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# Effusion rate estimations during the 1999 summit eruption on Mount Etna, and growth of two distinct lava flow fields

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**Abstract**

Detailed studies of the evolution of two major flow fields during the 1999 eruption on Mount Etna provide useful insights into the development of different types of flow fields. During this eruption, two large lava flow fields were emplaced. The Eastern flow field, which formed between February and November, was erupted from three primary vents at the base of the Southeast Cone, one of four eruptive centres in the summit region of Mount Etna. This compound flow field was characterised by a complex tube network, skylights, ephemeral vents and tumuli. Between mid-October and early November, while the Eastern flow field was still active, another flow field was erupted from the western rim of the Bocca Nuova, one of the other eruptive centres. This Western flow field was emplaced during one month of discontinuous activity and is composed of discrete, channel-fed a′a flow units that formed a fan-shaped flow field. Major periods of flow advance within this flow field took place during phases of relatively high flow rate that lasted a few hours to days. The discontinuous supply prevented the formation of lava tubes within this flow field. The Eastern and Western lava flow fields from the Southeast Cone and Bocca Nuova have distinctive morphologies that reflect their emplacement mechanisms. Many of these morphological features are large enough to be seen on aerial photographs. This has implications for assessing the emplacement conditions of older flow fields on Earth and on other planets.



*Keywords:* lava flow; effusion rate; Mount Etna

## 1. Introduction

The onset of eruptive activity on populated volcanoes is often a time of uncertainty, not only for those living on the volcano, but also for those with responsibility for hazard prediction. For effusive eruptions, the most important questions are, firstly, how rapidly will flows advance, secondly, how large an area will be covered by lavas, and, thirdly, how far will the furthest lavas flow. For volcanoes such as Mount Etna, long-term supply rates of magma to the volcano are relatively stable (Wadge et al., 1975; Wadge, 1981). Consequently, the time interval between a new eruption and previous activity can be used as a guide to the maximum volume of lava that is liable to be discharged. However, we need to know more than volumes. For example, there

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are large variations in the thickness of lava flows and flow fields. These are influenced by a number of factors including whether lavas, on eruption, form single channel-fed flows or long-lived flow fields. The importance of this and other factors became clear during the 1999 eruption of Mount Etna. This was an excellent opportunity to investigate the factors that control the formation of two distinct, dominantly a′a flow fields. At least one of us was present during all important phases of this eruption, and we were able to investigate the effects of eruption duration, vent location, variations in effusion rate and gradient on the nature of flow fields and the lengths of lava flows. Our detailed study of the complex evolution of two major flow fields allows us to define clear criteria that can be used to separate flow fields into those erupted at relatively high and low effusion rates.

The present study builds upon earlier work by Guest et al. (1987) who compared two lava flow fields that developed during the 1981 and 1983 flank eruptions on Mount Etna. These flow fields had similar maximum flow lengths even though there was a 6-fold difference in erupted volume and a 16-fold difference in effusion rate. Guest et al. (1987) concluded that most of the flows erupted during the 1983 eruption stopped flowing when cooling of lava in the flow fronts and/or interior prevented further advance of the flow. They referred to these as cooling-limited lava flows. By contrast, the 1981 lava flows were erupted at high effusion rates for relatively short periods. These flows stopped advancing because the supply vents stopped discharging lava. Lava flows of this type were referred to as volume-limited flows.

We begin by reviewing current views on the evolution of lava flow fields. This is followed by a detailed description of the 1999 flow fields, and finally we use this information to identify criteria that can be used to distinguish between high- and low-effusion rate flow fields on Etna.

## 2. Lava flow fields: a brief review

Few effusive eruptions form single, simple lava flows; flow fields are more common. A flow field is defined as a collection of morphologically distinct lava flows (Nichols, 1936; Walker, 1971; Self et al., 1996; Thordarson and Self, 1998). In the remainder of this paper, we consider only a′a lava flow fields, since all lava flows formed during this eruption, with the exception of those erupted within the first 5–40 m of some vents, were a′a. For recent excellent reviews on the formation of pahoehoe flow fields, see Hon et al. (1994), Peterson et al. (1994), Self et al. (1996), Kauahikaua et al. (1998), Thordarson and Self (1998), Anderson et al. (1999), Crown and Baloga (1999), and Blake and Bruno (2000).

The overall shape of a lava flow field is defined by the distribution of a few major lava flows, modified by smaller flows filling in gaps and locally modifying the periphery of a flow field (Kilburn and Lopes, 1991; Kilburn and Guest, 1994). During sustained eruptions, and when eruption rates are not fluctuating widely, a stable crust can form, and lava can drain through ephemeral vents at the fronts or margins of stationary or slowly advancing lava flows (Pinkerton and Sparks, 1976; Calvari and Pinkerton, 1998). Under these conditions, lava tubes can form (Calvari and Pinkerton, 1998). These have the potential to lengthen flow fields because of reduced heat loss from tubes compared with channels (Keszthelyi and Pieri, 1993; Calvari et al., 1994; Pinkerton and Wilson, 1994; Keszthelyi, 1995; Calvari and Pinkerton, 1998; Kauahikaua et al., 1998; Sakimoto and Zuber, 1998). By contrast, a fluctuating supply results in channel overflows, breaching of channels, and the formation of new flows (Guest et al., 1987; Jurado-Chichay and Rowland, 1995). This generally inhibits lava tube development, and results in lava flow field widening. Of course, channel breaching and overflows can also form by other mechanisms (e.g. through reduced flow advance rates following extensive cooling of a flow front; see Pinkerton and Wilson, 1994). Flows thicken by one or more of the following processes: cooling of distal parts of an advancing flow, advance of a flow over shallow slopes, inflation of a stationary flow by endogenous growth (Hon et al., 1994) or superposition of discrete flows.

In view of the importance of effusion rate on the morphology of lava flows and flow fields, we measured this whenever possible during the 1999 Etna eruption. In the next section we review the problems of measuring effusion rate, the methods we employed, and the terminology used in the remainder of this paper.

## 3. Effusion rate measurements: problems and terminology

Effusion rates during basaltic eruptions are often difficult to measure because of restricted access to the active flow field and problems of estimating mean lava flow thickness. For Mount Etna, effusion rate measurements are available only for limited periods of many eruptions (Guest et al., 1974; Pinkerton and Sparks, 1976; Frazzetta and Romano, 1984). Continuous records exist only for the most recent eruptions (Bertagnini et al., 1990; Calvari et al., 1994). In view of the importance of effusion rate measurements, particularly at the onset of an eruption (Calvari and Pinkerton, 1998; Kilburn, 2000), a number of methods have been used to measure this parameter (Pinkerton and Sparks, 1976; Calvari et al., 1994; Harris et al., 1998; Kauahikaua et al., 1998).

