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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# The Summit of Mount Etna Prior to the 1971 Eruptions [and Discussion]

J. E. Guest and Alison Brown

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# The summit of Mount Etna prior to the 1971 eruptions

By J. E. Guest
*University of London Observatory, Mill Hill Park, London, N.W. 7*

The summit cone of Mt Etna is cut by an approximately NNE–SSW trending, narrow fissure zone that controls much of the terminal activity of this volcano. Within the central crater, which lies at the top of the summit cone, there are two main vents alined on this fissure zone: the chasm, a deep pit; and the 1964 crater. Both of these vents were blocked before 1971. The NE crater first opened in 1911 on the lower slopes of the summit cone on the same fissure zone, and has had an open conduit from which lava has been erupted at a constant rate from 1966 to the beginning of the 1971 eruption.

In 1968 a small gas bocca known as the Bocca Nuova opened near a fissure that had previously erupted lavas in 1956. The Bocca Nuova collapsed in early 1970 to give a 100 m wide crater. It is suggested that collapse resulted from movement of magma at depth into the 1956 fissure causing sudden lowering in the magma column below the Bocca, and that continued migration of magma into the fissure eventually lead to the eruption of April 1971, the site of this eruption being in line with the fissure. A rise in temperature of fumaroles at the edge of the central crater after the Bocca Nuova collapse is attributed to this incursion of magma across the crater.

## Introduction

Mt Etna is the largest and one of the most active volcanoes in Europe, and is in a state of almost continuous activity at its summit. Because of this the top of the volcano is constantly changing in form and deserves detailed study. This paper is based on work carried out during October 1969 and July 1970; its aim is to describe the conditions at the summit during these periods of observation, and to relate changes in activity that occurred to movements of magma high in the volcano as a prelude to the 1971 eruptions. Aerial photographs taken by the Italian Air Force provided a base on which the main geological features were mapped (figures 3 to 5).

The summit of Etna (latitude 37° 45′, longitude 15° 01′) stands at 3323 m above sea level (a.s.l.), and it is interesting to note that this differs little from the heights of 10874 ft (3320 m) and 10972½ ft (3345 m) measured respectively by Captain Smyth in 1815 and Sir William Herschel in 1824 (Lyell 1847). Etna terminates in a summit cone which itself rests on a wider bench marking an ancient caldera. Below this the flanks of the volcano slope down to sea level in a series of shallow steps.

Three types of activity characterize this volcano: (*a*) almost continuous emissions of lava erupted at a relatively low rate from near the summit; (*b*) spasmodic, short-lived eruptions at or near the summit; and (*c*) flank eruptions from radial fissures resulting in the eruption, within a few months, of as much as or more lava than may 'leak' out over several years during the type of eruption listed as (*a*). Within the last decade all three types of eruption have occurred.

One other type of activity occurs at rare intervals, that of caldera collapse at the summit. This, however, has only taken place a few times in historical record. A classification of eruptive types is discussed in more detail by Rittmann (1973, this volume).

Eruptions at the summit are rarely of danger to life and property, as the upper part of the volcano is above the vegetation line. Flank eruptions, on the other hand, can cause considerable damage, the lavas flooding towns, villages and agricultural land, sometimes as far as the coast. One of the largest flank eruptions was that of 1669 when it is estimated that over

1 $km^3$ of lava was erupted as a 'fiery stream' that extended from Monte Rossi near Nicolosi to the town of Catania on the coast. The eruption lasted four months during which time many villages were destroyed by lavas.

It is likely that, with certain exceptions, all three types of eruption mentioned above are related, and the steady emission of lava at the summit usually terminates when there is an eruption elsewhere. During much of this century the site of continuous eruption has been the northeast cone situated on the flank of the summit cone: activity here stopped during both the 1964 and 1971 eruptions. Presumably this almost continuous activity results from the steady introduction of magma into the volcano from the mantle. While the volume of magma feeding into the volcano remains steady it leaks out relatively quietly from an established vent in the main conduit below the volcano's summit. However, a new surge or steady accumulation of magma into the volcano may cause lava to break out elsewhere at the summit, temporarily relieving magmatic pressure at the NE vent. If, however, the upsurge of new magma is large then the whole volcano becomes highly inflated, radial fissures develop and magma travels in vertical dykes from the central conduit to break out from fissures lower on the mountain. Presumably if the volume of lava erupted from the flanks is large enough a void is left in the central conduit and caldera collapse takes place at the summit (collapse may also be related to the height of the volcano at a given time, and there may be a maximum height that can be supported). Once the new surge of magma has been released the volcano slowly equilibrates to its normal condition when there is quiet leaking out of magma at the summit again.

If the situation described here is correct then continued observation of the milder summit activity and the changes that occur there may well lead to prediction of flank eruptions that are such a serious hazard to life and property in the region.

## Geology of the summit cone

When viewed from the west, the top of Mt Etna appears as a truncated cone with a broad platform at 2940 m a.s.l. On this platform stands the present summit cone which rises to 3260 m.

The platform represents the Cratere del Piano, a caldera now filled with lava (figure 1*a*), and it was at this level that the Volcano Observatory stood before it was destroyed by the 1971 lavas. This caldera was probably in existence at the time of Empedocles, the Torre del Filosofo on its southern lip being named in memory of this philosopher. However, a number of large-scale collapses appear to have taken place in more recent times reducing the height by appreciable amounts. Collapses in 1444, 1537 and 1669 all probably contributed to the form of the caldera before it was filled in by lavas. The last major collapse was probably that mentioned by Winchelsea (1669) in his eye-witness account of the 1669 eruption written to King Charles II.

During the latter part of the seventeenth century this caldera filled with lavas, and then during the early eighteenth century the present summit cone started to build up within the caldera area just north of centre. By the end of that century it had probably reached a height near that of its present one. The diameter of the cone's terminal crater, called here the central crater, is about 500 m and this dimension does not appear to have changed to any great extent since at least 1865.

