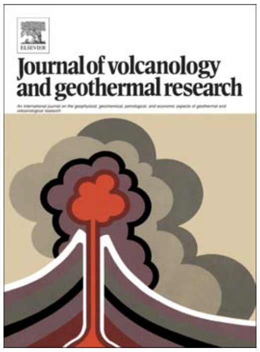

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Coupled Use of COSPEC and Satellite Measurements to Define the Volumetric Balance During Effusive Eruptions at Etna, Italy

Andrea M. Steffke[1*], Andrew J.L. Harris[1,2], Mike Burton[3], Tommaso Caltabiano [4], Giuseppe Giovanni Salerno [3,4]

1 – Hawai'i Institute of Geophysics and Planetology
School of Ocean and Earth Science and Technology
University of Hawai'i at Manoa
1680 East-West Road
Honolulu, HI 96822 USA
steffke@higp.hawaii.edu
Phone: +1-808-956-0182
Fax: +1-808-956-6322

2 – Laboratorie Magmas et Volcans
Université Blaise Pascal
5 Rue Kessler, 63038
Clermont-Ferrand, France
A.Harris@opgc.univ-bpclermont.fr
**current address

3 - INGV-Catania
Piazza Roma 2
95123 Catania, Italy
burton@ct.ingv.it

4 - Department of Geography
University of Cambridge
Downing Place
Cambridge, CB2 3EN, UK
ggs25@cam.ac.uk

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Abstract

Mt. Etna is one of the most studied and extensively monitored volcanoes on earth (Bonaccorso et al., 2004). One of the most frequent hazards are due to the eruption of lava flows, more specifically those flows produced during flank eruptions. These eruptions potentially can produce extensive flows that can inundate densely populated communities of the lower slopes (Guest and Murray, 1979; Behncke et al., 2005). Satellite remote sensing can be used during effusive eruptions to help monitoring the volcano, by determining effusion rates of the flows, aiding in hazard management. The degassing that takes place when magma is rising to the surface can be regularly monitored using ultraviolet spectroscopic methods (e.g. Andres et al., 2001, Sutton et al., 2001). Sulfur Dioxide (SO_2) fluxes have been derived from correlation spectrometer (COSPEC) measurements at Mt. Etna (Italy) on a regular basis since 1987 (e.g. Caltabiano et al., 1994; Allard, 1997; Andronico et al., 2005; Burton et al., 2005; Burton et al., in press). Previous studies have compared field-based effusion rates with the measured SO_2 fluxes to determine how much of the degassed magma is erupted onto Etna's flanks in the form of lava flows (Allard, 1997; Harris et al., 2000). However, most of these studies examine bulk volumes erupted over an eruption rather than examining the short-term variations during eruptions. Determining the amount of lava erupted and/or the balance between the amount supplied and the amount erupted remains an unresolved issue. The main objectives of this paper are to examine such short-term variations using satellite-based effusion rates along with regularly measured SO_2 fluxes. Using these measurements we determine how and when the volume of supplied magma is balanced by the volume of erupted lava during individual effusive eruptions.

1. Introduction

Etna is one of the most studied and monitored volcanoes on earth (Bonaccorso, 2004), where the most frequent hazard is due to the eruption of lava flows; specifically those produced during flank eruptions. These can produce extensive flows that can inundate densely populated communities of the lower slopes (Guest and Murray, 1979; Behncke et al., 2005). Satellite remote sensing can be used during effusive eruptions to determine effusion rates, aiding in hazard monitoring. The degassing that takes place when magma rises to the surface can be monitored using ultraviolet spectrospic methods. Sulfur Dioxide (SO_2) fluxes have been derived from correlation spectrometer (COSPEC) measurements at Etna on a regular basis since 1987 (e.g. Caltabiano et al., 1994; Allard, 1997; Andronico et al., 2005; Burton et al., 2005). Previous studies have compared field-based effusion rates with the measured SO_2 fluxes to determine how much of the degassed magma is erupted onto Etna’s flanks (Allard, 1997). However, such studies examine bulk volumes erupted annually rather than examining the short-term variations during eruptions. Determining the amount of lava erupted and/or the balance between the amount supplied and the amount erupted remains an unresolved issue. The main objectives of this paper are to examine such short-term variations using satellite-based effusion rates along with regularly measured SO_2 fluxes. We use these to assess how and when the volume of supplied magma is balanced by the volume of erupted lava during individual effusive eruptions.