In this paper we use 'flow rate' for the rate of lava that was discharged through single vents, and 'effusion rate' for the estimated instantaneous total effusion rate at which lava is erupted from a source vent or fissure. These values typically vary during an eruption. 'Eruption rate', on the other hand, is the mean effusion rate throughout the eruption, and 'mean flow rate' is calculated for single flow units during their emplacement. Effusion rate and flow rate measurements were performed during field surveys every time conditions permitted during the 1999 eruption. Measurements of effusion rate were made using various techniques. Local flow rates were calculated for individual boccas by measuring the channel widths and peak surface velocities of lava within channels. Flow thickness was estimated from levée heights. Regular observations and mapping at different stages of the eruption allowed us to measure the depths of a number of these channels after drainage. When such measurements were made, we used the drained depth as the flow thickness instead of the levée height. The error of these measurements is considered to be less than 10%, because we have found good agreement between flow thickness estimated on the basis of levée height and channel depth measured after drainage. However, a few drained channels were up to three times deeper than levée heights. This may arise (1) from mechanical erosion, (2) because the floor of the channel collapsed into an underlying tube (Calvari and Pinkerton, 1999), or (3) because the channel lies along the eruptive fissure. Errors were greatest for the part of a flow within 100 m from the source vent. Estimated flow rates are generally maximum values, because continued cooling of flow margins reduces the cross-section of final channels.

We calculated the mean lava flow rate ($Q$) using the equation for flows of Newtonian fluids in hemispherical tubes. The flow rate is calculated from $Q = 0.67\ (V_{max}\ A)$ where $V_{max}$ is the maximum flow surface velocity and $A$ is the area of the flow section. We estimate a maximum error of 10% for channel width, 30% for thickness and 20% for flow surface velocity, which gives a cumulative error of $\pm 37\%$ for flow rates.

Larger errors are inevitable when estimating flow rate measurements inside active lava tubes. Here, the main source of error comes from depth estimates; these are difficult measurements to make during an eruption. Another source of error during some eruptions is the formation of a number of small, short-lived (or ephemeral) vents, many of which can be active simultaneously. In large a′a flow fields, it is not possible to visit them all during each series of measurements. On the rare events when this is done, there is a possibility of 'double accounting' because new ephemeral vents can form at the fronts of flows the flow rates of which had already been measured. During the 1999 eruption we measured flow rates at all of the major vents on each visit, and we took care to exclude flow rates made at ephemeral vents that were fed by flows or tubes the flow rates of which had already been measured.

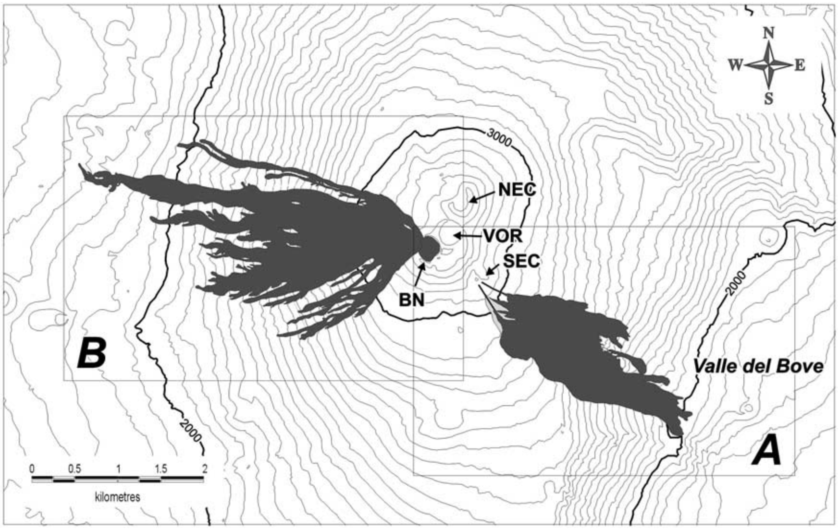


Fig. 1. Map of the summit region of Mount Etna, showing the four active craters (abbreviations: VOR, Voragine or Chasm; SEC, Southeast Cone; NEC, Northeast Cone; BN, Bocca Nuova), the lava flow fields which were emplaced from the base of the Southeast Cone and from the rim of the Bocca Nuova, and the eruptive fissure that propagated from the southern base of the Southeast Cone on 4 February 1999. Contour lines are 50 m apart.

## 4. The formation of the 1999 lava flow fields

The 1999 Etna eruption began on 4 February and ended on 14 November. During this eruption, two large lava flow fields were emplaced. The first of these formed between February and November, and we refer to it as the Eastern flow field. This flow field, which was erupted at relatively low flow rates from three primary vents at the base of the Southeast Cone, one of the four eruptive centres on the summit region of Mount Etna, was characterised by a complex tube network, skylights, ephemeral vents and tumuli. Between mid-October and early November, another flow field was erupted from the western rim of the Bocca Nuova, currently the largest summit crater on Mount Etna. This Western flow field is composed of discrete channel-fed a′a flows and forms a fan-shaped flow field. Major periods of flow advance in the Western flow field took place during phases of relatively high flow rate that lasted a few hours to days.

During the formation of the Eastern flow field, three primary vents formed at different locations at the base of the Southeast Cone, and these formed distinct flow fields. The first of these lasted significantly longer than the other two, and it was more complex than those that followed. To make it easier for the reader to follow the development of the Eastern flow field, we will subdivide it into five distinct phases.

### *4.1. Formation of the Eastern flow field: 4 February–14 November*

#### *4.1.1. Phase 1*

The frequency of Strombolian activity at the Southeast Cone on 4 February (Fig. 1) gradually increased and climaxed with the formation of a 3-km high sustained eruption column. While violent explosions were still continuing at the Southeast Cone, a fissure opened on its southeastern flank (Figs. 2 and 3). Strombolian activity shifted from the Southeast Cone to the newly opened fissure while it was propagating to the southeast. The fissure had a final length of 700 m and stopped at 2920 m a.s.l. (Fig. 1).

#### *4.1.2. Phase 2*

This was the longest phase, and it was the period during which most of the Eastern flow field was formed. It began with the discharge of lava

