the volcanoes looked at in this study show some level of quasi-constant heat output that is responsible for keeping the system open to the atmosphere, at least on the time scales for this study. Without the necessary magma input or cycling required to maintain a liquid lava at the surface, each volcano would inevitably close off and cease being open-vent.

**GAS FLUX**

In this section, we compare the gas flux ratios of SO$_2$, CO$_2$, and H$_2$O for the six studied volcanoes. Magma contains dissolved gases that are released into the atmosphere during eruptions or during quiescent states by passive degassing. Gases can escape by exsolution (bubbles rising through magma) or convective overturn. The most abundant gas released is water vapor (H$_2$O), followed by carbon dioxide (CO$_2$) and sulfur dioxide (SO$_2$). Trace gases include hydrogen sulfide (H$_2$S), hydrogen (H$_2$), carbon monoxide (CO), hydrogen chloride (HCL), hydrogen fluoride (HF), and helium (He). Gas plume composition is determined either by direct sampling (e.g., gas traps at fumaroles) or by spectroscopic remote sensing techniques (e.g., COSPEC, FLYSPEC, DOAS, FTIR, OMI). SO$_2$ is a rare component in the ambient atmosphere and easily detected, whereas H$_2$O and CO$_2$ are present in the high quantities in the background and therefore more difficult for which to obtain accurate volcanic plume data.

Average SO$_2$ flux values were collected from the literature for the six volcanoes studied. CO$_2$ and H$_2$O flux values for Erebus were also collected. CO$_2$ and H$_2$O flux values for the remaining volcanoes were calculated by interpolating between mass ratios of two end member lava

Table 2. Estimated gas flux.

<table>
<thead>
<tr>
<th></th>
<th>SO$_2$ flux (kg/s)</th>
<th>CO$_2$ flux (kg/s)</th>
<th>H$_2$O flux (kg/s)</th>
<th>Sum (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semeru</td>
<td>0.0174*1</td>
<td>0.1675</td>
<td>0.5</td>
<td>0.6849</td>
</tr>
<tr>
<td>Erebus</td>
<td>0.706*2</td>
<td>15*4</td>
<td>10*4</td>
<td>25.706</td>
</tr>
<tr>
<td>Arenal</td>
<td>1.5*5</td>
<td>28</td>
<td>13</td>
<td>42.5</td>
</tr>
<tr>
<td>Karymsky</td>
<td>1.57*4</td>
<td>12.5</td>
<td>45.7</td>
<td>59.77</td>
</tr>
<tr>
<td>Villarrica</td>
<td>6.94*5</td>
<td>59</td>
<td>128</td>
<td>193.94</td>
</tr>
<tr>
<td>Popocatepetl</td>
<td>114.7*6</td>
<td>440</td>
<td>4527</td>
<td>5081.7</td>
</tr>
</tbody>
</table>

* Data taken from literature; the rest are calculated values.
1 Iguchi et al., 2008.
2 Davies et al., 2008; Oppenheimer and Kyle, 2008.
4 Fischer et al., 2002.
5 Palma et al., 2008
6 Delgado-Granados et al., 2001; Witter et al., 2005; Delgado-Granados, 2008.

SO$_2$ flux values are more reflective of lava composition and may not well indicate degree of open-ventedness. For example, both Erebus and Villarrica are characterized by persistent lava lakes, but the SO$_2$ flux values vary by two orders of magnitude. A better indicator of openness may be total gas flux (SO$_2$+CO$_2$+H$_2$O). If we consider Erebus anomalous (whose low gas flux is derivative of a gas-poor parent basanite magma (Oppenheimer et al., 2008)), there still seems to be a lack of correlation between total gas flux and openness as determined by timescales of activity. Semeru and Arenal experience several eruptions daily, yet exhibit lesser gas fluxes than Karymsky, which operates on a much longer time scale. Gas-flux is not indicative of openness alone, but perhaps can be combined with other characteristics to develop a more accurate definition of openness.