1.2 Magma volumetric balance dynamics

Once magma enters the shallow system three scenarios are possible. In scenario 1, degassed magma can remain unerupted, resulting in endogenous growth (Dzurisin et al., 1984; Dvorak and Dzurisin, 1993). In scenario 2, it can sink back to deeper levels to mix with a deep reservoir (resulting in cryptic growth) (Allard et al., 1994; Allard, 1997). Alternatively, in scenario 3, it can be erupted onto the surface resulting in exogenous growth (Francis et al., 1993; Sutton et al., 2001). As a result, three different mass balance scenarios can occur: (1) The volume of erupted lava (V_{erupt}) is less than the volume of supplied magma ($V_{supplied}$), meaning that a portion of the degassed magma has not been erupted; (2) V_{erupt} can be greater than $V_{supplied}$, meaning that previously degassed magma in temporary storage within the shallow system has contributed to the erupted flux, or the magma has risen at a rate faster then it can degas; or (3) V_{erupt} can equal $V_{supplied}$ if all of the degassed magma then erupted.

These scenarios have been documented at several volcanoes. At Kilauea (Hawaii) between 1956-1983, $V_{supplied}$ was greater than $V_{erupted}$ with 45–65 % of the supplied magma remaining within the volcano's rift zones (Dzurisin et al., 1984; Dvorak and Dzurisin et al., 1993). In contrast, during 1983-2002 $V_{supplied}$ equaled $V_{erupted}$ (Dvorak and Dzurisin et al., 1993; Sutton et al., 2001). At Krafla (Iceland) deformation data revealed an excess in supply during 1975–1978, resulting in endogenous growth by rift zone intrusion (Bjornsson et al., 1979). At Etna $V_{supplied}$ has been determined from the volume of degassed magma (V_{degas}) derived from gas flux data, where, during 1975-1995, V_{degas} greatly surpassed V_{erupt} (Allard, 1997). This excess volume of degassed magma likely resulted in the creation of a cryptic plutonic complex within Etna's sedimentary basement (Allard, 1997) as well as contributing to some endogenous growth by intrusion (Harris et al., 2000). However, most studies have examined volume fluxes over periods of decades and have not examined the potential variation in volume partitioning during individual eruptions. Here we compare the volumes of degassed magma with the amount of erupted lava during three effusive eruptions of contrasting style and locations at Etna between 2002 and 2006. To do this we use COSPEC-derived SO_2 measurements and effusion rates obtained from Advanced Very High Resolution Radiometer (AVHRR) thermal data. We show that the balance between the volumes of degassed magma and erupted lava not only vary from eruption to eruption, but also vary during single eruptions.

2. Etna eruptions: 2002-2006

Three eruptions occurred at Etna during 2002-2006: the 2002-2003 flank eruption, the 2004-2005 summit eruption and the 2006 summit eruption. The 2002-2003 flank eruption began on 28 October 2002 when two eruptive fissures opened on the South and NE flanks (Andronico et al., 2005). The eruption lasted 3 months ending on 28 January 2003 when effusive activity ceased at the south vent. The eruption was characterized by moderate lava effusion ranging from 2–15 m^3/s, as well as long periods of intense explosive activity, with particularly explosive phases occurring during 27 October–12 November and 26 November–10 December. The eruption was preceded by a slight increase in SO_2 emission, which increased from a background flux of 1,000 t/d to 2000 t/d (Andronico et al., 2005).

The 2004-2005 summit eruption began on 7 September 2004 with the opening of a fracture on the lower eastern flank of the South East Cone (SEC). The eruption was characterized by low but steady effusion at 2.3–4.1 m^3/s to feed lava flows that extended 2.5 km (Burton et al., 2005). The eruption lasted 6 months ending in March 2005

(BVGN, 2005). Unlike most Etnean eruptions no precursory activity, such as an increase in SO_2 flux, preceded the eruption (Burton et al., 2005).

The 2006 eruption began on 14 July 2006 when a fissure opened on the east flank of the SEC (BGVN, 2006). The eruption lasted 11 days ending on 24 July The eruption was characterized by lava flows emplaced at highly variable effusion rates that ranged between 2-10 m^3/sec and was accompanied by Strombolian activity at SEC. Lava flows had not reach lengths longer than 3 km when the eruption ended (BGVN, 2006).

