Causes of Explosive Basaltic Volcanism in the 2001 Eruption of Mount Etna, Sicily

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1.0 Abstract

This paper attempts to better understand the chronology, processes and products involved in the explosive ash-forming events of the July-August 2001 eccentric eruption at Mount Etna, Sicily. A literature review, coupled with analysis of geochemical results published in recent journal articles, has been combined to answer these questions. The findings are therefore used to elucidate the stance on the events involved, with four stages defined to represent the aforementioned objectives. Stage 1 is considered to involve phreatomagmatic activity; Stage 2 represents a transitional stage towards Strombolian events; Stage 3 wholly involves Strombolian activity; whilst Stage 4 is considered indicative of Vulcanian activity.
2.0 Introduction

Situated on the eastern coast of Sicily (Fig. 1), Mount Etna is a stratovolcano, rising to a height of some 3330m a.s.l and dominating the lives of more than 2 million people (Kilburn & McGuire, 2001, p. 115), including Catania, Sicily’s second largest city (Fig. 2).

Etna’s activity has long been thought of as mild, typified by lava flows, fire fountaining and mild Strombolian activity from both summit craters and parasitic vents. Chester et al. (1985, p. 17) noted that in historical times (up to 1985) violent activity had been rare, with the exception of the 1979 eruption, which generated enough ash to disrupt population centres to the east and southeast, including Catania’s Fontanarossa airport.

The 2001 eruption (Fig. 3) represents one of the most explosive events in living memory, which included the release of juvenile ash, predominantly of 0.4 to 1mm in diameter, with a plume height of 5km a.s.l. (Taddeucci, Pompilio, & Scarlato, 2004, p. 33). Accompanying ash falls trended in an E and SE direction (Figure 9) and were recorded as far away as Cefalonia, Greece, 500km from the eruption site, reaching the island just 24 hours after the eruption (Dellino & Kyriakopoulos, 2003, p. 341). Involving both lateral and eccentric eruptions simultaneously (Andronico, Cristaldi, Del Carlo, & Taddeucci, 2009; Behncke & Neri, 2003; Coltelli, Miraglia, & Scollo, 2008; Corsaro, Miraglia, & Pompilio, 2007; Dellino & Kyriakopoulos, 2003; Lanzafame, Neri, Acocella, Billi, Funiciello, & Giordano, 2003; Metrich, Allard, Spilliaert, Andronico, & Burton, 2004; Neri, Acocella, Behncke, Maiolino, Ursino, & Velardita, 2005; Scollo, Del Carlo, & Coltelli, 2007; Taddeucci, Pompilio, & Scarlato, 2004; Viccaro, Ferlito, Cortesogno, Cristofolini, & Gaggero, 2006) it may be considered that this could pave the way for future violent eruptions such as that of 2002-03.

Much has been written and documented specifically on both the surface and subsurface processes and the eruptive products of the July 2001 event. However, it is not considered that a great degree of agreement has been forthcoming between authors on the processes involved in the eccentric eruption, with different hypotheses on the processes involved in the production of tephra during this eruption type. This could represent a number of serious flaws in the accuracy of the overall understanding of the hazards represented by this eruption, potentially leading to incorrect analysis of any similar future eruptions (such as 2002-03), and the hazards posed to the Mount Etna region. It is therefore the aim of this report to: (1) outline the timescale of violent basaltic events of the 2001 Etnean eruption, as considered by
Behncke and Neri (2003); (2) identify the products involved; and (3) discuss the processes involved in the formation of these products, by means of a literature review.