The geology within the central crater has changed considerably since that time. Waltershausen's map (figure 1*b*) of the situation in 1865 shows that there were then small cones on

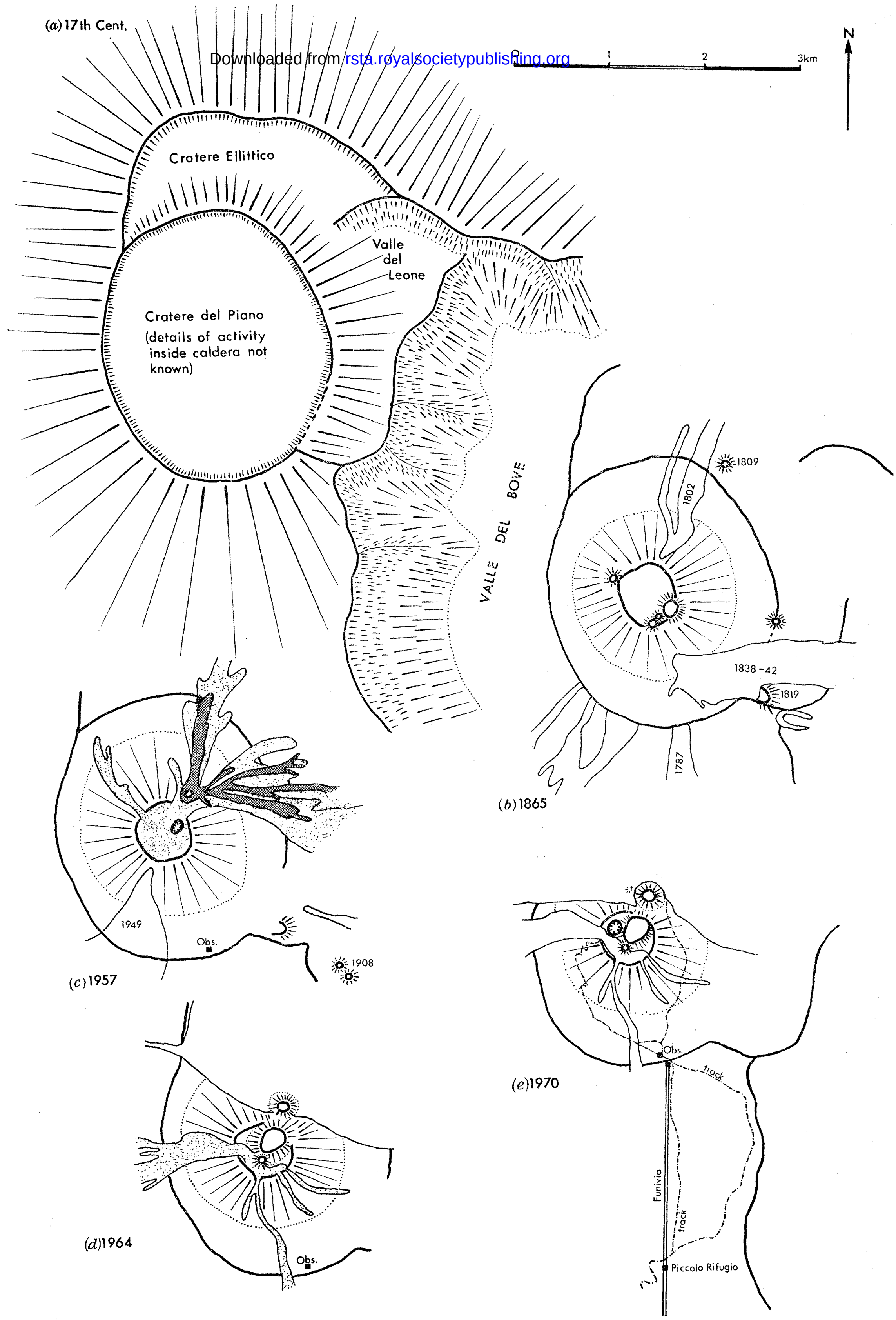


Figure 1. Maps showing the development of the summit region of Etna. (*a*) The main structural features existing in the seventeenth century; at this time the summit cone had not been superimposed on the Cratere del Piano. (*b*) The form of the summit in 1865 (after Waltershausen 1880); at this time the summit cone had been built up to near its present height, although its detailed form was being changed by repeated activity. (*c*) The summit cone in 1957, when the central crater was floored by a congealed lava lake, and eruptions from the NE crater had built up a fan of lavas. (*d*) The summit cone in 1964 showing the chasm, lavas from the 1964 eruption in the central crater and the much enlarged fan of lavas from the NE crater. (*e*) The summit area in 1970; the enlarged Bocca Nuova is shown on the western side of the central crater; during the 1st phase of the 1971 eruption the Observatory (obs) was destroyed as was the funivia above the Piccolo Rifugio. The outline of the Cratere del Piano is marked on *b*, *c*, *d* and *e* for reference with *a*.





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the southern and southeastern lip of the central crater; none of these cones exists at the present time. Explosive activity has occurred from time to time in the central crater throughout much of its history. Ponte (1923) records that it was blocked between 1918 and 1923; but on 6 June 1923 there was a great explosion when the central crater 'cleared its throat' ejecting 'gigantic pine-tree clouds to a great height above the crater'. Much of the present cone is covered by pyroclastic material, some of which covers lavas as young as those erupted in 1949.

During April 1956 the central crater was almost filled with a lake of lava (figure 1*c*). This spilled over the lip on the northeastern side to form a long flow extending eastwards into the Valle del Bove for nearly 3 km. Within the central crater on the western side a chain of fissure cones built up over the congealing lava lake, and lava from this fissure flowed down the side of the cone (Silvestri 1957) as shown in figure 3. It is on this floor to the central crater that all the present landforms in the crater stand, and a pit existing in the floor during that time remained an open vent eventually to give rise to the chasm described later in this paper.

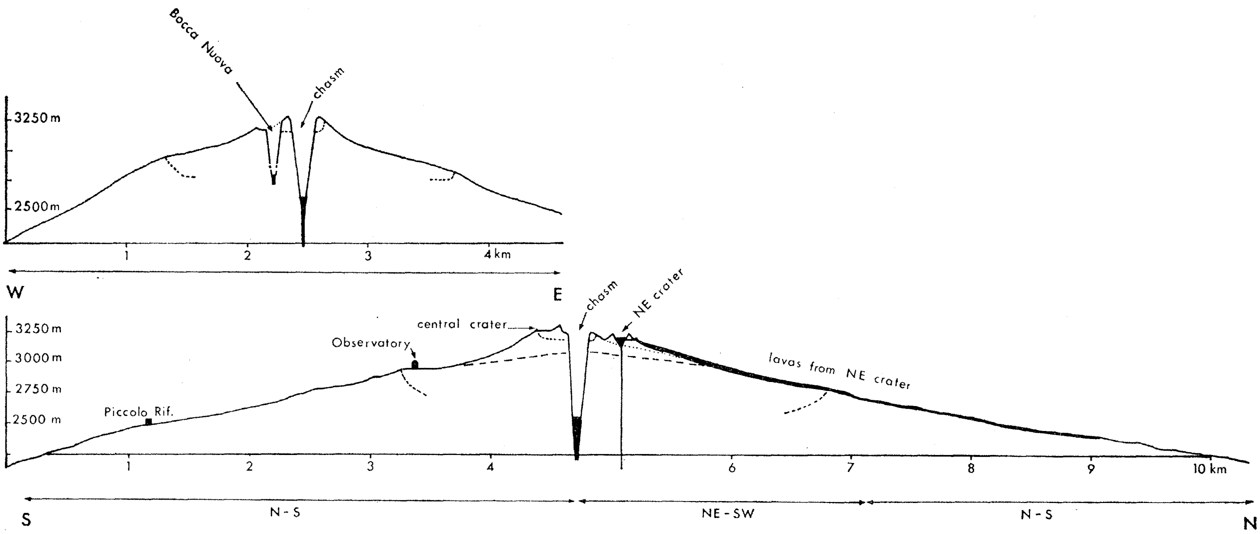


FIGURE 2. True scale sections through the summit of Etna.