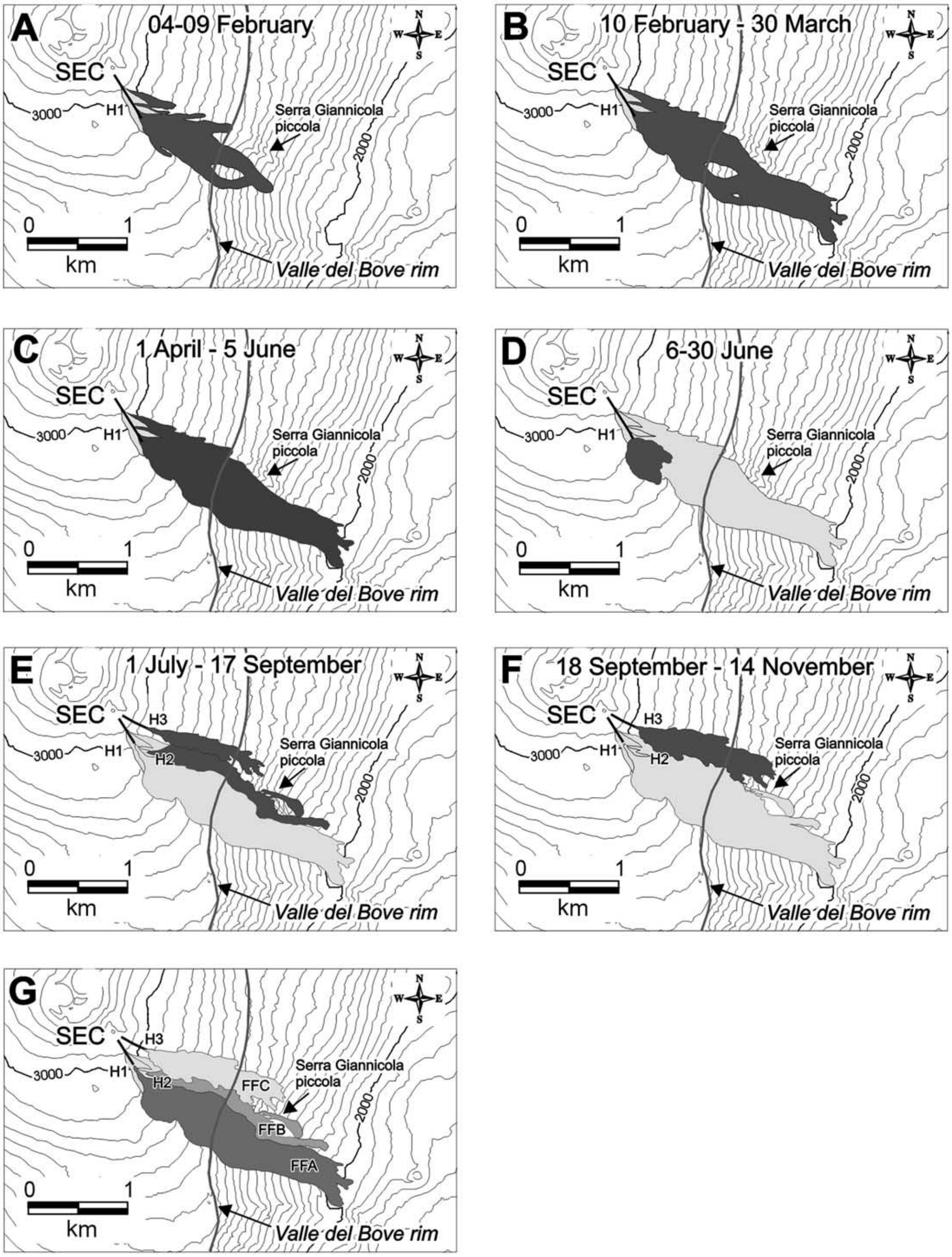


Fig. 2. Map of the main stages of growth of the three flow fields that were erupted from the base of the Southeast Cone between February and November 1999. Active flows are dark grey. The three resulting flow fields, which together form the Eastern flow field, are shown in (G). H1, H2 and H3 represent the primary vents where mild Strombolian activity was concentrated at different times during the eruption.

Fig. 3. Aerial view from the south of the Southeast Cone (right) and the Bocca Nuova (left). The eruptive fissure on the south-eastern flank of the Southeast Cone and the lava flow field emerging from its base are also visible (right margin of the image). Photograph taken on 21 May 1999.

from the lower part of the fissure. Lavas flowed east and southeast (Fig. 2A), and 36 hours later reached the rim of the Valle del Bove, 900 m from the lower end of the fissure. Three stable vents formed along the fissure and these fed three separate flows that merged after a few hundred metres to form a 450-m wide flow field that extended from the fissure to the rim of the Valle del Bove (Fig. 2A). On 7 February the lava flows entered the steep (35–65°) headwall of the Valle del Bove. In this region, flow fronts broke into boulders that rolled downslope. On 9 February the area covered by the flow field was $\sim$0.5 km$^2$ (Fig. 2A). At this time, lava was fed through two large channels that merged on the western wall of the Valle del Bove at 2400 m a.s.l. Lava then flowed into the Valle del Bove. Cooling of the frontal zones reduced advance rates of the flow front, and this was one of the two mechanisms for generating overflows from proximal and medial lava channels, the other being increased effusion rate. On the upper part of the flow field (i.e. the part that extended from Hornito H1 (Fig. 2), the primary source of lava during this part of the eruption, to the rim of the Valle del Bove) many ephemeral vents opened, and lava channels started to roof over by the mechanism described in Calvari and Pinkerton (1998). The flow field attained a maximum length of 2.8 km on 10 March (38 days after the eruption began; Fig. 2B), when the lava fronts reached 1970 m a.s.l. On 14 March the lava flow field covered more than 1 km$^2$.

From March to mid-April, ephemeral vents formed along the upper and lower parts of the flow field and the total flow field increased in width and thickness (Fig. 2C). During this period, there were no active vents in the proximal parts of the flow field. Instead, ephemeral vents migrated downhill from the fissure system, suggesting tube growth (Mattox et al., 1993; Calvari and Pinkerton, 1998). The only exception was the morning of 24 March, when a new primary vent opened at the base of the eruptive fissure and produced three lava flows that flowed on top of existing flows in the upper part of the flow field. On the same day, new flows reached the rim of the Valle del Bove. At that time, the most distal flow fronts in the lower flow field were stationary, and no lava advanced beyond this point during the remainder of the eruption.

By 31 March the flow field area was 1.14 $km^2$. During April, lava continued to emerge from the eruptive fissure, leading to an increase in the thickness and width of the flow field (Fig. 2C). At this time, there were a large number of ephemeral vents on the upper part of the flow field, mainly near the fissure, and a few in the steep headwall of the Valle del Bove. These fed thin (1–2 m), narrow (2–5 m) lava flows with maximum lengths of a few hundred metres. In common with the majority of flows in the Eastern flow field, these flows behaved as classic cooling-limited flows (see Guest et al., 1987; Pinkerton and Wilson, 1994). During this phase of activity, the central part of the flow field increased in thickness.

By March, a stable network of lava tubes had formed in the upper part of the flow field, and skylights in the roof of the tubes allowed us to measure surface velocities of lava flowing within tubes. Estimated flow rates in the main lava tube, based on measurements through skylights, were $\sim 1$ $m^3$ $s^{-1}$. However, cumulative measurements of local flow rate from ephemeral vents confirmed that the total effusion rate was up to 2 $m^3$ $s^{-1}$ (Table 1). This difference suggests that either there were more tubes, or that tube depths were greater than estimated. Since some of the active tubes were directly above the eruptive fissure, estimated flow depths will be conservative.

By 15 April, all skylights in the upper part of the flow field had roofed over, and active lava flows were almost entirely restricted to the Valle del Bove. Ephemeral vent migration downflow at this time was accompanied by the growth of many tumuli, some exceeding 10 m in height. Some of these were located along the eruptive fissure whilst others were above active tubes. Tumuli were characterised by the eruption of pahoehoe lava in their proximal channels. These were dominant features of the lava field during the following two months. Lava continued to flow through tubes in the upper lava field until 15 May, and most of the lava within the Valle del Bove emerged from ephemeral vents between 2400 and 2600 m a.s.l., feeding flows several hundred metres long. The increase in thickness of the lower part of the flow field partially buried the southern flank of Serra Giannicola Piccola, a prominent landmark in this part of the Valle del Bove, and formed a wide lava terrace south of this ridge (Fig. 2C).