Figure 1: Location of Mount Etna in relation to other volcanic centres in Italy. Inset: location of the main population centres on Etna’s flanks. Modified from Chester, Duncan, & Dibben (2008, p. 218).
Figure 2: Populations of the main towns and cities of the Etna region in 1985. (After Chester et al 1985, p.60).
Figure 3: Map of the eruptive fissures and lava flows during the 2001 July-August eruption of Etna. (Scollo, Del Carlo, & Coltelli, 2007, p. 148)
3.0 Background

3.1 Structural Setting

The tectonic history of Eastern Sicily is greatly complex (Figure 4), chiefly governed by the collision of the Eurasian and African plates, comprising the opening and closing of the Ionian Sea, and the subduction, bending and possible compression of the Aeolian-Calabrian arc (Scarth & Tanguy, 2001, p. 55; Patane, Agostino, La Delfa, & Leonardi, 2009, p. 307). As subduction neared an end, thrusting of the Eurasian plate over the African plate occurred, forming the Appeninic-Maghrebian mountain chain situated to the west of the volcano (Barberi, Civetta, Gasparini, Innocenti, Scandone, & Villari, 1974, p. 123; Catalano, Torrisi, & Ferlito, 2004, p. 315). As a result of this, the Tyrrehnian part of Sicily is under contraction, whilst the Ionian side is under extension (Lanzafame, Neri, Acocella, Billi, Funiciello, & Giordano, 2003).

Figure 4: The main regional tectonic features of Mount Etna identifying the compressive domain to the west, considered to be a result of Africa-Europe plate collision, and the tensional domain of the Calabrian Arc Appeninic to the east (Barberi, Cocina, Neri, Privitera, & Spampinato, 2000, p. 319).
3.2 Local Setting

The collision of the African and Eurasian plates, as well as more complex regionalised structural patterns, has resulted in distinct rift zones (Figure 4) which has allowed magma to move laterally and radially away from the volcano’s more centrally-located vertical to sub-vertical network of dikes (Rust, Behncke, Neri, & Ciocanel, 2005, p. 141), producing flank eruptions at distances greater than 10km from the central craters.

Several hypotheses have been put forward for Etna’s volcanic formation. Tanguy, Condomines, & Kieffer (1997, p. 239) have proposed a hot-spot theory, which has been backed up by the $^{3}$He/$^{4}$He ratio of olivine phenocrysts in lavas having remained steady throughout the volcano’s history, and suggests the sub-continental lithosphere as the single source feeding Etna’s magmas (Clocchiatti, Schiano, Ottolini, & Bottazzi, 1998, p. 399). This theory involves the presence of a mantle diapir resulting from a localised high strain in the lithosphere, which acts as a heat flow channel (Tanguy, Condomines, & Kieffer, 1997, p. 239).

A ‘slab-window’ theory has been suggested by (Doglioni, Innocenti, & Mariotti, 2001, p. 25). This considers a vertical slab window, caused by the rollback of the Ionian lithosphere, which allowed for alkali magmatism beneath Etna. The area of rollback is thought to occur along the Malta escarpment, between Sicily and the Ionian Sea (Patane, La Delfa, & Tanguy, 2006, p. 832), with this heavily faulted zone of the volcano allowing the percolation of magma through the host rock, to the surface.
Figure 4: Map identifying the main North and South - and, to a lesser extent – West rift zones of the volcano. The main eruptive fractures and parasitic cones are also denoted (after Crisci, Iovine, Di Gregorio, & Lupiano, 2008). Key: 1. Eruptive fracture; 2. Parasitic cone; 3. Volcanics; 4. Sedimentary basement.
Figure 5: A simplified cartoon of the tectonic evolution of the eastern Sicily-Ionian Sea transition, and related emplacement of Mount Etna along the active right-lateral transtensional fault, resulting from the theory of differential rollback in the footwall of the accretionary wedge. Modified from Doglioni, Innocenti, & Mariotti, (2001).