As well as this activity in the crater itself there have also been outbreaks of lava on the flanks of the summit cone. Those on the southwestern side, partially covering the cinder cone of the 1819 eruption, were erupted between 1838 and 1842. These flows were later mantled by ashes from the central crater and large bombs nearly 1 m across testify to the violence of some of the explosions. One small flow south of the recently destroyed Observatory was probably formed in 1787; other flows formed later than this and some appear in Waltershausen's map of 1865.

In December 1949 fissures opened on the southwestern and northern slopes of the summit cone and some $11 \times 10^6$ m$^3$ of lava was erupted (Imbo 1965). The northern flows are now covered by younger ones from the NE crater. Those on the southwest side were erupted from a vent now marked by a red-brown cinder cone situated in a deep gash in the side of the summit cone and surrounded by the lavas of 1964 (figure 3).

This gash that cuts the lip of the central crater formed on what must be a fundamental fissure zone running NNE–SSW through the summit cone, and it is this structure that has controlled much of the activity in the summit area. Alined along this structure are the 1964 crater and the chasm within the central crater, and the northeast crater on the flank of the summit cone (figure 3).

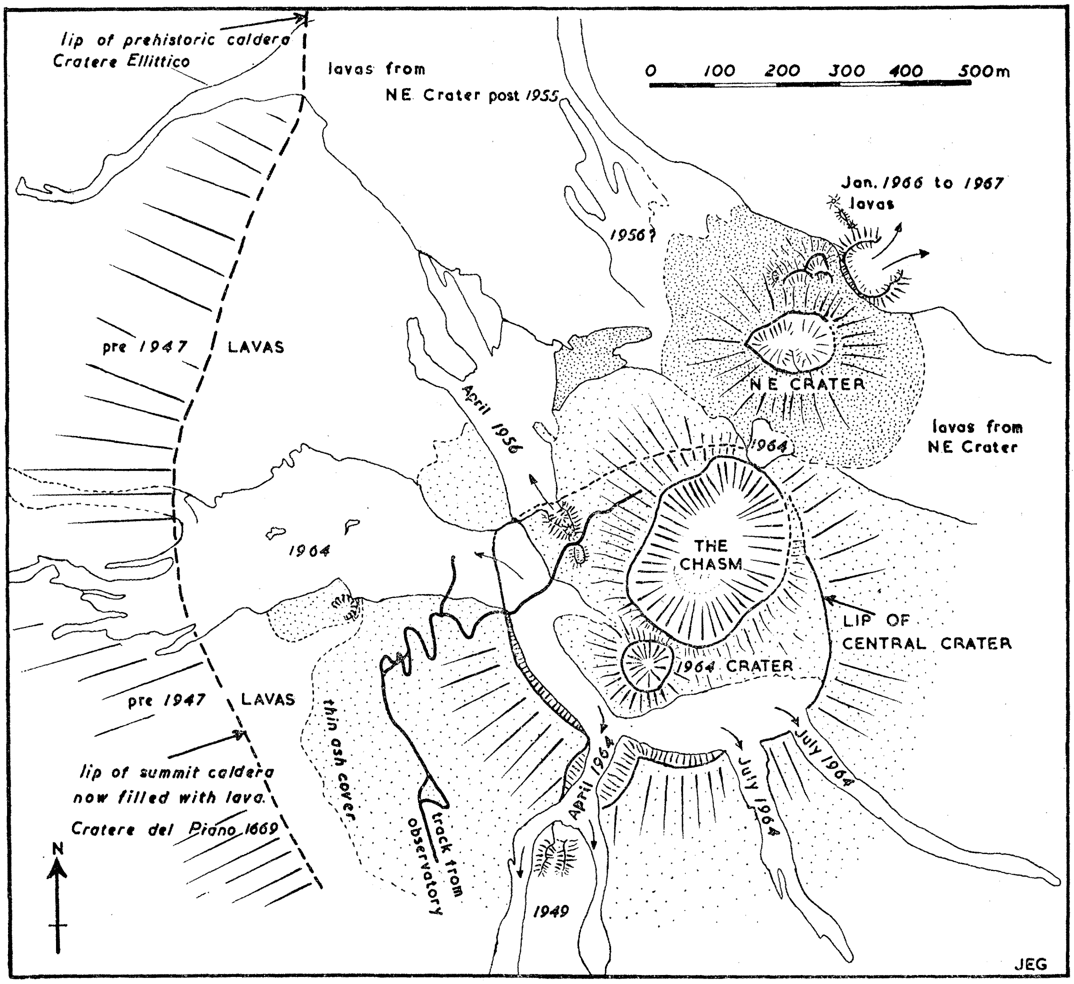


FIGURE 3. Geological sketch map of the summit of Etna in June 1967 based on an aerial photograph taken at that time.

## THE CHASM (LA VORAGINE)

Following the 1956 eruption there was a large pit some 100 m across on the surface of the lava filling the central crater. Between 1956 and 1964 explosive activity together with at least two lava effusions built up a cone over this pit to form what is now the principal cone within the central crater. The total height of the cone is about 65 m and the lower flanks partially bury the 1956 fissure cones mentioned earlier. The crater of this cone is known as the chasm (La Voragine). It consists of two coalescing craters alined on the main fissure zone, the deeper one being at the northeastern end. Tazieff and his team (personal communication) measured the depth of this crater (by dropping flares into it) as more than 700 m in July 1970.

In the years before the 1971 eruption little activity was apparent in the chasm, possibly because of its great depth and the near impossibility of seeing to its bottom. However, billowing




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clouds of $SO_2$ gas were emitted from at least 1966 until 1971. Spasmodic rumblings were often heard from deep in the crater. On some occasions bangs could be heard at frequent intervals (e.g. on 18 July 1970 an explosion rate of about one per minute was recorded). At times ash fragments of several centimetres in size were thrown out.

The role played by this crater in the magma régime before the 1971 eruption is uncertain, but the presence of lava high in the volcano and at a level several hundred metres above the floor of the chasm in both the Bocca Nuova (only 100 m away) and also in the northeast crater probably suggests that at this time the chasm was blocked by fallen talus at the base of its deep shaft. It is possible that the conduit leading from the main magma column was also blocked by congealed lava and that the observed explosions resulted from accumulations of gas in a cooling body of magma. The deep rumblings heard were most likely to be falls of talus from the near vertical sides of the shaft.