On 16 May, ephemeral vents began to form again on the upper part of the flow field, with many breakouts close to the eruptive fissure. The resulting lava flows were up to a few hundred metres long, and a few of these reached the rim of the Valle del Bove. At the same time, ephemeral vents within the Valle del Bove were active, with no obvious change in their flow rates. This suggests that, at that time, the entire tube network was full of lava. Cumulative flow rates, measured on 23 May (Table 1), indicate a temporary increase in the effusion rate to 4 $m^3$ $s^{-1}$. Simultaneous activity from ephemeral vents in both the proximal and distal parts of the lava field continued until 6 June. After this, we conclude that a combination of cooling, collapse of the roof and walls of lava tubes, and/or a decrease in effusion rate led to the complete closure of the lower tube system. Thereafter, effusive activity ceased in the Valle del Bove, and active flows were restricted to the area close to the eruptive fissure (Fig. 2D; H1 site). During this phase, some short lava flows widened the upper part of the flow field, but the calculated cumulative volume denoted a clear decrease in effusion rate (Table 1). The flows increased the thickness of the upper lava field, almost totally burying the many tumuli formed during April and May.

#### *4.1.3. Phase 3*

On June 6, Strombolian activity was observed at the summit craters of the volcano, suggesting the injection of fresh magma into the high level plumbing system of the volcano. However, the effusion rate from the base of the Southeast Cone was low at that time (0.3–0.6 $m^3$ $s^{-1}$; Table 1), and a number of tumuli formed. On 25 August effusive activity stopped at the base of the Southeast Cone, and there was no evidence of activity on any other part of the flow field.

Table 1
Effusion rates from the Southeast Cone (Eastern flow field) during the 1999 eruption

| Date (dd/mm/yy) | Calculated effusion rate ($m^3$ $s^{-1}$) | Maximum effusion rate ($m^3$ $s^{-1}$) | Minimum effusion rate ($m^3$ $s^{-1}$) |
|---|---|---|---|
| 5/2/99 | 4.891 | 6.701 | 3.081 |
| 9/2/99 | 4.506 | 6.173 | 2.839 |
| 19/2/99 | 1.155 | 1.583 | 0.728 |
| 3/3/99 | 5.863 | 8.032 | 3.693 |
| 9/3/99 | 0.436 | 0.598 | 0.275 |
| 10/3/99 | 1.372 | 1.880 | 0.865 |
| 11/3/99 | 0.118 | 0.161 | 0.074 |
| 12/3/99 | 0.075 | 0.102 | 0.047 |
| 13/3/99 | 0.140 | 0.192 | 0.088 |
| 14/3/99 | 0.457 | 0.626 | 0.288 |
| 15/3/99 | 0.381 | 0.521 | 0.240 |
| 25/3/99 | 1.500 | 2.055 | 0.945 |
| 31/3/99 | 0.329 | 0.451 | 0.207 |
| 14/4/99 | 1.91 | 2.616 | 1.203 |
| 20/4/99 | 1.441 | 1.973 | 0.908 |
| 29/4/99 | 0.838 | 1.147 | 0.528 |
| 17/5/99 | 1.479 | 2.026 | 0.932 |
| 18/5/99 | 2.948 | 4.039 | 1.857 |
| 21/5/99 | 0.286 | 0.392 | 0.180 |
| 22/5/99 | 0.059 | 0.081 | 0.037 |
| 23/5/99 | 3.981 | 5.454 | 2.508 |
| 6/6/99 | 0.436 | 0.597 | 0.274 |
| 9/6/99 | 0.117 | 0.160 | 0.073 |
| 28/6/99 | 0.536 | 0.734 | 0.338 |
| 22/7/99 | 0.089 | 0.122 | 0.056 |
| 19/8/99 | 0.158 | 0.216 | 0.099 |
| 25/8/99 | 0 | 0 | 0 |
| 28/8/99 | 0.905 | 1.239 | 0.570 |
| 30/8/99 | 0.083 | 0.114 | 0.052 |
| 31/8/99 | 0.004 | 0.006 | 0.003 |
| 5/9/99 | 12.075 | 16.543 | 7.607 |
| 6/9/99 | 0.145 | 0.199 | 0.091 |
| 7/9/99 | 0.252 | 0.345 | 0.159 |
| 8/9/99 | 0.543 | 0.744 | 0.342 |
| 9/9/99 | 0.342 | 0.468 | 0.215 |
| 17/9/99 | 0.033 | 0.045 | 0.020 |
| 27/9/99 | 0.306 | 0.419 | 0.193 |
| 28/9/99 | 0.083 | 0.114 | 0.052 |
| 6/10/99 | 0.142 | 0.194 | 0.089 |
| 14/10/99 | 0.042 | 0.057 | 0.026 |
| 16/10/99 | 0.286 | 0.391 | 0.180 |
| 21/10/99 | 0.338 | 0.463 | 0.213 |
| 22/10/99 | 0.467 | 0.639 | 0.294 |
| 23/10/99 | 0.150 | 0.205 | 0.095 |
| 24/10/99 | 0.075 | 0.103 | 0.047 |
| 27/10/99 | 5.997 | 8.216 | 3.778 |
| 4/11/99 | 0.022 | 0.030 | 0.014 |
| 10/11/99 | 0.001 | 0.001 | 0 |

#### *4.1.4. Phase 4*

Between 26 and 27 August, Strombolian activity increased both in frequency and energy at the Bocca Nuova, and mild explosive activity resumed at the base of the Southeast Cone on 27 August, forming four new hornitos located above a new fissure (H2 site; Fig. 2E), 30 m northeast of primary vent H1. A new flow field (FFB; Fig. 2G) then formed on the northeast flank of the previous field (FFA; Fig. 2G). Flows were erupted at low effusion rates, and these had maximum lengths of 2 km. The maximum width of the FFB flow field (Fig. 2G) was 250 m, and its area was ∼0.32 km$^2$.

#### *4.1.5. Phase 5*

Another significant change in effusion rate occurred on 4 September, following paroxysmal explosions within the Bocca Nuova and the Chasm or La Voragine (VOR; Fig. 1). A new lava flow emerged from the upper part of the eruptive fissure on the southeastern flank of the Southeast Cone (Fig. 3), and a new primary vent (northeast of the H2 site) formed at the eastern base of the Southeast Cone. Mild explosive activity from this vent formed another hornito (H3; Fig. 2E), and lava flows were discharged from its base at an initially high rate of ∼8–17 $m^3$ $s^{-1}$, over twenty times the mean effusion rate estimated during the whole emplacement of the Eastern flow field. Flow fields FFB and FFC were both active between 4 September and 17 September (Fig. 2E), suggesting an increase in effusion rate. Between 18 September and 14 November only flow field FFC was active (Fig. 2F), suggesting a gradual decrease in the effusion rate (see Table 1). Flow field FFC had a maximum length of 1.5 km, a maximum continuous width of 320 m and an estimated thickness of up to 30 m. There was virtually continuous Strombolian activity from hornitos H3 between early September and early November.