3.3 Volcanic Evolution

Reasonably accurate documentation over the last 400 years of Etna’s eruptive activity has been used to better understand the pattern of volcanic behaviour from historic eruptions (Tanguy, Kieffer, & Patane, 1996, p. 259). Indications from this data are that effusive activity is dominant, with lava flows and Strombolian activity from active centres. However, more recent eruptions – particularly in 2001 – indicates a further stage of evolution with more explosive eruptions and the emission of, at times, two compositionally distinct magmas (Neri, Acocella, Behncke, Maiolino, Ursino, & Velardita, 2005, p. 253), and voluminous ash emissions. Consequently, Tanguy, Condomines & Kieffer (1997, p. 247) indicate the activity of eruptions previous to 1997 were a result of “subtle interactions” between mantle diapirism, the development of a permanent deep magma reservoir at a depth of 20-30km, and temporary shallow chambers allowing crystal fractination (Figure 6).
Figure 6: A schematic representation of the magmatic and structural evolution of Mount Etna, modified from Tanguy, Condomines, & Kieffer (1997, p. 245). Arrows indicate the movement in the mantle and resulting tensional stresses in the crust. Note the change in scale from early magma evolution in the asthenosphere, to present day. Porphyritic trachybasalts have formed where magma ponding occurs at shallower depths, whilst aphyric trachybasalts are erupted directly from a deep chamber.
4.0 Overview of the 2001 Eruption

The eruption was characterised by an initial paroxysmal fire fountaining event located at the Southeast Crater on the 13\textsuperscript{th} July 2001 (Viccaro, Ferlito, Cortesogno, Cristofolini, & Gaggero, 2006, p. 141), followed, days later, by seven separate lava flows – two originating from vents on the Southeast Crater, and five erupting from vents on five separate newly-formed fissure systems on the southern flank (Behncke & Neri, 2003, p. 465). Whilst lava flows were ongoing explosive activity in the form of two end-member, predominantly ash-forming events, and a transitional Strombolian and fire fountaining (Metrich, Allard, Spilliaert, Andronico, & Burton, 2004, p. 3) phase took place. These explosive products were almost exclusively formed at one fissure system locted at an elevation of 2570m in an area known as the “Piano del Lago” (Behncke & Neri, 2003, p. 466; Corsaro, Miraglia, & Pompilio, 2007, p. 402; Viccaro, Ferlito, Cortesogno, Cristofolini, & Gaggero, 2006, p. 141). Lava flows ceased on the 9\textsuperscript{th} August 2001 (Behncke & Neri, 2003, p. 466), marking the end of the eruption.

A brief chronology of the explosive eruptive activity and products produced from the Piano del Lago fissure system is outlined in Table 1, with an isopach map of the first ash event in Figure 7. The geochemical composition of lavas and ash are defined in Table 2 and Figure 8.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Start Date</th>
<th>End Date</th>
<th>Products</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19/07/2001\textsuperscript{1}</td>
<td>24/07/2001\textsuperscript{1}</td>
<td>Ash &amp; Lapilli\textsuperscript{1}</td>
<td>200-300m high pyroclastic column\textsuperscript{1,4}</td>
</tr>
<tr>
<td>2</td>
<td>24/07/2001\textsuperscript{1}</td>
<td>25/07/2001\textsuperscript{1}</td>
<td>Lava fountaining\textsuperscript{2,3,4} Ash, Lapilli &amp; Scoria</td>
<td>Up to 500m high\textsuperscript{4}</td>
</tr>
<tr>
<td>3</td>
<td>25/07/2001\textsuperscript{1}</td>
<td>01/08/2001\textsuperscript{1}</td>
<td>Lava fountaining\textsuperscript{3,4} and Scoria\textsuperscript{2,3}</td>
<td>100-120m high scoria cone formed\textsuperscript{1,3,4} Lava flowed from vent at base of cone from 26th to 1st August\textsuperscript{1,3}</td>
</tr>
<tr>
<td>4</td>
<td>01/08/2001\textsuperscript{1,3}</td>
<td>06/08/2001\textsuperscript{3}</td>
<td>Ash &amp; dense non-vesicular blocks\textsuperscript{3}</td>
<td>Pulsing ash explosions up to 5km high\textsuperscript{1,3} Progressively diminishing until 6th August\textsuperscript{1}</td>
</tr>
</tbody>
</table>