It is probable therefore that the chasm was not involved in the migrations of magma leading to the events of 1971. It was observed (Booth 1971) that during this eruption the amount of gas discharged from it decreased, but this was probably due to the redistribution of ground water in the top of the volcano during the eruption. However, after the main 1971 eruptions had ceased a column of fresh lava rose up in the chasm to within 150 m of the lip (Rittmann 1971) indicating that this vent had again been cleared allowing free access of lava, or that lava was pouring into it from a fissure in the wall.

## The 1964 crater

This crater is situated near the southwestern end of the chasm, on a line with the 1947 gash. The crater itself is about 70 m across, on top of a cone rising about 50 m above the present floor of the central crater. The surface of the cone is veneered by thin lava flows and spatter. In the years between 1964 and 1971 it emitted steam and $SO_2$ in much the same way as the chasm.

The 1964 eruption lasted from 7 April to 5 July. During this time lavas spread over the floor of the central crater to the south of the chasm and spilled over a low point to the west to flow some kilometres beyond the edge of the Cratere del Piano. Lava also flowed through the gash and surrounded the 1949 vent. On the night of 4/5 July lava spilled over the lip of the central crater on the southeastern side to form two narrow flows some 410 and 500 m long (figure 3). These flows took about 5 h to form and by 2 a.m. on 5 July the eruption had ceased (V. Barbagallo, personal communication). The total volume of lava erupted was of the order of $0.7 \times 10^6$ m$^3$. During this eruption the flow of lava that had been erupting normally from the northeast crater ceased, not to be resumed again for some 18 months.

The 1964 crater, like the chasm, although steaming before 1971, played no part in the events that lead to the 1971 eruptions.

## The northeast crater

Since its formation in 1911 this vent has been the main outlet for lavas and has been in operation much of the time except when there have been outbreaks of lava elsewhere on the volcano. It lies outside the central crater, but from its position in a line with previously described vents is considered to lie on a fissure zone running through the top of the mountain in a northeast–southwesterly direction. It consists of a cinder cone from which lavas are emitted at its base.

The northeast crater opened as a small gas *bocca* in May 1911. Since that time it has built up successive new cones over the same site. As the cone increased in size it covered lavas erupted from its base so that a section through its lower part would show inter-fingered lavas and pyroclastic deposits. The highest point on the cone was at about 3247 m a.s.l. in 1967 and continued activity had built it up to about 3300 m a.s.l. by mid-1970.

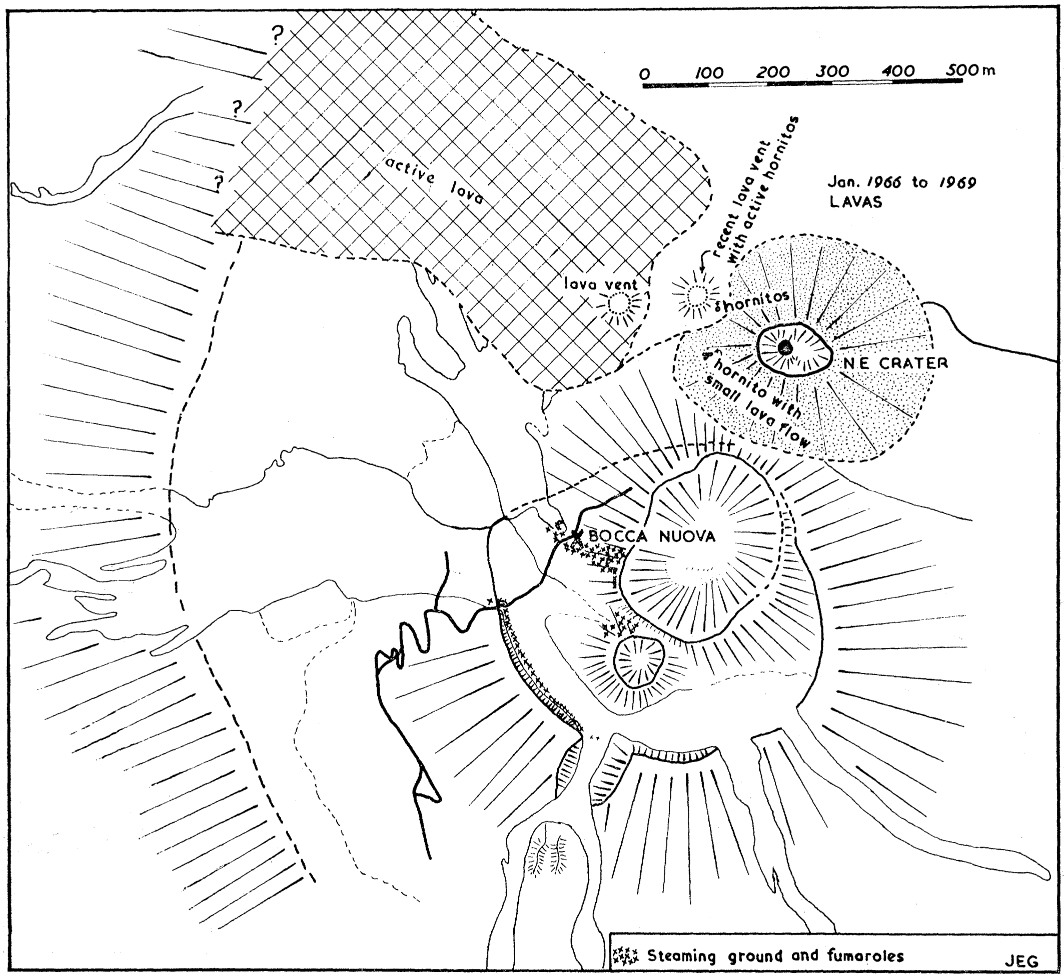


FIGURE 4. Geological sketch map of the summit of Etna in October 1969. Base map the same as figure 3.

There is a general connexion between the magma that feeds this vent and, except in certain cases, magma that erupts elsewhere on the mountain, as it has been observed that whenever there is a new eruption, activity at the NE crater stops. For example, in 1923 when there was a great explosion in the central crater the eruption at the NE crater ceased; similarly, when the 1964 eruption commenced activity again stopped at the NE crater, not to be resumed again until January 1966.

Before April 1971 when the new eruptions started the NE crater had been in a state of constant activity since January 1966. Eruptions of lava since at least 1922 had built up a large fan of flows over the NE side of the mountain extending for some 4 to 5 km on its northern side.