SEISMIC CHARACTERISTICS:

Seismic signals associated with volcanic activity can typically be categorized into three general types: volcano-tectonic (VT), long period or very long period (LP, VLP), and tremor. These categories are not rigorously defined, nor are there definitive limits to the characteristics of each type of signal. However, for the purposes of this study, the classification proposed by McNutt (2005) will be followed. VT signals are those with rapid onset, a quickly decaying and non-harmonic coda, and most closely resemble purely tectonic earthquakes. LP and VLP signals are those with a dominant frequency less than ~5Hz, and a harmonic coda, while tremor exhibits a gradual onset and decay, with low frequency content, and harmonic behavior, including overtones. Both LP/VLP and tremor signals are associated with fluid and gas movement, and therefore are often recorded at active volcanic systems.

The six volcanoes investigated in this study all show seismic characteristics consistent with LP/VLP events, frequent or persistent tremor, or both. The dominant seismic signal for Semeru is harmonic tremor lasting 40-1000 seconds, with a spectral signal ranging from .5-8Hz (Iguchi et al., 2008). Erebus, on the other hand, is characterized by VLPs with spectral peaks at 20.7s,
11.3s, and 7.8s, associated with gas-slug movement and bursting (Aster et al., 2008). According to Benoit & McNutt (1997), the seismic signal of Arenal appears to be tied to the short term eruption cycle where strong tremor is recorded in conjunction with gas release, then the frequency of the signal increases, as amplitude decays. The general pattern is a ‘whoosh (of gas) –chug (frequency increase) -strong tremor.’ Both spasmodic and harmonic tremor are recorded at Arenal (Lesage et al., 2006). Popocatepetl appears to have the widest range of seismic signal of the volcanoes included in this investigation. Like Arenal, this variation is associated with different types of activity. In this case, LP signal characterizes the bursts of degassing, and tremor is associated with eruptive activity. LP and hybrid (showing characteristics of both LP/VLP type events, and VT type events) are recorded with effusive activity. In addition, during Vulcanian eruptions VLP signals with periods >2s are recorded. (Arciniega-Ceballos et al., 2008) The final two volcanoes have similar seismic characteristics: Villarrica has a constant background tremor of ~1Hz, which increases to ~2.3Hz when the system is more closed (Wright et al., 2004). The tremor at Karymsky is harmonic, with a dominant frequency of ~2.5Hz, 1s acoustic pulses that sound like train chugs (Johnson & Lees, 2000). Some high frequency (>6Hz) hybrid events are associated with ‘jetting’ activity, and an infrasound signal typically follows at ~3-7s (Lees, 2004).

While the source for seismic signals is often difficult to uniquely determine in a volcanic system, the similarities between these six volcanoes are fairly obvious. All of these systems are currently active, and, with the exception of Erebus, show persistent seismicity that is typically caused by magma movement. Erebus can be exempted from the need for a seismic signal to determine if it is an open-vent system since the VLP/gas slug movement is clearly a part of magma overturn in the lava lake.

On its own, seismic signals are not enough to determine whether a volcano should be labeled open-vent or not. However, the consistency of the signal, type of seismicity, and association with eruptive activity can support an assertion of ‘open-vent.’

**DEFORMATION:**

Newhall (2005) presented three examples of open vent volcanoes (Stromboli, Mayon, and Iwo-Jima), some of the characteristics included: typical but variable small frequent eruptions, minimal seismicity and ground deformation before eruptions. A closer look will be given to the deformation characteristics at the possible open vent systems that were chosen for this study.