### *4.2. Formation of the Western flow field: 17 October-5 November*

During early to mid-October, Strombolian activity at the Bocca Nuova gradually increased in

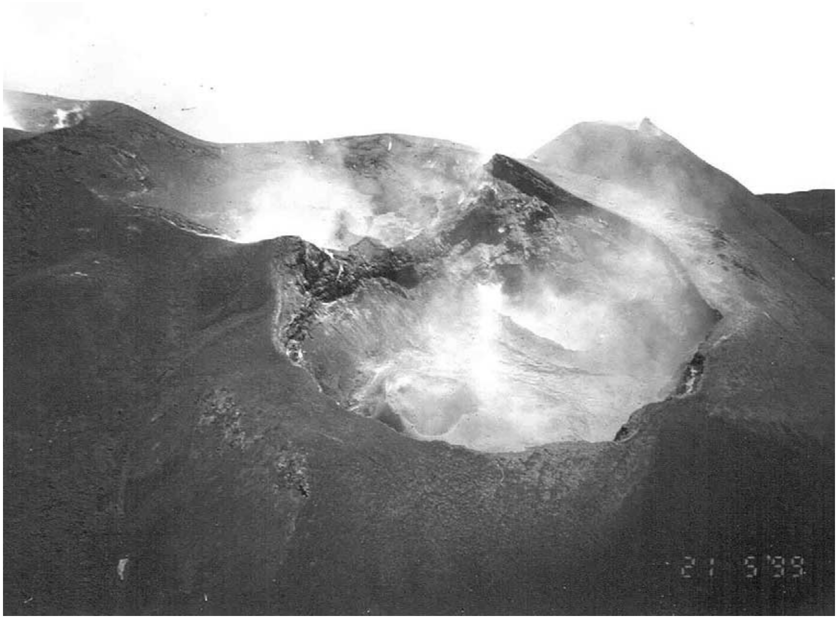


Fig. 4. Aerial view from the northwest of the Bocca Nuova, showing two pits on the crater floor. The depth of the crater was ~80 m at that time. The ridge in the middle of the image separates Bocca Nuova from the Chasm (middle left of the photo). The Southeast Cone is on the background to the right, and Northeast Cone is on the upper left of the image. Photograph taken on 21 May 1999.

intensity, and culminated in paroxysmal phases on 12, 14 and 16 October. The rise of magma within the conduit and the accumulation of spatter and bombs from the explosive phases gradually filled the Bocca Nuova. The crater floor was ~80 m below the lowest part of the crater rim when observed on 9 September (Fig. 4). Between then and mid-October the amount of lava that accumulated within the crater was $\sim 2.5 \times 10^6$ $m^3$, suggesting a minimum magma supply rate at this crater of $\sim 0.8$ $m^3$ $s^{-1}$. On 17 October there was an overflow from the western crater rim of the Bocca Nuova (Fig. 5). This overflow, which had a flow rate of 18–25 $m^3$ $s^{-1}$, spread on the western flank of the volcano, covering an area of 1 $km^2$ (Table 2; Fig. 6). One km from the crater, the lava flow split into four major branches. The northernmost branch had a maximum length of 3 km and reached an elevation of 1970 m a.s.l. (Fig. 6A).

On the night of 18 October there was increased explosive activity within the Bocca Nuova, and new overflows emerged from the western crater rim. On 19 October the effusion rate fluctuated between 12 and 16 $m^3$ $s^{-1}$ (Table 2). Flows erupted during this phase flowed on top of the previous flow field. The effusion rate decreased, and there was a corresponding reduction in maximum flow lengths of subsequent flows. Peaks in effusion and flow advance rates occurred during the most explosive events at the Bocca Nuova. Frequent, high intensity Strombolian activity continued at the Bocca Nuova until 20 October, and this was accompanied by large overflows from the western crater rim. The new lavas flowed along the northern part of the previous flow field (Fig. 6C). Once again, as soon as explosive activity lessened in the Bocca Nuova, overflows from its western rim slowed and then halted. There was an increase in Strombolian activity on 22, 23 and 25 October, and this was accompanied by large overflows from the western crater rim (Fig. 6C–E). The explosive event on 25 October was the most energetic (Fig. 6E), although the effusion rate of the overflows on this occasion was only 6.8–9 $m^3$ $s^{-1}$ (Table 2). The level of lava within the crater increased, and a small portion of the upper crater rim failed on October 25 (Calvari and Pinkerton, 2002).

Fig. 5. Aerial view of the Bocca Nuova on 17 October 1999, when the crater was filled by lava. This image shows a cone that was the main locus of Strombolian activity during late October. A large lava flow was erupted from its northwest base, and this flowed rapidly down the western flank of the volcano.

Strombolian activity continued on 26 October, and again culminated in a paroxysmal phase on 27 October (Fig. 6F). The effusion rate from the crater rim increased again, reaching 17–23 $m^3 s^{-1}$ (Table 2). The new lava flowed down the northern flank of the previous flow field, and reached a maximum length of 4 km. This flow crossed over the Corpo Forestale road at ~1730 m a.s.l. (Fig. 7). Another overflow moved down the western flank on 28 October (Fig. 6G), but with a lower effusion rate of 10–14 $m^3 s^{-1}$ (Table 2). Additional smaller flows were emplaced from 29 October to 2 November (Fig. 6H and I), and their flow fronts stopped at 2600 m a.s.l. The reduced effusion rates were accompanied by lower intensity Strombolian activity at the Bocca Nuova. The ejection of lithic ash occasionally accompanied explosive activity, suggesting a drain-back of the feeder system and small-scale, localised collapse of the inner crater walls. Effusion rates decreased to less than 1 $m^3 s^{-1}$ on 1 November (Fig. 6I), and active flows remained above 3000 m a.s.l. On 3 November, during another increase in Strombolian activity, there was an increase in effusion rate from this crater (Fig. 6L). A lava flow spread along the northern flank of the earlier flow field and reached 3 km before stopping at 1950 m a.s.l. On 4 and 5 November Strombolian activity at the Bocca Nuova gradually decreased, and small lava flows that had erupted from a vent at the western base of the cone became inactive (Fig. 6L). By the end of this eruption, the Western flow field covered ~3 $km^2$ and had a volume of ~$13\times10^6$ $m^3$. The end of eruptive activity was accompanied by sporadic eruptions of lithic ash.

## 5. Effusion rate measurements on the Eastern and Western flow fields

During the 1999 eruption, we measured effusion rates of lava flows on the Eastern flow field on 48 occasions. Effusion rates in Table 1 have been calculated from repeated flow surface velocity measurements along active lava channels. In Fig. 8, field measurements (black symbols) can be seen