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Lavas erupted between 1966 and 1971 considerably enlarged the area of lavas from this vent. Lavas were erupted from a number of places round the foot of the cone but in the author's experience only vents in one area operate at a given time. During the early part of the 1966 eruption lavas were erupted on the eastern side of the cone, and infrared photographs taken in July 1966 (Friedman & Williams 1968) show lavas being erupted from an area of vents to the NE spreading out to fill the Valle del Leone and extending 1.5 km from the vent to the west

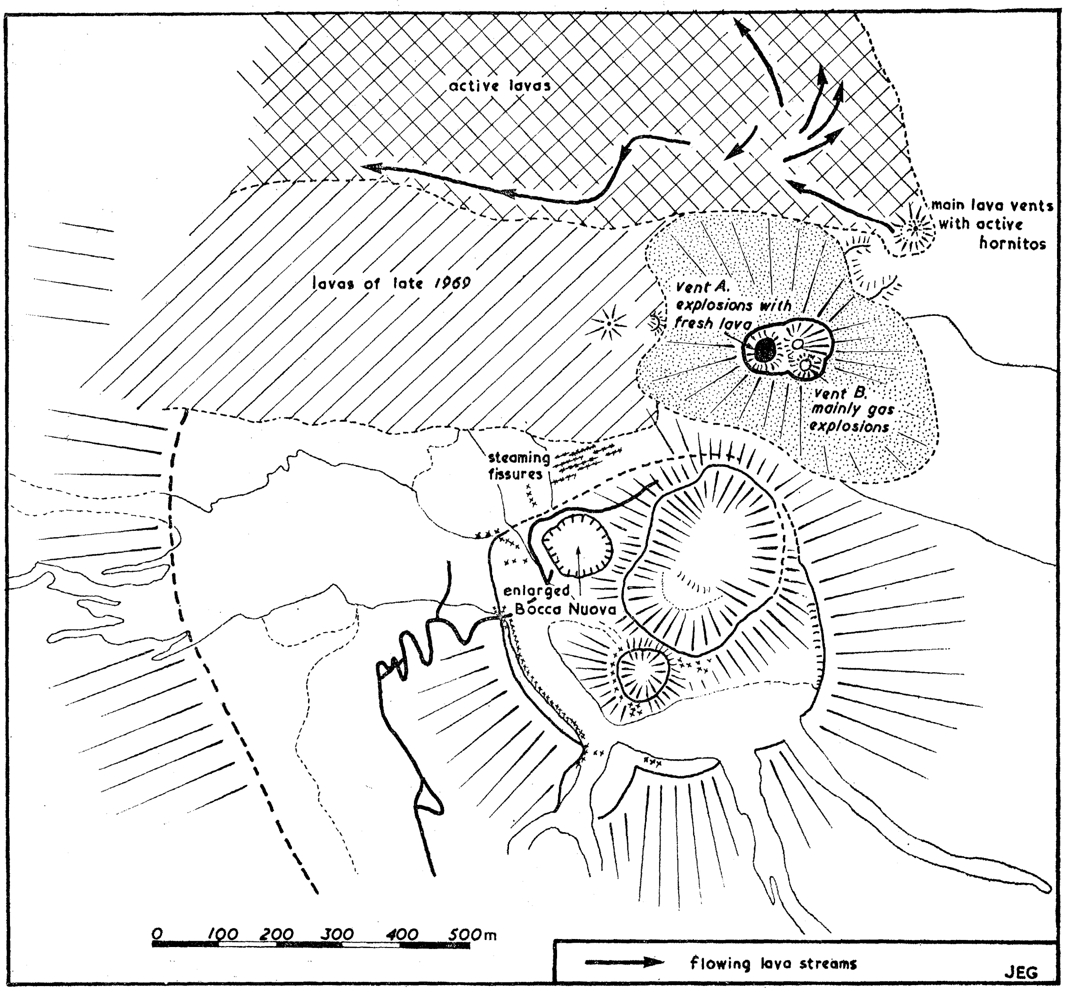


FIGURE 5. Geological sketch map of the summit of Etna in July 1970. Base map the same as figure 3.

of the Valle del Leone scarp. This northeasterly vent area is the most pronounced topographic feature at the foot of the cone and its position is probably controlled by the NNE–SSW fissure zone.

By October 1969 all the lavas on the northern side of the mountain had cooled sufficiently to support snow; new vents opened on the western side of the cone and lavas flowed round the foot of the summit cone on this side (figure 4). During 1970 the activity moved back to near the principal vent area on the northeastern side which was the site of the author's observations in July 1970 (figure 5). However, lavas erupted the year before on the western side were still hot to the touch, especially near the vents.


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Vent areas were marked by numerous *hornitos*. These range in size from a few centimetres to metres in height. Normally they consist of tall, hollow spires of lava with narrow terminal openings through which gas is forced, making a high-pitched hissing sound that can usually be heard as far as a kilometre away. The emission of gas tends to be rhythmic rather than continuous.

Lava erupts in several ways. It may rise up the hornitos and overflow from the orifice to form festoons of lava around the hornitos and adjacent ground. Unless the honito is a big one, only a small amount of lava is erupted in this way and the flows are not *viable* as defined by Walker (1967, see Walker, this volume). The larger flows usually originate from small boccas: these may be within the area of hornitos or farther down the slope, although in the latter case the lava probably originates in the hornito area and flows below previous lavas to emerge at a lower level.

During October 1969 there was strong hornito activity close against the foot of the cone on the western side. Most of the lavas however were erupted from subsidiary vents downslope to the west; these vent areas were also marked by hornitos.

In mid-1970 the vent area on the northeastern side consisted of a thick mound of lavas, the summit of which was marked by a large conical hornito from which lavas were erupted spasmodically. During the period of observation by the author only one vent within the hornito area was constantly emitting lava at the surface in any great volume. This erupted from a small bocca and flowed for a distance of several metres in a narrow leveed channel which was about 1 m wide and rather less than 1 m deep, and thickly covered with yellow and green sublimates. The flow then disappeared beneath the older lavas, presumably to reappear lower down the slope.

All other flows that were longer than 2 or 3 m started from vents some 200 m away from the main hornito area to the west. As described by Walker (1967) for earlier activity in 1966 the positions and sources of lavas changed from day to day. There were normally five or six distinct lava streams flowing at any given time during the period of observation in July 1970: Walker (1967) estimated about the same number were active at any one time per day in late May 1966.



The author made a number of estimates of viscosities of the lavas in July 1970; these were made by measuring the velocity ($V$ in cm/s), the thickness of the flow ($h$ in cm) and the angle of slope ($a$ in degrees) using the formula:

$$\eta = g\rho h^2 \sin a/3V$$

where $\eta$ is the viscosity in poises ($10^{-1}$ Pa s), $g = 980.6$ cm/s$^2$, and $\rho$ is the density of the lava (taken as 2.0 g/cm$^3$).

Measurements showed that *pahoehoe* flows at the foot of the northeast cone some 150 m away from the main hornito area had viscosities ranging from 6.5 to 7.6 kPa s ($6.5$ to $7.6 \times 10^4$ poises) (lavas were about 1 m thick and had velocities of about 8 cm/s on a 5° slope). The viscosity of one flow where it was in the process of changing from *pahoehoe* to *aa* was measured to be about 11 kPa s ($1.1 \times 10^5$ P), close to Walker's (1967) extrapolated viscosity of 20 kPa s ($2 \times 10^5$ P) for the same phenomenon. *Aa* lava some 600 m from its source was estimated to have a viscosity of 15 kPa s ($1.5 \times 10^5$P).