Table 1: An overview of the explosive activity observed at the Piano del Lago fissure system during the 2001 eruption, compiled from data available from 1: Behncke & Neri (2003); 2: Metrich et al (2004); 3: Taddeucci, Pompilio & Scaroato (2004); 4: Viccaro et al (2006).
Figure 7: Isomass map of the tephra deposits formed between 21-24 July 2001. Curves are given in kg m$^{-2}$, with coordinates in UTM-Datum ED50. From Scollo, Del Carlo, & Coltelli (2007, p. 152).
4.1 Geochemical Results for Erupted Products

<table>
<thead>
<tr>
<th>Eruption Type</th>
<th>Plagioclase (%)</th>
<th>Clinopyroxene (%)</th>
<th>P.I Index (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral</td>
<td>16-23%</td>
<td>10-19%</td>
<td>33-40%</td>
</tr>
<tr>
<td>Eccentric</td>
<td>5-7%</td>
<td>8-13%</td>
<td>18-22%</td>
</tr>
</tbody>
</table>

Table 2: Comparison of plagioclase, clinopyroxene and Porphyricity Index (P.I.) of Lateral and Eccentric lavas from the 2001 eruption using data gathered by Corsaro, Miraglia, & Pompilio (2007, p. 403).

Figure 8: Daily componentry of the airborne ash collected during the 2001 eruption, modified from Taddeucci, Pompilio, & Scarlato (2004, p. 40). The numbers to the right indicate 1: Ash and lapilli stage; 2: Lava fountaining and scoria stage; 3: Ash and block stage.
5.0 Discussion

For the purpose of this section each of the four events, as described in Table 1, will be considered separately.

5.1 First Stage (19-24 July)

As mentioned in Table 1 the explosive products of this phase were predominantly ash and Lapilli, as attested by the proximal section in Fig. 7. Taddeucci et al (2004, p. 40) indicated that these ash particles were sideromelane rich, although it should also be noted that a large proportion of lithics were incorporated during this stage relative to the other stages (Fig. 8). The same authors also suggest that, throughout the whole period of the eruptive events (Stages 1-4) emission rates were at an intermediate level during this stage.

It is considered by Behncke and Neri (2003, p. 465) that visual evidence of continuous “uprush” and “tephra-finger” activity of the pyroclastic column points to phreatomagmatic activity. This is backed up by evidence of a high lithic content during this stage (Table 1), which is considered to represent a high energy event, such as phreatomagmatic activity (Houghton & Smith, 1993, p. 414).

It was previously considered by Chester et al. (1985, p. 139) that such activity was unlikely at Mount Etna, and that any activity would be “limited”. However, evidence of previous phreatomagmatic eruptive activity at Etna is considered in the 18.7 ka flank eruption at Etna (Andronico, Branca, & Del Carlo, 2001, p. 235). Whilst this historic eruption was at an elevation of 800m a.s.l. where impermeable Pleistocene clays are located (Andronico et al. 2001, p. 235), no such deposits are considered to exist at the level of the 2001 eruption (2570m). In this instance, where only volcanic products exist, the presence of a shallow impermeable ash layer (of unknown depth) beneath the Piano Del Lago, inferred by Behncke and Neri (2003, p. 472) seems the most plausible location for groundwater to pond, especially as the same authors consider meltwater to collect at this location following each winter.

It is widely accepted by authors (Andronico, Cristaldi, Del Carlo, & Taddeucci, 2009; Behncke & Neri, 2003; Corsaro, Miraglia, & Pompilio, 2007; Dellino & Kyriakopoulos, 2003; Guest, Cole, Duncan, & Chester, 2003, p. 199; Lanzafame, Neri, Acocella, Billi, Funiciello, & Giordano, 2003; Metrich, Allard, Spilliaert, Andronico, & Burton, 2004; Neri, Acocella, Behncke, Maiolino, Ursino, & Velardita, 2005; Patane, La Delfa, & Tanguy, 2006; Taddeucci, Pompilio, & Scarlato, 2004; Viccaro, Ferlito, Cortesogno, Cristofolini, &
that an eccentric dike cut through this shallow aquifer, allowing magma-water interaction. This has also occurred at a number of other basaltic volcanoes, most notably Surtsey, but also including (but not limited to) Taupo Volcanic Centre (Wilson & Smith, 1985, p. 329), Crater Hill, New Zealand (Houghton, Wilson, & Smith, 1999, p. 119), Croscat, Garrotxa Volcanic Field (Di Traglia, Cimarelli, de Rita, & Gimeno Torrente, 2009, p. 89), Fontana, Nicaragua (Costantini, Houghton, & Bonadonna, In Press) the Canary Islands (Clarke, Troll, & Carracedo, 2009, p. 226) and the Prebble and Mawson Formations, Antarctica (Elliot & Hanson, 2001, p. 183). In such magma-water interactions, it is not considered that the chemistry of the magma is an important factor in the explosivity of the eruption compared other variables such as the depth of the interaction and the amount of water made available.