3. Methodology

We calculated magma degassing rates and volumes of magma degassed using COSPEC-derived SO_2 measurements. Previous studies have shown how SO_2 flux can be measured using COSPEC and that, given SO_2 flux, the volume of degassed magma can be calculated (Caltabiano et al., 2000). The SO_2 source is degassing magma, ascending toward the surface. Melt inclusion studies (Metrich et al., 2002; Spilliarert et al., 2006) have constrained the original sulfur content of Etnean magma to be ~ 0.32 wt%. Therefore assuming a primitive magma density of 2700 kg/m^3 (Pompilio and Corsaro, 2002) we can calculate what a specific volume of unvesiculated primitive magma can produce. In order to compare SO_2 fluxes with lava effusion rates, we must determine the volume of lava that each primitive volume of magma can produce; the main volume change being controlled by the presence of vesicles. Typically Etnean lava flows are ~25% vesiculated. For each of the eruptions considered here SO_2 measurements were made daily (Andronico et al., 2005; Burton et al., 2005; Burton et al., in press). We then used these measurements to calculate the degassed magma flux (in m^3/s). We use this to define the amount of magma that is degassed over a given time period, in this case a day, and term this time-averaged (daily) magma supply rate (S_r). Given S_r we can integrate through time to calculate the volume of degassed magma over each measurement period. We term this the volume of supplied magma ($V_{supplied}$) (Table 1).

Effusion rates were calculated using cloud–free AVHRR data. The pixel mixture model initially proposed by Dozier (1981) and adapted for use with one AVHRR band (Harris et al. 1997) was used; allowing us to determine the area of lava that occupied each thermally anomalous pixel. These were then summed to obtain total lava area and used to calculate the radiative and convective heat losses from the active lava following Oppenheimer (1991). Heat loss was then converted to effusion rate using the methodology derived for Etna by Harris et al. (1997; 2000). This approach is based on a relationship whereby the amount of heat lost from a flow is equal to the heat generated from crystallization and advection (Pieri and Baloga, 1986). These values are then averaged over time and we term this the time-averaged discharge rate (D_r). These rates were used to calculate the volume of lava erupted over a given period ($V_{erupted}$) (Table 1).

4. Results

The balance between S_r and D_r, supplied magma volumes and erupted lava volumes for each eruption is given in Table 2. The temporal variations during each eruption are also plotted in terms of S_r and D_r (Figure 1a), supply versus erupted volume difference (V_{supply}-$V_{erupted}$) (Figure 2), and cumulative volumes (Figure 1b). Each eruption was split into phases based on characteristic levels in S_r and D_r, and thus differences between supplied magma and erupted lava volumes (Figure 1).

The 2002–2003 eruption began with a five-day phase (Phase I) during which D_r exceeded S_r (Figure 1a), meaning that more lava was erupted than was degassed (Figure 2; Table 2). As a result, the output exceeded supply (Figure 1a). However, during the following phase (Phase II) S_r exceeded D_r (Figure 1a; Table 2), causing an excess in magma supplied (Figure 2). Consequently, the volume of supplied magma greatly surpassed the volume of erupted lava (Figure 1b). During the third phase (Phase III) S_r equaled D_r (Figure 1a); so $V_{supplied}=V_{erupted}$ (Figure 2; Table 2). During the final phase (Phase IV) there was an excess of supplied magma (Figure 2; Table 2). Overall $V_{supplied}$ exceeded V_{erupt} by $3.4x10^7$ m^3 (Figure 1b; Table 2). Field-based measurements of erupted lava during this eruption were measured to be 3.5 – $4.0x10^7$ m^3 (Allard et al., 2006) (assuming a vesicularity of 25%), these values fall within the given range of erupted volumes calculated in this study (Figure 1b).