The volume of lava estimated during July 1970 to be added to the lava pile per day from six flows was about 83 000 m$^3$: this is surprisingly similar to Walker's (1967) estimate of near

86000 $m^3$ per day. These measurements suggest that the rate of lava production remained essentially constant during the period 1966 to 1971. If so, then some $160 \times 10^6$ $m^3$ of lava was erupted during this time.

Activity in the crater of the NE cone is not so regular. During October 1969 the level of lava in the crater was high, and fragmenting curtains of red hot lava were thrown some tens of metres above the lip of the crater on several occasions (notably on 11 October). Large explosions occurred at a rate of about one per minute, and between each large explosion there were two to four smaller ones. The maximum height to which bombs were thrown was measured as 250 m above the lip of the crater. Initial velocities of bombs were estimated to be about 50 m/s. On several occasions it appears that the inner wall of the crater became undermined and unstable, collapsing into the vent and blocking it. Such events were marked by billowing clouds of brown ash rising out of the crater; this phenomenon was observed to occur six times on one day, but very rarely on other days.

During this period in October 1969 all the activity in the NE crater occurred in the western side of the crater. However, in July 1970 several vents were clearly in operation. As in October of the previous year, there was a vent on the western side, containing liquid lava (vent A in figure 5) but on the eastern side of the crater there were also several vents from which gas was being expelled explosively. One of these (vent B in figure 5) was particularly active and was observed to explode on average about three times every 2 min, at regular intervals, throwing up fine grained particles of lithic material at high velocity; each explosion was accompanied by a loud report. At night some of the fine material thrown up during these explosions was seen to glow with a dull red, and presumably most of these consisted of rocks torn from the walls of the vent where they had been heated by the erupting gases; some particularly bright bombs may have been fresh lava. On 18 July this vent threw up very little fragmentary material, and explosions of gas were accompanied by long reverberating bangs probably indicating that the vent had become very much deeper.

Compared with October of the previous year, the lava-filled vent on the western side of the NE crater was much less violent in its activity although it still contained active lava at a relatively high level. Rates of explosions were lower, ranging from one to three per minute. Not only were explosions less frequent but they were less violent and rarely accompanied by a bang, the only noise being the dull thuds from large bombs landing. This lessening of activity may have been a result of the lava being more fluid and of the gas vents to the east acting as a safety valve and reducing the gas pressure in the lava column below the lake in the western vent.

As is the case with many cones of this type, a lake of lava forms the top of the column in the crater, and is the main outlet for gases. The vast majority of the lava erupted on the surface does so by extrusion along feeders extending laterally from near the top of the column in the cone to the cone's outer flanks where it breaks out at the surface. The orientation of such feeder dykes will be influenced by the main NE–SW fissure running through the volcano, leading to a principal vent area on the fissure to the northeast of the cone; however, other orientations may develop radially to the cone.

## The Bocca Nuova

The youngest major feature to have developed on this volcano in the 10 years prior to 1971 was the Bocca Nuova, which opened on the 12 June 1968 as a small gas vent (see figure 4). According to V. Barbagallo (personal communication) this event occurred between two groups of tourists walking along the path: it is not surprising that it took the guides responsible for the two parties some time to gather together very startled tourists who had scattered over the mountainside!

For the first year and a half of its life the Bocca Nuova consisted of a hole 5 m in diameter from which gas was expelled at high velocity and temperature. Optical pyrometer measurements of the glowing inner walls of the Bocca gave a temperature of near 1000 °C; more detailed measurements of temperature, gas velocities and compositions have been made by Tazieff and his team, and are reported elsewhere (Tazieff 1970).

Activity from the Bocca was initially quite regular, consisting of alternate strong *blows* occurring every few minutes, and quiet expulsion of gas at lower pressure. *Blows* were accompanied by regular dull booming, each boom separated by an interval of about 2 s. By treating the Bocca tube as an organ pipe (and correcting for temperature of the gas) the length of the shaft below the opening was calculated as 300 m or more. The angle at which gas was expelled suggests that at least the upper part of this tube was inclined at a few degrees into the mountainside.

In October 1969 the Bocca was more active than it had been previously. Although *blows* still occurred at intervals, these were punctuated by loud explosions: on 14 October three big explosions were recorded within about 8 h. They threw out fragments of hot wall rock; equipment inserted into the Bocca for gas collection was also thrown out, and one crucible was recovered from about 200 m away. During the early afternoon of 15 October the frequency of booms during blows was much reduced to about 1 to 1.5 s; this was thought to indicate that the length of the shaft was effectively shorter, either as a result of collapse in the shaft or magma rising to a higher level. These irregularities were considered at the time as indications of possible collapse of the Bocca at the surface.

Collapse in fact took place during the winter of 1970. The date is not known, but V. Barbagallo (personal communication) observed from Nicolosi a dark dust cloud rising from about the position of the Bocca during February (date unknown). In July 1970 the enlarged Bocca had a diameter of about 100 m (figure 5). The walls were then near vertical and the outer rim, especially on the southern side, was cut by open fissures concentric to the lip, suggesting the possibility of further collapse. It is interesting to note that the area of collapse was mainly the area of hot ground indicated by rising steam observed during October of the previous year.

Ground temperature measurements were made by Dr Alison Brown during October 1969 and July 1970. The temperatures within the area that later collapsed were about 40 °C at a depth of 20 cm in the steaming ground, and up to nearly 80 °C at the same depth in small active fumaroles. Outside this area, however, the ground was cold enough to hold snow. In July 1970 after the collapse had occurred temperatures ranged from 30 to 76 °C in the area between the lip of the Bocca and the edge of the 1964 flow. It was also noted that steam was rising from new areas on the 1964 flow, to the southwest of the Bocca where snow had rested in the previous year.

The lack of ejected material around the enlarged Bocca shows that it resulted largely from collapse. The volume of collapsed material may be estimated to be in the order of $9.5 \times 10^6$ m$^3$. To accommodate this volume of collapsed material it would be necessary to remove a column of magma 30 m wide and some 200 m long. This massive removal of magma from below the Bocca is explained in the next section.

Gas escaped from the enlarged Bocca Nuova in much the same way as it does from the chasm.

From the smell this appeared to contain $SO_2$ but on several occasions whiffs of $H_2S$ were detected.

*Cause of the Bocca Nuova collapse*

The initial Bocca Nuova is considered to represent a pipe of magma that penetrated below the central crater but was unable to reach the surface, probably having reached its maximum height at near the same level that lava was standing in the NE crater. Gases rising from the top of the magma-filled tube cored a narrow pipe to the surface to produce the Bocca.