5.2 Second Stage (24-25 July)

Characterised by a mixture of ash, lapilli, fire fountaining and scoria production (Table 1) this activity was marked by decreasing lithic ejecta and increasing Sideromelane (Figure 8). It is considered that this stage is characteristic of an transitional phase between the first (phreatomagmatic stage) and the third stage, indicated by the waning of phreatomagmatic activity (Behncke & Neri, 2003, p. 472) and a change to gradually increasing lava fountaining and scoria production (Taddeucci, Pompilio, & Scarlato, 2004, p. 35; Viccaro, Ferlito, Cortesogno, Cristofolini, & Gaggero, 2006, p. 142).

In order for a change in events it is considered that magma-water interaction must have been reduced in one of three ways: 1) All of the groundwater was consumed; 2) the fragmentation level of the magma rose above the watertable (Behncke & Neri, 2003, p. 472); 3) An increase in emission rates of the magma allowed the conduit to seal itself, preventing water interaction (Taddeucci, Pompilio, & Scarlato, 2004, p. 52).

Behncke & Neri (2003, p. 473) consider the first point to be unlikely, because of their hypothesis that phreatomagmatic activity occurred at Stage 4, and therefore consider the second option. They noted that when ejection angles were low (with magma high in conduit) activity moved from phreatomagmatic to Strombolian and vica verca. However, more recent evidence suggests that the underlying eccentrically located magma was volatile rich and microlite (crystal) poor ((Table 2) (Clocchiatti, Condomines, Guenot, & Tanguy, 2004, p. 397; Taddeucci, Pompilio, & Scarlato, 2004, p. 37)). This increase in volatiles, whilst being
microlite poor and therefore of a lower viscosity, would suggest a more rapid ascent, contributable to the theory of an increased emission rate. It can be hypothesised that whilst this magma was more volatile rich, the low crystal content of the magma allowed a significant portion of the volatiles to readily exsolve from the magma, resulting in Strombolian activity.

5.3 Third Stage (25th July – 1st August)

It is considered that the third stage is marked by the complete transition of activity to dry magmatic eruptions, with a reduction of lithic fragments within ash samples and an increase in sideromelane content (Fig. 8), leading to predominantly lava fountaining and scoria cone production over ash-forming events (Behncke & Neri, 2003, p. 465). Over the coming days it is noted that a more tachylite-rich ash with a greater crystal content was erupted on the 30th July to the 1st August, at the end of this third stage (Fig. 8).

The trend towards more tachylite-rich erupted products suggests the presence of magma mixing at depth (Taddeucci, Pompilio, & Scarlato, 2004, p. 52). A greater crystal content of the magma suggests that it had a residence time greater than the previously erupted magma, allowing crystallisation and loss of volatiles either through this process, or by slower migration due to the higher viscosity attributable to crystallisation. This hypothesis agrees with that of Clocchiatti et al. (2004, p. 411), Taddeucci, Pompili & Scarlato (2004, p. 53) and Viccaro et. al (2006, p. 156).

5.4 Fourth Stage (1st-6th August)

This stage was marked by the eruption of block and ash deposits (Table 1) and coincides with the almost complete replacement of sideromelane ash with tachylite ash (Figure 8). It has been considered by Behncke & Neri (2003, p.466) that this activity marks a final phreatomagmatic phase. However, this stage was marked by a much higher eruption column of 5km a.s.l. (Taddeucci, Pompilio, & Scarlato, 2004, p. 33), with Dellino and Kyriakopoulos (2003, p. 341) noting that ash falls occurred as far away (500km) as Cefalonia, Greece. These observations suggest that different mechanisms may have been involved.