During the 2004–2005 eruption D_r and S_r were approximately constant throughout the eruption, with periods of small differences (<3 m^3/sec) (Figure 1a). We classified the eruption into four phases (Phases A–D). During two of the phases (Phases A & C) V_{erupt} exceeded $V_{supplied}$, but only by small amounts (Figure 2; Table 2). In the other two phases (Phase B & D), the two volumes were coupled and so that $V_{supplied}$ was equal to the $V_{erupted}$ (Figure 2; Table 2). The total difference between V_{erupt} and $V_{supplied}$ was $6.6x10^6$ m^3. Field-based measurements of V_{erupt} were $5.0x10^7$ m^3 (Allard et al., 2006), also falling within the range of volumes calculated in this study (Figure 1b).

The 2006 eruption was characterized by almost constant S_r. However, D_r was highly variable (Figure 1a). During the first four days (Phase X) D_r was lower than S_r. However after July 25th (Phase Y) D_r increased to surpass S_r (Figure 1a; Table 2).

Therefore, the $V_{supplied}$ was greater than V_{erupt} during Phase X, but greater than $V_{supplied}$ during Phase Y (Figure 1b; Table 2).

5. Discussion

The three eruptions encompass the three different volume balance scenarios: i.e. (1) $V_{supplied}$=V_{erupt}, (2) $V_{supplied}$>V_{erupt}, (3) $V_{supplied}$<V_{erupt}. When $V_{supplied}$ is greater than V_{erupt} a portion of the ascending magma reaches a depth at which the magma can degas (<4 km) but does not erupt. This occurred during Phase IV of the 2002–2003 eruption when $V_{supplied}$ exceeded V_{erupt} by 8.7x10^{6} m^{3} (Figure 1b). In such a scenario the excess of degassed magma must either be stored in the edifice or be removed from the shallow system to be emplaced at depth. However, if the magma were erupted explosively the satellite sensor would not be able to detect the emission. Therefore there would be an underestimate in the volume of erupted material. This was the case for Phase II of the 2002–2003 eruption. During that time Etna experienced a highly explosive phase simultaneous with the effusive activity with tephra volumes of up to 2.2±0.4x10^{7} m^{3} being erupted (Andronico et al. 2005; Spilliaert et al., 2006). Therefore the difference between the effused and degassed magma (2.9x10^{7} m^{3}) during this phase could be explained by volume lost to tephra. Magma may also rise at a rate slower than the gases are able to escape; therefore degassed magma fluxes can outrun D_r. In such cases the volume of degassed magma will eventually erupt, but will be observed later in the eruption. We use this scenario to account for the volume differences during the 2006 eruption. Early in the eruption SO_2 fluxes were elevated, but discharge rates were low (0.4–1.1 m^{3}/sec). Later in the eruption the D_r reached higher levels (8–4 m^{3}/sec) while the

SO_2 fluxes remained constant (Figure 1). This change indicates that magma that had been degassed during the initial phase of the eruption (Phase X) had finally reached the surface during the latter phase (Phase Y) so that overall $V_{supplied}$ and $V_{erupted}$ were balanced (Table 2).

When V_{erupt} exceeds $V_{supplied}$ two different scenarios can occur. Either the excess erupted volume is accounted for by eruption of previously degassed magma, or magma rises from depth at a faster rate than it is able to degas. The first scenario can occur at the beginning of an eruption when magma that has been stagnant within the shallow reservoir becomes incorporated with the eruption of new magma. Etna experiences almost constant degassing at the summit craters, at a time-averaged rate of ~1000 t/day (Caltabiano et al., 1994). Therefore there is potentially a substantial volume of degassed magma that can reside within the volcano's edifice at most times. This is available for incorporation with the next eruption. We observe this discrepancy at the onset of the 2004-2005 eruption (Figure 2). This eruption was preceded by a 20 month period of quiescence and was not preceded by an increase in SO_2 emissions (Burton et al., 2005). Thus, time was available to generate a degassed volume that could contribute to the onset of the eruption, in the case of the 2004–2005 eruption this contributed to an excess of $2.6x10^6$ m^3 of lava. The second scenario can occur during eccentric eruptions in which magma that feeds the eruption bypasses the central conduit (Andronico et al., 2005; Spilliaert et al., 2006). This scenario is observed during Phase I of the 2002–2003 eruption when an excess of 4.3×10^6 m^3 was erupted in the first five days. Therefore at the onset of the eruption a large volume of magma was able to erupt without having adequate time to degas.