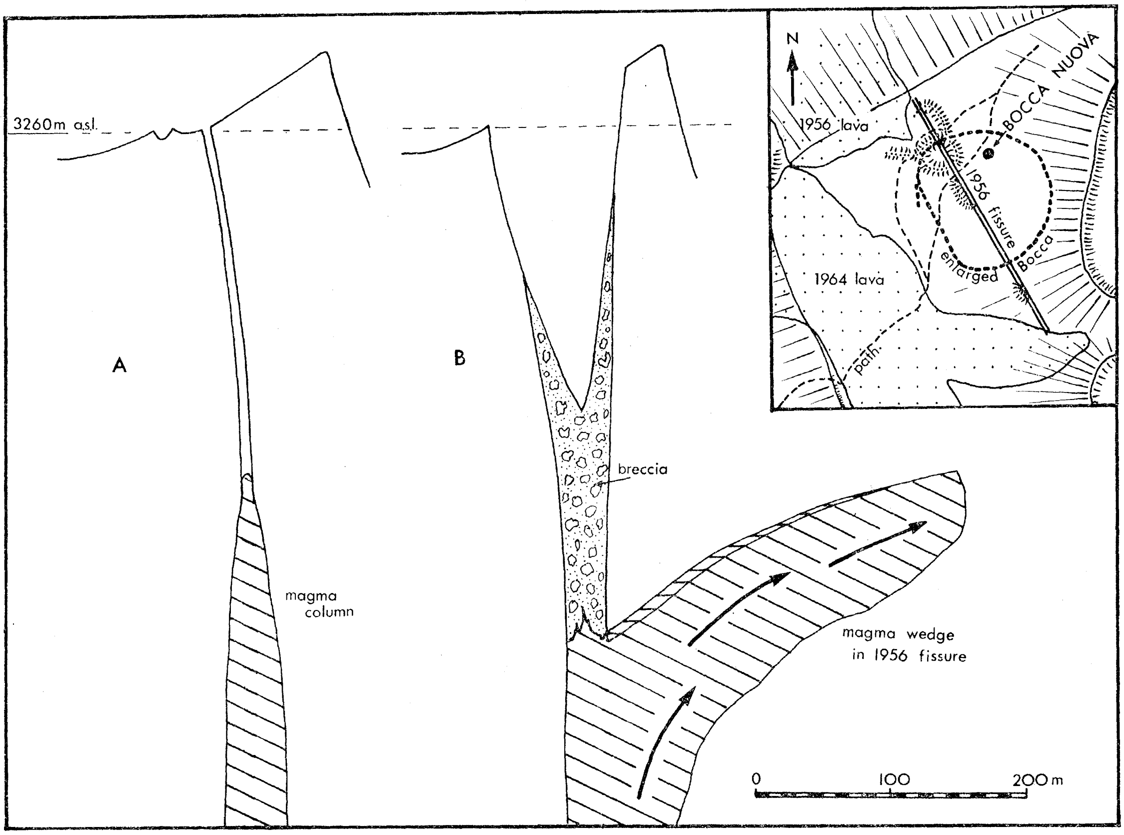


Figure 6. Hypothetical sections (true scale) through the Bocca Nuova: (A) in 1968–9 before collapse; and (B) after collapse in 1970. The insert map on the same scale shows the western side of the central crater in the Bocca Nuova area.

Although there were no eye witnesses to the enlargement of the Bocca Nuova it would appear that this was accomplished entirely by collapse. This collapse presumably resulted from the sudden withdrawal of the magma column that had previously stood at near 300 m below the Bocca opening. It will be noted that the Bocca Nuova was located next to a small chain of craters opened on a fissure during the 1956 eruption. This fissure, if extended in an easterly direction, intersects the flank of the summit cone in the area of the April 1971 eruptions.

An explanation of the collapse of the Bocca that would be in keeping with the later events that occurred on the volcano is that the magma column below the Bocca, instead of withdrawing downwards to give the collapse, burst into the 1956 cross-fracture at depth, causing a sudden lowering of the level of magma below the Bocca and forming a vertical wedge of lava extending beneath the central crater. The removal of magma from directly below the Bocca would cause it to collapse. This is shown diagrammatically in figure 6.

New magma rising in this area could then penetrate into this fissure, slowly enlarging it until lava eventually reached the far side of the cone to erupt as the opening phase of the 1971 eruption.

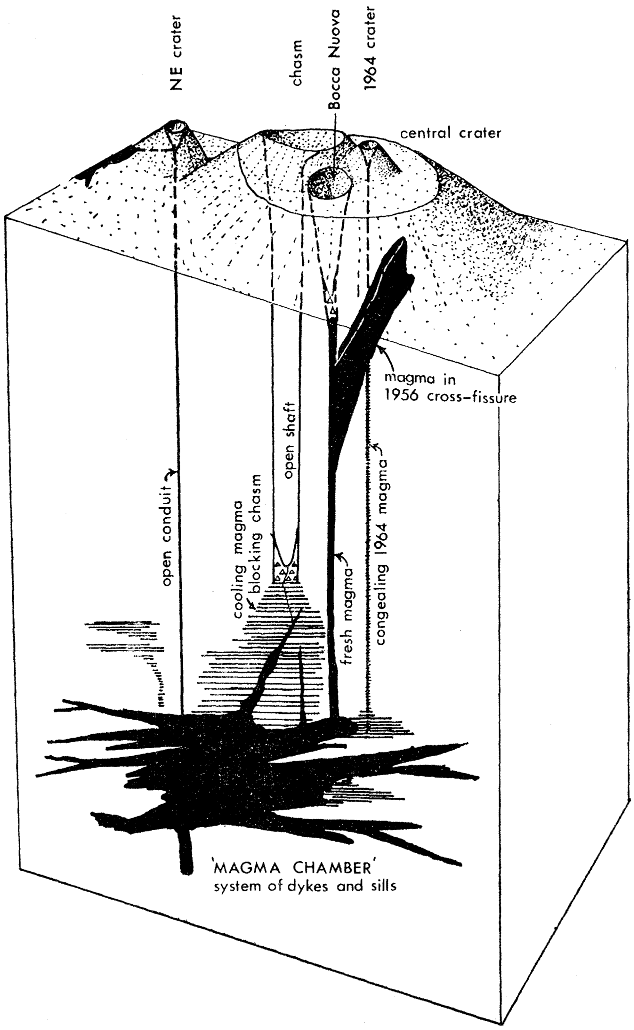


FIGURE 7. Hypothetical block diagram of the summit cone, showing the inferred distribution of magma within the volcano during 1971. The vertical distances are not necessarily to scale.

## Ground and fumarole temperatures

Active fumaroles and areas of steaming ground occur in a number of places in or near the central crater. Some are marked by yellow, green, brown and white sublimates (mainly calcium sulphate) at the surface. The positions of hot areas change with time and older now cool areas are only apparent because of the presence of sublimates and altered rock.

