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The output of the Etna volcano

ETNA shows two types of eruptive activity: persistent activity during which lava issues continuously at a low volumetric rate over a long time, and periodic eruptions during which lava issues at a high rate over a short time. The former is from vents at or near the summit, the latter most commonly from flank vents. In some flank eruptions the lava degasses from the central vent, and in others partly from the flank vents, building scoria cones there.

The historical record of activity on Etna is unrivalled in the large number of lava flows of known date and areal extent: Sartorius von Waltershausen[1] compiled a map of the lavas formed before 1839, and each eruption since then has been documented. Nevertheless, few attempts have been made to determine the volumetric output of new rock over the historic period, in spite of the importance of such data to understanding the mechanism of the volcano.

The problem of determining the output is not, however, straightforward, because although the volume of each dated, flank lava flow can be readily estimated, it is difficult to assess the contribution from persistent summit activity. We consider here the present output and attempt to relate this to the earlier history.

The years immediately before 1971 were characterised by persistent activity from the north-eastern crater. During that time we made estimates of the effusion rate on three occasions (refs 2 and 3, and G. P. L. W., unpublished) and arrived at a consistent value of around 1 $m^3 s^{-1}$. The accumulated products of the persistent summit activity from 1932 to 1967 amount to 270×10^6 m^3, based on a comparison of two editions of the 1:25,000 topographic map of Etna; flank activity during this period contributed a further 60×10^6 m^3, giving a total of 330×10^6 m^3 or 0.3 $m^3 s^{-1}$ averaged over this period of 35 yr.

The persistent activity ceased with the commencement of an eruption during the spring of 1971 but resumed again in late

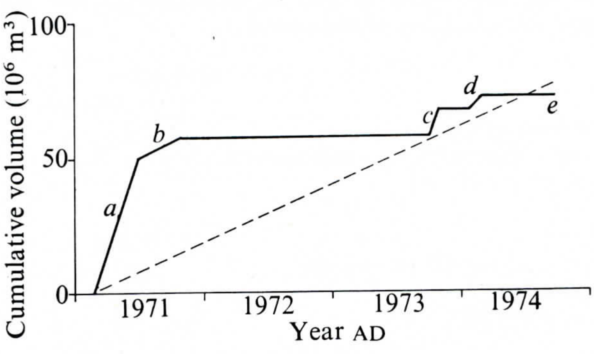

Fig. 1 Cumulative output of Etna by summit and flank activity during the period April 1971–September 1974. *a*, 1971 eruption; *b*, partial infilling of the Chasm; *c*, partial infilling of the Chasm and Bocca Nuova; *d*, January–March 1974 flank eruption; *e*, resumption of persistent activity from the North-eastern Crater. Dashed line, average output rate (0.68 $m^3 s^{-1}$).

1974. Between the 1971 eruption and late 1974 there were, however, several eruptive events, notably a partial infilling of the Chasm (the main crater at the summit of Etna) by lava in 1973. A small flank eruption also occurred in January–March 1974 (ref. 4). The estimated volume of lava produced during all the activity from spring 1971 to the present (Fig. 1) gives an average rate of 0.68 $m^3 s^{-1}$. These figures compare with the higher average rate of 3.4 $m^3 s^{-1}$ for Kilauea[5].

Reasonably complete records of flank eruptions span the period from 1535 to the present. One of us[6] has measured the area of each historic flank flow and has visited each locality to estimate the average thickness of the flows. The assessed volumes (Fig. 2) are, in general, smaller than volumes given in the literature, but if there is any subjective error in estimating the thickness of the flows it should be consistent.

The striking feature (Fig. 2) is that there were four periods of contrasted outputs: first, 1535–1610, characterised by a rather low effusion rate; second, 1610–1669, characterised by a high effusion rate, averaging 0.83 $m^3 s^{-1}$; third, 1669–1763, during which there were no major flank eruptions; fourth, from the 1759 resumption of flank activity to the present, characterised by a uniform and moderate effusion rate averaging 0.17 $m^3 s^{-1}$.

The high effusion rate between 1610 and 1669 could be correlated with the absence of summit activity during that period: flank eruptions accounted for the entire output. Following that period a large caldera formed at the summit during the 1669 flank eruption, and the contemporaneous absence of