6. Conclusions

Typically SO_2-derived volumes of degassed magma have been used to calculate volumetric budgets of volcanoes on time scales of years to decades. On such a time scale we find that during Etna's three eruptions of 2002-2006 there was a volumetric imbalance, with an excess of 2.3×10^7 m^3 (i.e. 24% of the magma supplied to the shallow system remained unerupted). However, over the time-scale of days-to-weeks we find that partitioning can vary within single eruptions. Once magma reaches a depth where sulfur exsolves several scenarios can occur: (1) the magma can erupt (sometimes incorporating excess volumes of previously degassed magmas), (2) it can remain within the edifice resulting in endogenous growth, or (3) it can be recycled (and perhaps intruded beneath the edifice). During an eruption lasting just a few weeks, all three scenarios can be encountered. During 2002–2006, over a total of 280 days of eruptive activity, only on 141 days did S_r couple with D_r. Therefore, only over 50% of the time were the gas-based measurements and satellite-based measurements coupled. This does not mean that either measurement is in error, but instead points to different processes that control the volume partitioning. Several processes can cause these volumetric imbalances: (1) magma can be rising at a faster rate than it is able to degas ($V_{supply}<V_{erupt}$), (2) magma is erupted in an explosive manner ($V_{supply}>V_{erupt}$), (3) degassed magma is not erupted ($V_{supply}>V_{erupt}$), or (4) the eruption of previously degassed magma occurs ($V_{supply}<V_{erupt}$).

SO_2 fluxes and measurements of discharge rates when used together can be used to assess volume partitioning during effusive eruptions. Because effusion rate can influence flow length and area (Walker, 1973; Pieri and Baloga, 1986) this allows potential hazards posed by emitted lava flows to be assessed, especially if we can resolve whether all or only a portion of the degassed magma is being erupted. Given our findings, to assess the actual eruption flux, discharge rates have to be measured. SO_2 fluxes can be used to determine discharge rates for eruptions where all magma supplied is subsequently effusively erupted, as is the current case at Kilauea (Sutton et al., 2001). However, SO_2 data should be coupled with other monitoring, such as measurements of discharge rates, during more complex cases to allow a correct assessment of volume partitioning.

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Figure 1. Etna 2002-2006 (a) Discharge, supply rates and partitioning, (b) Cumulative volumes of erupted lava and degassed magma. Note that when the two curves overlap $V_{supplied}$ and V_{erupt} are coupled. The square shows the field-based volumes of erupted lavas (*Allard et al.*, 2006). The two lines given in (a) and (b) for each of the rates and volumes show the derived upper and lower bounds calculated for each technique.