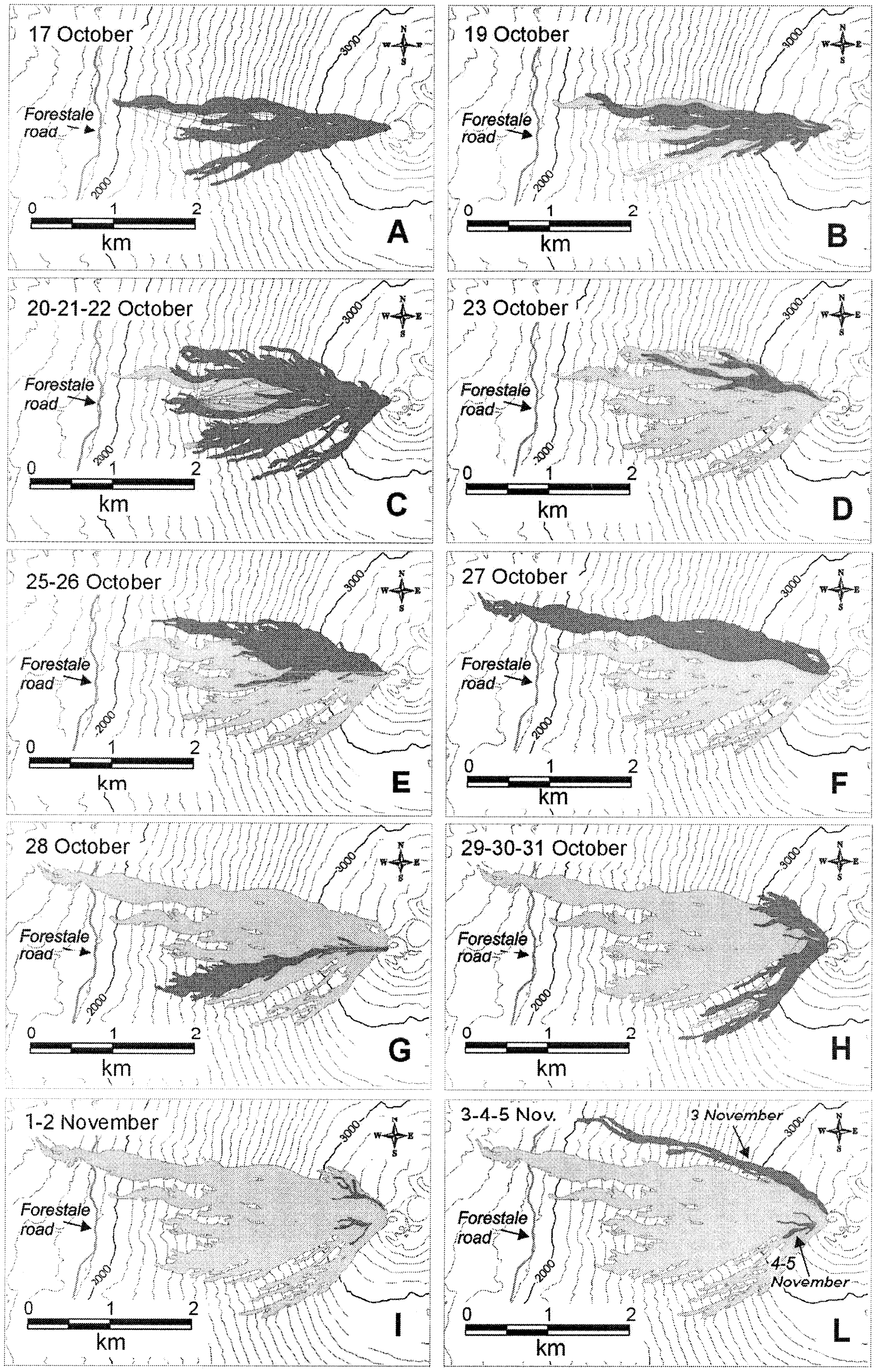


Fig. 6. Map of the Western lava flow field which was erupted from the Bocca Nuova and then flowed down the western flank of Mount Etna during October and November 1999. Active flows are dark grey.

to be similar to effusion rate estimates by Harris et al. (2000) which are based on thermal satellite data (see Harris et al., 1997, 1998). Satellite data were particularly useful between March and mid-May (Fig. 8) when the absence of active vents on the upper part of the flow field made field measurements difficult. Most of the measurements for the Eastern flow field fall in the range 0.1–2 $m^3$ $s^{-1}$, apart from occasional peaks (16.5 $m^3$ $s^{-1}$) and troughs (0.001 $m^3$ $s^{-1}$) (see Table 1 and Fig. 8). Long periods with small variations in effusion rate during the first few weeks of emplacement of the Eastern flow field resulted in the formation of a compound flow field with flows and lava tube systems at different levels (Fig. 2G).

Effusion rates during the emplacement of the Western flow field are shown in Fig. 9 and on Table 2. When mapping of the flow field allowed us to calculate lava surface area, we estimated mean flow thickness from field surveys, and from this we calculated volume and effusion rates at different times (Table 2). Errors are estimated to be less than 30%, and these arise mostly from uncertainties in thickness. Eleven measurements of flow rate were made during the 19 days of emplacement of the Western flow field. These measurements relate to the emplacement of single flows. Minimum and maximum values are based on mean flow thickness of 1.5 and 2.0 m. Fig. 9 shows clearly that effusion rate during the growth of the Western flow field decreased from the highest initial peak of between 18.8 and 25.1 $m^3$ $s^{-1}$ to the lowest value of 0.23–0.30 $m^3$ $s^{-1}$ on 5 November (Table 2), with mean rates between 8.7 and 11.6 $m^3$ $s^{-1}$. Peaks in flow rate from the western rim of the Bocca Nuova occurred on 27 October (see Fig. 6F) and 3 November (Fig. 6L, northern flow), during highly explosive activity at this crater and renewed hornito growth at the base of the Southeast Cone (H3 site; Fig. 2F).

Our measurements, and those of Harris et al. (2000), suggest that effusion rate during the 1999 eruption fluctuated in both the Eastern and Western flow fields (Figs. 8 and 9). This strongly affected the resulting flow field morphologies. When flow rate ceased for more than 24 h during the eruption of flows on either of the two flow fields, existing flows stopped advancing and new flows formed when the vents were reactivated. This appears to be the time required for sufficient cooling and/or crystallisation following undercooling of degassed magma to prevent reactivation of a stationary lava flow on Mount Etna. This can be seen clearly on the Western flow field where, after each reduction in flow rate, new lava flows formed and these flowed either on top of previous flows or they formed new flows along the flanks of previous flows (Fig. 6).

## 6. Effect of effusion rate on the growth of the 1999 lava flow fields

During the 1999 Etna eruption, flow field

Table 2
Measured parameters of the lava flows from the Bocca Nuova (Western flow field) during the 1999 eruption

| Date (dd/mm/yy) | Area new flows ($km^2$) | Total area ($km^2$) | Emplacement time (h) | Minimum partial volume ($m^3$) | Maximum partial volume ($m^3$) | Minimum cumulative volume ($m^3$) | Maximum cumulative volume ($m^3$) | Minimum effusion rate ($m^3$ $s^{-1}$) | Maximum effusion rate ($m^3$ $s^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| 17/10/99 | 1.08400 | 1.08400 | 24 | 1 626 000 | 2 168 000 | 1 626 000 | 2 168 000 | 18.82 | 25.09 |
| 19/10/99 | 0.70060 | 1.18660 | 24 | 1 050 900 | 1 401 200 | 2 676 900 | 3 569 200 | 12.16 | 16.22 |
| 22/10/99 | 1.56900 | 2.00860 | 72 | 2 353 500 | 3 138 000 | 5 030 400 | 6 707 200 | 9.08 | 12.11 |
| 23/10/99 | 0.23350 | 2.00950 | 12 | 350 250 | 467 000 | 5 380 650 | 7 174 200 | 8.11 | 10.81 |
| 26/10/99 | 0.78830 | 2.11230 | 48 | 1 182 450 | 1 576 600 | 6 563 100 | 8 750 800 | 6.84 | 9.12 |
| 27/10/99 | 0.99720 | 2.54420 | 24 | 1 495 800 | 1 994 400 | 8 058 900 | 1 0745 200 | 17.31 | 23.08 |
| 28/10/99 | 0.42230 | 2.66830 | 17 | 633 450 | 844 600 | 8 692 350 | 11 589 800 | 10.35 | 13.80 |
| 31/10/99 | 0.53100 | 2.88560 | 72 | 796 500 | 1 062 000 | 9 488 850 | 12 651 800 | 3.07 | 4.10 |
| 2/11/99 | 0.05960 | 2.88560 | 48 | 89 400 | 119 200 | 9 578 250 | 12 771 000 | 0.52 | 0.69 |
| 3/11/99 | 0.27180 | 3.08910 | 12 | 407 700 | 543 600 | 9 985 950 | 13 314 600 | 9.44 | 12.58 |
| 5/11/99 | 0.02633 | 3.08910 | 48 | 39 495 | 52 660 | 10 025 445 | 13 367 260 | 0.23 | 0.30 |