All the vents in the central crater are surrounded by hot areas. Before its collapse the Bocca Nuova was surrounded by steaming ground and active fumaroles giving thick crusts of sublimates in places. Fumarolic activity was particularly strong above the Bocca on the slope leading up to the chasm.

Low on the northwestern side of the summit cone there are a number of open steaming fissures. These are marked on the map for mid-1970, but it is likely that they had existed before that time. Presumably they were produced by collapse in the central crater area.

Steam rises copiously from the lip of the central crater on the southern side, especially between where the path crosses the lip and the fissure gash. Most of the steam rises from the low inward-facing scarp of the crater lip, in some places through small holes or just percolating through the ash, while at others through open fissures. Fumarole temperatures showed a noticeable rise

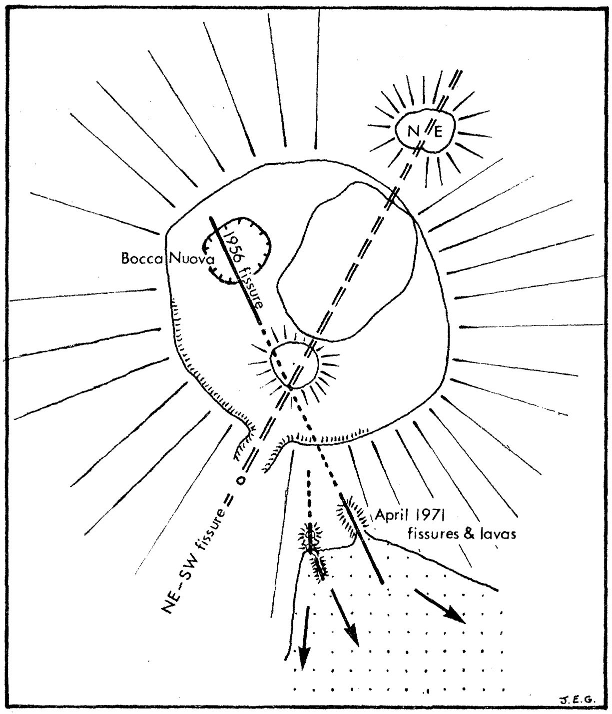


FIGURE 8. Sketch map of the summit of Etna showing the relations between the Bocca Nuova, the 1956 fissure and the April 1971 eruption site. The inferred position of the main NNE–SSW trending fissure through the summit is also shown.

between 1969 and 1970. In 1969 steam vents near the path had temperatures of between 40 and 52 °C, while in 1970 they had risen to about 74 °C. A number of other measurements on this scarp in 1970 showed that temperatures ranged from 64 to 78 °C (Alison Brown, Ph.D. thesis, London 1971).

This rise in temperature was taken at the time to indicate a build up of magma below the central crater.

## CONDITIONS WITHIN ETNA BEFORE THE 1971 ERUPTION

From examination of the activity at the NE crater it would appear that the 'normal' activity of Etna is the steady eruption of lava at a rate of near 1 $m^3$ per second. This rate of eruption probably relates to a steady injection of magma into the volcano from the mantle, inferred from the continuous activity from the NE crater for a period of nearly six years. The rate will also depend on the viscosity of the magma and the diameter of the conduit.

These observations suggest that this crater lies over a thin column of magma leading directly down to a 'magma chamber' within or just below the volcanic pile of Etna. The constant position of this leaking vent and its obvious connexion with other vents that open on the higher parts of the mountain does not support the view that it has a direct connexion with the mantle but that there is a 'magma chamber' at a high level, probably consisting of a network of dykes and sills lying directly below a central conduit system and that it is within this system that magma leading to eruptions on the mountain rises. Flank eruptions result from horizontal movement of magma along fissures opened at least in part by inflation of the volcano.

The output of lava during the 1971 eruption was considerably greater than the 'normal' output, Booth (1971) records a rate of 10 $m^3/s$ during the first few weeks of this eruption and later when the site of eruptions had migrated farther down the mountain it was in the order of 20 to 50 $m^3/s$. This implies that this, and other eruptions like it, result not just from a change in site of the centre of eruption, but from a surge of magma into the volcanic edifice many times greater than the normal input or that an accumulated mass of magma within the volcano was released.

Evidence from observations made in the central crater area during the two years before 1971 suggest that an influx of new magma started in mid-1968 when the Bocca Nuova opened. It is suggested that a column of magma rose under the central crater somewhat displaced from the chasm which was blocked by lava. This magma penetrated to near the surface utilizing the 1956 fissure. However, when it reached about the same level as lava standing in the NE crater it was unable to climb further and only gas evolved from the top of the magma column was able to make itself evident at the surface. Pulsing of lava of the type probably witnessed on 15 October 1969 together with sharp explosions, caused the 1956 fissure to split early in 1970 allowing the upper part of the magma column to burst into the fissure, lowering the level of magma and causing collapse of the Bocca above. From that time onwards magma penetrating from below entered the fissure that was being wedged open. This migration of magma below the central crater caused a marked increase of the temperature of the fumaroles on the edge of the central crater. As the magma progressed along the fissure it split into two parts and eventually reached the far side of the cone to form two active fissures just above the Volcano Observatory marking the initiation of the 1971 eruption in April, as described by Booth (1971).

During this lateral movement of magma just below the central crater magma was probably accumulating in the magma chamber and in the central conduit causing inflation of the whole of the upper part of the volcano and preparing the way for the flank eruptions that characterized the later part of this large eruption.

The help of Dr Alison Brown and Mr J. B. Murray who accompanied the author on Etna in both 1969 and 1970, and Mr J. H. Foster who joined the team in 1970 is gratefully acknowledged. Logistic support willingly provided by Dr H. Tazieff and his team did much to make this work possible. Permission to stay at the Volcano Observatory was granted by the University of Catania; and the International Institute for Volcanological Research helped by providing, amongst other things, transport. Professor C. W. Allen found funds from the University of London Observatory for the 1969 field work. The author is particularly grateful to V. Barbagallo, a guide on Etna for over 40 years, for information about the courses of previous eruptions and the ages of many flows mapped. Dr G. P. L. Walker kindly read the MS for this paper, suggesting many helpful improvements.

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## Discussion

Dr Alison Brown: As well as the fumarole temperature measurements mentioned by Dr Guest and reported in more detail in my Ph.D. thesis (1971, University of London), I also made measurements in the central crater in July 1971, immediately after the eruption. At that time I noted that the fumarole field on the edge of the central Crater to the southeast had increased in temperature to 80° C. A new area of fumaroles covering about 2 $m^2$ was found on the shoulder between the 1964 crater and the chasm: here temperatures were about 112° C. These rises of temperature could be related to the continued rise of magma within the central conduit after the 1971 eruption had ceased.



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