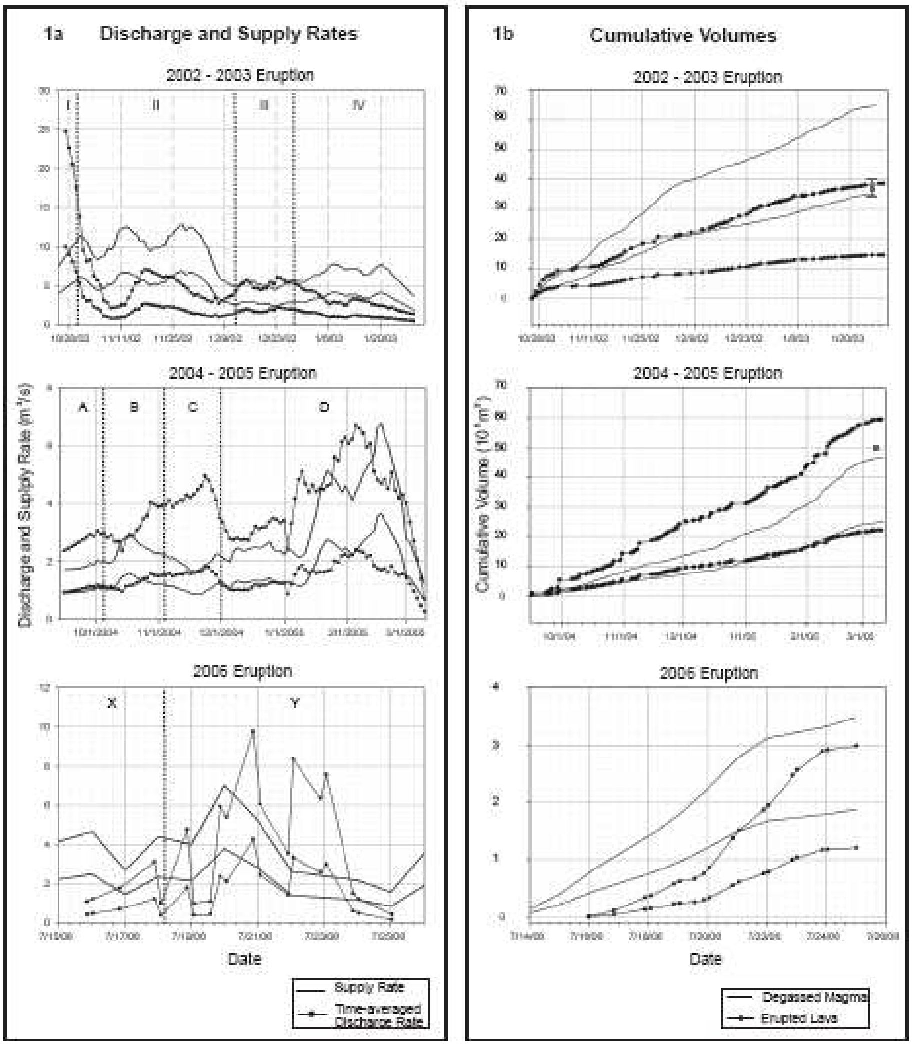

Figure 2. Volume partitioning for Etna, 2002-2006 eruptions.. Any value greater than zero indicates an excess of erupted lava, while any value less than zero indicates an excess of supplied magma

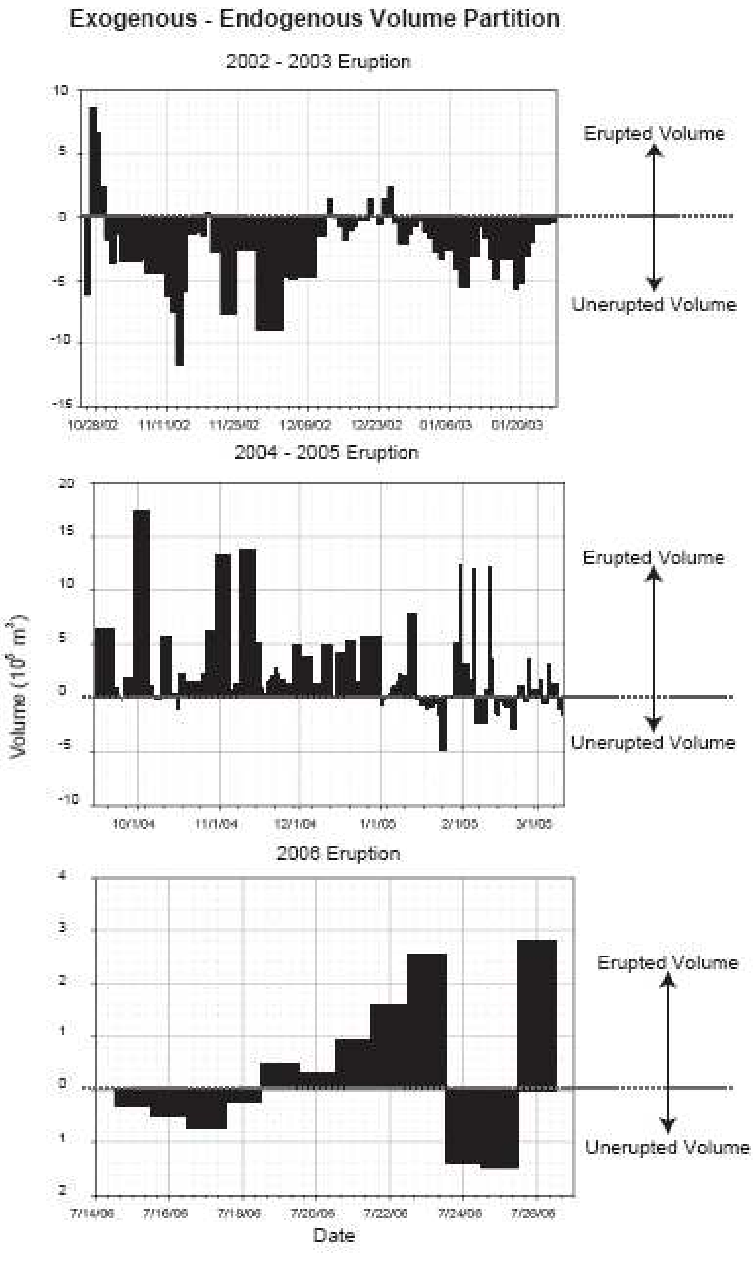

Table 1: Parameters, values and supporting references for constants used in calculating discharge and supply rate.