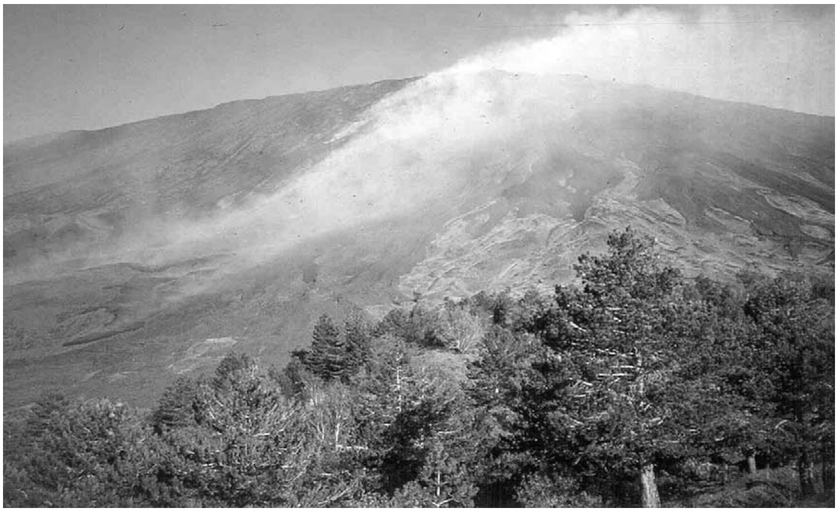

Fig. 7. Photograph from the Corpo Forestale road on 27 October 1999, showing the active flow field on the western flank of the volcano.

growth was strongly influenced by effusion rates. A steady supply over weeks to months led to the formation of lava tubes and a thick compound flow field consisting mostly of cooling-limited lava flows and large tumuli (Fig. 2G). By contrast, large fluctuations in effusion rate during the emplacement of lava flow fields resulted in the formation of discrete, relatively short-lived, volume-limited flows (Fig. 6). The fan-shaped Western flow field is an excellent example of this type of flow field. It is composed mostly of thin, discrete flows. In this section we describe the events that led to the formation of these two distinct flow fields.

### *6.1. Lava flow fields from the Southeast Cone: 4 February–14 November*

As discussed earlier, flow fields were erupted from the base of the Southeast Cone from three primary vents, and each formed a separate flow field. The first flow field (FFA; Fig. 2G) formed between 4 February and 25 August and had an estimated total volume of $\sim 12 \times 10^6$ m$^3$. The mean eruption rate at FFA was $\sim 0.7$ m$^3$ s$^{-1}$, and the final flow field was 2.8 km long, 450 m wide and up to 35 m thick. The flow field attained 60% of its final flow length during the first five days of the eruption, though it continued to lengthen during the following 33 days. This was followed by the eruption of a number of a′a flows, some of which formed a stable roof. The development of ephemeral vents at the fronts of these flows, some of which in turn roofed over, resulted in the growth and propagation of a tube network which then supplied a new generation of ephemeral vents. These migrated towards, and then stabilised within, the Valle del Bove. A temporary increase in effusion rate in May filled the tubes system and the excess lava discharged through new breakouts in the upper part of the flow field. During this stage, a higher level tube network developed in the upper part of flow field FFA. The continued supply of lava to the lower part of the flow field suggests that the upper and lower tube systems in the upper part of the flow field were active at the same time. The tumuli that formed on the flow surface at that time covered previous flow features, and the resulting morphology of the flow field was characterised by a′a flows with localised pahoehoe flow surfaces within proximal channels.

The second flow field (FFB; Fig. 2G) was emplaced between 27 August and 17 September from a new primary vent (H2; Fig. 2E) at the base of the Southeast Cone. The resulting flow field was 2 km long, with a maximum width of 250 m and a maximum thickness of 15 m. It covered a surface area of 0.3 km$^2$ with a total estimated volume of $1.9\times10^6$ m$^3$ at a calculated eruption rate of 1.2 m$^3$ s$^{-1}$. Many tumuli formed during localised inflation of the proximal flow field.

Flow field FFC (Fig. 2G) was emplaced between 4 September and 14 November from the new primary vent H3. The maximum flow length of 1.5 km is consistent with a low eruption rate (0.2 m$^3$ s$^{-1}$). The surface area of the flow field was 0.4 km$^2$ and its total volume was $\sim1.1\times10^6$ m$^3$. The very low effusion rates during this phase were accompanied by flow inflation. While we are unable to quantify inflation rates during the emplacement of this or the earlier flow fields, it was clear that considerable vertical thickening of the flow field took place during periods of restricted development of new lava flows. We tentatively concluded that endogenous growth rates may have been similar to exogenous growth rates during the emplacement of this flow field. In common with many effusive eruptions on Mount Etna, a large number of viscous squeeze-ups formed during the latest few days of the eruption.

### 6.2. *Lava flow field from the Bocca Nuova: 17 October–5 November*

The Western flow field is composed of a number of long, thin, channel-fed a′a lava flows that were erupted from the rim of the Bocca Nuova. The majority of lava flows on this flow field were longer than those in the Eastern flow field, and the area covered is larger than that of the Eastern flow field, even though the Western flow field was emplaced during one month of intermittent supply, compared with nine months of virtually continuous activity during the formation of the Eastern flow field. The relatively long flow lengths (compared with the Eastern flow field) can be attributed mainly to the higher peak effusion rates for the Western flow field (Fig. 9 and Table 2). There is no evidence of any significant difference in the rheological properties of lavas erupted on the two Eastern and Western flow fields. In addition, mean gradients are similar for the first 1–2 km, after which the gradient on the Eastern flow field is greater than that of the Western flow field.

The fan shape of the Western flow field is the result of both the cone-shaped topography of the Etna summit and the persistence of a small number of primary feeder vents in a restricted area close to the western rim of the Bocca Nuova (Fig. 6). The flow field is composed of a series of volume-limited lava flows (Guest et al., 1987) produced during intense Strombolian phases. While some of these flows travelled on top of previous lavas, others flowed along their margins.