Combined with evidence from the ash componentry (deficient in lithics), it is not considered that this phase involved water-magma interaction, or that, at the very least this was not the main cause of the eruption style. However, Dellino and Kyriakopoulos (2003 p. 342), in assessing ash fall at large distances, identified stepped features, considered to relate to melt-
fragmentation in a brittle mode, known to occur during magma-water interaction. The same authors noted that the glass particles showed blocky textures with few isolated vesicles of spherical form (2003, p. 342), suggesting that exsolution and expansion did not play a major role in the eruptive dynamics.

It is hypothesised that the final stage, dominated by ash pulsations (Taddeucci, Pompilio, & Scarlato, 2004, p. 33), is related to the ingress of this new tachylite- and crystal-rich magma into the conduit system, which, owing to its higher viscosity, is assumed to have ascended at a slower rate relative to the previous magma. Slow ascent would allow the magma to degas, reducing the fragmentation potential. This contradicts the hypothesis posed by Clocchiatti et. al. (2004, p. 411) who consider the high explosivity to be a result of this magma moving from a minimum depth of 30km below the volcano to mix with the eccentrically erupting magma within the space of a few months, as inferred from $^{210}$Pb-$^{226}$Ra disequilibria, and hence a high emission rate. However, a high emission rate was not observed during this final stage according to Taddeucci, Pompilio & Scarlato, 2004, p.52).

It is considered that a combination of these aforementioned events led to the voluminous ash production event. With low effusion rates of this final phase magma it is considered that voluminous and pulsating ash production could not have occurred. Instead, it is proposed that a deep magma ascended relatively rapidly, possibly through a network of dikes, to mix with the eccentrically erupting magma. Ascent was slowed at depth where mixing of the two magmas occurred due to the presence of the original, now more viscous (higher microlite content) magma, resulting in degassing of this new magma body. It is then considered that the hypothesis of Taddeucci, Pompilio & Scarlato (2004, p. 53) fits well, whereby a plug of this combined, microlite-rich magma – with a high yield strength and high liquid and bulk viscosities – prevents the upward migration of magma. Ash pulsations are therefore produced when the build up of volatiles from the degassing magma, collecting beneath this plug, exceed the plug’s strength, causing Vulcanian behaviour.

This is not considered to represent the first time an Etnean ash-forming event has occurred in this way, with the Plinian eruption of 122BC thought to have involved increased viscosity caused by microlites (Sable, Houghton, Del Carlo, & Coltelli, 2006, p. 351). Other basaltic volcanoes, such as Fontana, Nicaragua (Costantini, Houghton, & Bonadonna, In Press) and Tarawera in 1886 (Houghton, Wilson, Del Carlo, Coltelli, Sable, & Carey, 2004, p. 12) have acted similarly in the past.
6.0 Conclusions

The 2001 eccentric explosive basaltic eruption is considered to be representative of the following stages:

1) Initial phreatomagmatic activity (19th-24th July, 2001), caused by the intrusion of magma into a shallow aquifer, creating a 200-300m high eruption column which dispersed predominantly ash and Lapilli with a high lithic content.

2) Transition from phreatomagmatic to Strombolian activity (24th-25th July, 2001), resulting from an increase in the emissivity of a volatile- and sideromelane-rich, but microlite poor magma.

3) Strombolian activity (25th July to 1st August, 2001) through the continued ascent of the magma involved in stage 2.

4) Vulcanian activity (1st-6th August, 2001) resulting in a 5km a.s.l. tephra column, forming block and ash deposits. It is considered that this activity was caused by a more tachylite- and microlite-rich magma essentially plugging the conduit. Pulsing ash and block events are therefore produced when the strength of the magma plug is exceeded by the strength of degassing volatiles from the underlying magma.

References