Parameter	Value	Reference
T_{surf} (℃)	100-500	Harris et al., 2000
T_{amb} (℃)	0	Harris et al., 2000
σ (W $m^{-2}K^{-4}$)	5.67×10^{-8}	Harris et al., 2000
h_c (W $m^{-2}K^{-1}$)	~10	Harris et al., 2000
DRE ρ (kg m^{-3})	2600	Harris et al., 2000
DRE c_p (J kg^{-1} K^{-1})	1150	Harris et al., 2000
Vesicularity	10-34	Harris et al., 2000
Bulk ρ (kg m^{-3})	1720-2340	Harris et al., 2000
Bulk c_p (J kg^{-1} K^{-1})	810-1035	Harris et al., 2000
Cooling Range (K)	200-350	Harris et al., 2000
□ (%)	45	Harris et al., 2000
C_L (J kg^{-1})	3.5×10^{5}	Caltabiano et al., 2004
x_c	30	Caltabiano et al., 2004
ρ_m (kg m^{-3})	2600	Caltabiano et al., 2004

Table 2: Definitions, descriptions and significance of parameters used in determining volumetric balance.

Parameter	Description and Significance	Derivation
S_r	Time-averaged (daily) supply rate of magma. Rate of magma entering the shallow portion of the system	Calculated by supplied magma volume flux required to give the measured SO_2 flux.
D_r	Time-averaged (daily) discharge rate of lava. Rate of lava being erupted from the volcano	Calculated by erupted volume flux required to balance heat loss.
V_{supply}	Volume of magma degassed over a given period of time. Volume supplied to the shallow portion of the system	Calculated by integrating S_r through time
V_{erupt}	Volume of lava erupted over a given period of time. Volume of erupted lava	Obtained by integrating D_r through time

Table 3: Eruption information, supply rates (m^3/s), discharge rates (m^3/s), volumes of supplied magma (m^3), volumes of erupted lava (m^3) and volumetric differences ($\Delta V = V_{erupt} - V_{supplied}$ (m^3)) for Etna eruptions 2002-2006.

Eruption:	**2002-2003**					**2004-2005**					**2006**		
Phase:	I	II	III	IV	Total	A	B	C	D	Total	X	Y	Total
Start Date	26-Oct-02	31-Oct-02	13-Dec-02	28-Dec-02		16-Sep-04	7-Oct-04	4-Nov-04	2-Dec-04		15-Jul-06	19-Jul-06	
Stop Date	30-Oct-02	12-Dec-02	27-Dec-02	29-Jan-03		6-Oct-04	3-Nov-04	1-Dec-04	10-Mar-04		18-Jul-06	25 July-06	
Duration (d)	5	42	15	33	95	21	28	27	98	174	4	7	11
Max D_r	33	9	8	5		5	5	6	12		5	10	
Max S_r	15	22	7	10		2	2	4	11		4	6	
V_{supply}	1.6×10^6	3.9×10^7	5.6×10^6	1.4×10^7	**6.0×10^7**	1.4×10^6	2.4×10^6	2.9×10^6	2.8×10^7	**3.5×10^7**	8.1×10^5	1.8×10^6	**2.6×10^6**
V_{erupt}	5.9×10^6	1.0×10^7	5.1×10^6	5.3×10^6	**2.6×10^7**	4.0×10^6	5.9×10^6	6.9×10^6	2.4×10^7	**4.1×10^7**	5.2×10^5	2.2×10^6	**2.7×10^6**
ΔV	**4.3×10^6**	**-2.9×10^7**	**-5.0×10^5**	**-8.7×10^6**	**-3.4×10^7**	**2.6×10^6**	**3.5×10^6**	**4.0×10^6**	**-4.0×10^6**	**6.1×10^6**	**-2.9×10^5**	**4.0×10^5**	**1.1×10^5**