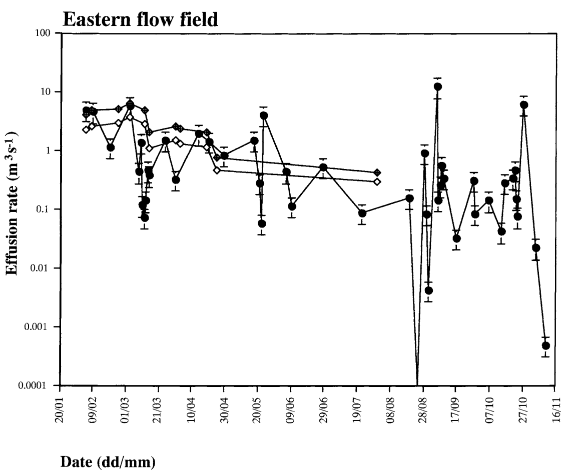


Fig. 8. Effusion rate versus time (filled circles) during the emplacement of the Eastern flow field. Diamonds are values from Harris et al. (2000). Open and filled diamonds represent minimum and maximum estimates, respectively.

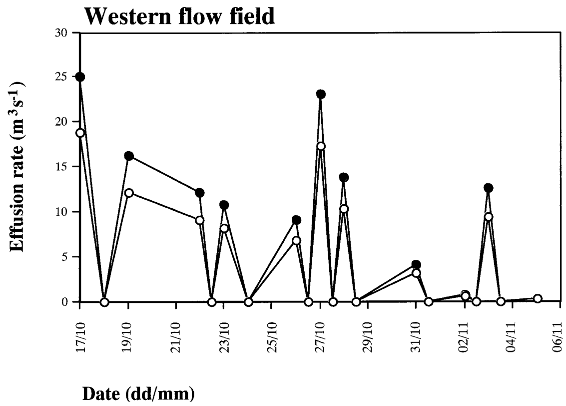


Fig. 9. Mean flow rate during the emplacement of the Western flow field. Black and white symbols represent maximum and minimum data, respectively.

The highly variable flow rates and short durations of individual flows are incompatible with the conditions required for lava tube formation. Calvari and Pinkerton (1998) suggested that a minimum of seven days of steady supply were required to form lava tubes during the 1991–1993 eruption of Mount Etna, when the effusion rate was comparable to that of the 1999 Western flow field. Maximum lava flow lengths agree with the empirical relationship proposed by Calvari and Pinkerton (1998): $L_{max} = (10^{3.11}\ E^{0.47})$ where $L_{max}$ is the maximum length (in metres) of a flow erupted at effusion rate $E$ (in m$^3$ s$^{-1}$).

The fluctuating supply rates resulted in the formation of discrete flows during each renewed increase in effusion rate. The result is that no first-order ephemeral vents opened along arterial flows (see Calvari and Pinkerton, 1998), and, apart from localised pahoehoe flow surface within proximal channels, only a′a lava flows developed.

## 7. Discussion

The 1999 eruption of Mount Etna provided an excellent opportunity to compare and contrast the emplacement mechanisms and resulting morphologies of two flow fields. The Western flow field had a maximum length of 4 km compared with 2.8 km for the Eastern flow field. The total volume and eruption rate of the Western flow field were $\sim 13 \times 10^6$ m$^3$ and 7.5 m$^3$ s$^{-1}$ compared with a similar volume ($\sim 15 \times 10^6$ m$^3$) and lower eruption rate (0.6 m$^3$ s$^{-1}$) for the total Eastern flow field. Lava flows on the Eastern flow field attained their maximum lengths when effusion rate exceeded 2 m$^3$ s$^{-1}$. By contrast, individual flows in the Western flow field attained their maximum flow lengths when effusion rates were typically in the range 10–25 m$^3$ s$^{-1}$.

During the 1999 Etna summit eruption, effusion rates varied significantly during both eruptions. However, there were significantly larger short-term changes at the Bocca Nuova than at the base of the Southeast Cone. This resulted in lava flow fields with distinctive features. The Eastern flow field was emplaced over a period of nine months. The low and relatively steady effusion rate during the first three months gave rise to flow field FFA, and promoted tube growth. A one-day pause at the end of this phase was enough to trigger the formation of a new flow field (FFB), which was emplaced northeast of FFA and flowed down its northeast flank. This flow field partially grew together with flow field FFC after a new primary vent opened at the base of the Southeast Cone on 4 September. At this stage of the eruption, effusion rate from the new H3 vent was low, and the maximum length of 1.3 km of the lava flow field was significantly smaller than those of FFA (2.8 km) and FFB (2 km). The increasingly smaller sizes of the flow fields from the base of the Southeast Cone result from a gradual decrease in flow rate from the active vents.

The emplacement history for the Western flow field was dominated by pulsating flow from the rim of the Bocca Nuova. The intermittent supply hampered tube development within this flow field. Maximum lengths of individual flows were controlled by effusion rate, and readily predicted using equations contained in Calvari and Pinkerton (1998) and Kilburn (1996, 2000)

## 8. Conclusions

The morphologies of the Eastern and Western flow fields were clearly related to their emplacement mechanisms. There is another factor. The general fan shape of the Western flow field reflects the different locations of the source vents on the wall of the Bocca Nuova and the sub-radial downflow topography of the ground covered by the flows. Widening of the Western flow field was accentuated by the tendency of newer flows to flow down the flanks of their predecessors rather than flowing on top of them. Individual flows were also characterised by drained lava channels and lateral levées. The flow field was composed of volume-limited lava flows. By contrast, the Eastern flow field surface was more complex. Here, individual flows were generally short, and at all stages of flow field evolution there were innumerable ephemeral vents. Well-defined channels and levées were relatively scarce. This, coupled with the large number of ephemeral vents and tumuli, suggests that these flows were cooling-limited. Once some of these flows stopped advancing, they began to inflate. This inflationary period was commonly followed by breakouts from the flow front or margins or by the formation of a new flow at the vent. During the initial part of the eruption, skylights were common. These effectively disappeared by May, after which tumuli formed on different parts of the flow field. Many of these were, in turn partially or completely buried by subsequent flows.

Lopes and Kilburn (1990) and Kilburn and Lopes (1991) argued that flow fields grow from an initial lengthening phase, through a widening phase and end with a thickening stage with decreasing effusion rate. While this emplacement model could be applied to the Eastern flow field, it does not apply to the formation of the Western flow field where periods of high effusion rate were punctuated by low effusion rates and where new flows formed during each significant increase in effusion rate. The situation we describe for the 1999 eruption may well be common during summit eruptions at Mount Etna (Rittmann, 1973) where, instead of a stable dike discharging lava, there is a more complex plumbing system.

In summary, key criteria that allow long-lived, low-effusion rate flow fields to be distinguished from short-duration, high-effusion rate flow fields include: (1) the presence of tumuli; (2) the presence of flows that were erupted from ephemeral vents, or tumuli, or inactive flow fronts or margins; (3) highly variable flow lengths of individual flows; (4) undrained channels (suggesting that flows are cooling-limited); (5) the presence of large 'deltaic' flow features that form where a master lava tube feeds lavas in the medial part of the flow field; and (6) frequent superposition of flows. In addition, skylights are common on low-effusion rate, long-lived flow fields, both during activity and at the end of effusive activity (e.g. in the 1991–1993 Etna flow field). By contrast, pulsating, low-duration flow fields are characterised by the absence of the above features and by the presence of readily identifiable, mostly volume-limited, lava flows.

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