Generally, ground surface expands before eruptions due to pressure increase within a shallow magma chamber caused by upward magmatic movements. After the eruption has ended, deflation occurs in the volcano. Patterns and rates of surface displacement can be used to obtain the depth and rates of pressure increase within the magma chamber, as well as size and shape of the center of deformation which may be related to the top of the magma chamber (Dvorak and Dzurisin, 1997). During our discussions, several arguments were brought up about the different attributes that should be clarified in order to determine if a volcano is an open system. Among the arguments, it was stated that a maximum “standard” depth of the top of the magma chamber should be established, information that can be obtained with an analysis of deformation characteristics and measurements from the volcanoes.
Volcanic ground deformation measuring techniques can be classified as being episodic or continuous. The episodic techniques include angle and distance measurements, leveling, InSAR, and repeated GPS signals. The continuous measuring techniques include the use of tiltmeters, strain meters and permanent GPS networks (Janssen, 2007). After doing a literature search for the volcanoes that are being compared, it was found that the measuring techniques for the volcanoes was very variable, and therefore the results varied as well. Semeru volcano is characterized by showing gradual upward tilts of the crater side with amounts ranging from 0.3-20.3 nrad about 16-300 seconds before an eruption. After an eruption, tilts turn downward and decrease by 0.7-50 nrad for 30-70 s (Kuswandarto et al., 2008). Deformation at Erebus is measured by continuous GPS stations with amounts of 1-4 mm/yr in the horizontal oriented radially outward from the summit crater and 4-8 mm/yr upward during the 2002-2004 time range. The same amounts were measured for the period of 2004-2006 but instead of outward and upward, it was inward and downward. This reversal in direction of motion is characterized by a change in size and frequency of volcanic activity. Also, some annual variations in the vertical component have been measured to range from 10-20 mm at several locations (Murray et al., 2006). Deformation at Popocatépetl volcano is measured by GPS as well, but the changes during single explosions are too small to be detected. It is characterized as a minimally deformation system (geodetic movement <1.5 mm/yr) (Cabral-Cano et al., 2007). Deformation at Villarrica volcano has not been measured, but GPS measurements have been recommended to test if deformation is occurring (Witter et al., 2004). In the case of Karymsky volcano, the available deformation measurements are from the occurrence of the 1996 Ms 6.7 earthquake and subsequent eruptions at the area with instantaneous vertical and horizontal displacements of about 140-150 mm (Zobin et al., 2003). Lastly, deformation has been studied in Arenal volcano (e.g. Muller, et al., 2009), but the available data was unable to be obtained. Since the instruments and techniques used to measure volcanic deformation were different for all of the volcanoes whose information was obtained, a comparison could not be done and therefore a description of openness from a volcano could not be achieved by this manner. For these reasons, recommendations are given for future research in order to be able to make comparisons in different locations around the world: (1) Integrated work of both types of volcanic deformation measuring techniques at each site; (2) Utilization of instruments that are able to detect very small amounts of deformation; (3) Obtain deformation measurements before and after volcanic eruptions, as well as the values per year. Data obtained in this way would have been useful to determine possible patterns and rates of surface displacement, which could have lead to the determination of the top of the magma chamber. Comparisons would then have been made between the volcanoes to determine whether they were open systems or not, and how open they were.

CONDUIT RADIUS:

An attempt was made to calculate conduit radius using the method introduced by Stevenson & Blake (1998). Using previously published Q values for Villarrica and Erebus, initial calculations yielded a conduit radius of 13.3m for Villarrica and 8.5m for Erebus. These values seem to be within a range of possibility. The parameters for the other four volcanoes are not constrained well enough to derive a conduit radius with any degree of reliability.
CONCLUSION

Based on the characteristics of the physical processes compared, we’ve attempted to derive a working definition of an “open-vent” system. It’s clear that no single characteristic can be used to categorize a volcano as open-vent, but perhaps the timescale in which a volcano is “open” is the most definitive characteristic. With some degree of certainty, we can safely declare that Erebus and Villarica are open-vent volcanoes as they continuously have lava exposed to the atmosphere, while Popocatepetl, Karymsky, Arenal and Semeru appear to only maintain open-vent conditions intermittently. Erebus, Villarrica, Arenal, and Semeru have frequent Strombolian explosions, erupting nearly continuously due to ascending gas slugs. These four volcanoes demonstrate well the previously observed link between eruption size and repose time, with increasing eruption size being directly proportional to repose time, which is most likely due to an increased degree of conduit sealing. From the characteristics discussed, we know that without a continuous heat flux, a pathway for degassing-driven convection, and a lower viscosity composition are all required to keep a system from closing. When any of these parameters change to values below the threshold for open-ventedness, the volcano will transition to a closed-vent state. Instead of open vent, the term open conduit should be applied when referring to volcanoes that are not in constant exposure to the atmosphere.

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Mount Erebus Volcano Observatory - http://erebus.nmt.edu/

APPENDIX A

**Figure 1:** Plots showing the relationship between the frequency of eruptions and the size of the eruptions from the studied volcanoes.

**Figure 2:** Plots showing the relationship between the frequency of eruptions and the SO$_2$ flux from the studied volcanoes, with the exclusion of Popocatepetl due to such a high amount of flux (114.7 kg/s).