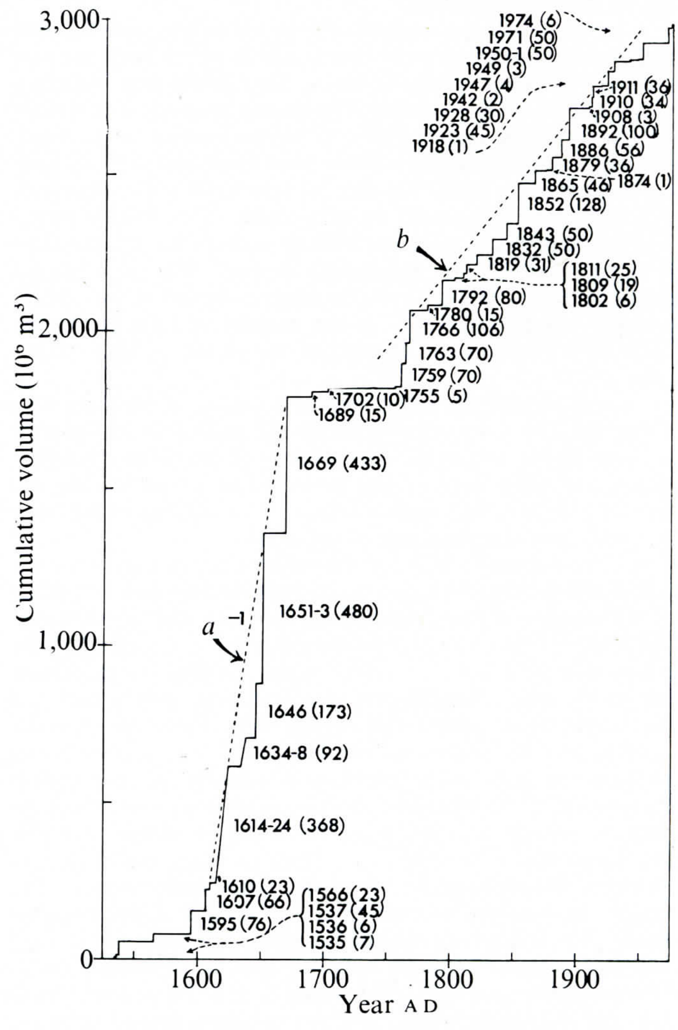

Fig. 2 Cumulative output of Etna by flank activity since 1535. Some of the eruptions listed in ref. 9 are omitted (1540, 1550, 1578–80—small eruptions, no volumetric data available; 1883—no lava flow produced; 1682, 1747, 1869—summit eruptions; 1764–45—confusion exists regarding the source, but very probably persistent activity; 1603—dubious eruption), but probably do not change the picture significantly. *a*, Average output rate: 0.83 $m^3 s^{-1}$; *b*, average output rate: 0.17 $m^3 s^{-1}$. Numbers in brackets following dates give the volume of output (10^6 m^3) for those dates.

flank eruptions could have been because the steady volcanic activity at the summit was filling in the caldera. By the time of Spallanzane's visit at the end of the eighteenth century[7], Etna again had a summit cone standing above the caldera rim.

Persistent summit activity occurred more or less continuously between 1759 and the present, and the average effusion rate of 0.17 $m^3 s^{-1}$ resulting from the flank activity is thus only part of the total. It is impossible to arrive at an accurate figure for the contribution by persistent summit activity. In particular, there are many undated lava flows which originated high on the volcano belonging to that period. A rough calculation of the volume of Etna standing above the 1669 caldera rim, and the volume of known summit lava flows of the past 200 yr gives a total of 500×10^6 m^3, and an average effusion rate of 0.09 $m^3 s^{-1}$. Some pyroclastics have fallen beyond the caldera rim or have been eroded from the summit cone, but a total output of close to 0.26 $m^3 s^{-1}$ for the period is indicated.

A volcano such as Etna is a system into which magma rises from the mantle and out of which lava is erupted at the surface. The input is generally greater than the output since some, perhaps rather more than 10% of the magma which enters the volcano congeals below the surface to form intrusions. There is general evidence that the input is continuous, and that high level magma reservoirs exist, within which some of the input is stored between eruptions.

A model which can reconcile the varied output over the past 450 yr with a uniform input rate is one in which there are two magma reservoirs within or below Etna filling and emptying independently of one another. The smaller reservoir would have a capacity of the order of 50×10^6 m^3 and would be partially or totally drained during normal flank eruptions such as have occurred roughly every 10 years between 1763 and the present. The large reservoir would be of an order of magnitude larger and would probably take hundreds of years to fill: the last time it emptied was in the seventeenth century. The most cogent evidence for the existence of this larger reservoir is the caldera collapse which took place at the summit of Etna during the 1669 flank eruption and terminated the period of high output (Fig. 2).

On this model, the input rate is constant at perhaps 0.3–0.4 $m^3 s^{-1}$. The output during the period 1610–1669 was greater because of the release of the contents of the larger reservoir which had filled over a long period. The output during the two later periods was smaller because slow refilling of the large reservoir then absorbed part of the input.

A second model which can reconcile a varied output with a uniform input requires only one storage reservoir, and the nature of the eruptive activity depends on the state and, particularly, the height of the volcano. Persistent activity is a steady leakage which acts as a form of safety valve. Perhaps it can release the entire input, although it normally releases only a part and flank eruptions release the remainder. Persistent summit activity steadily increases the height of the volcano, and because the hydrostatic pressure in magma at the summit decreases as its height increases[8] this results in a reduced leakage rate. A greater proportion of the input is stored, and the resulting inflation of the volcano then increases the likelihood of major flank outbreaks, as in the seventeenth century. The major channelways so opened divert summit activity to the flanks. The loss of a large volume of magma from the storage reservoir results in caldera collapse, thus terminating a cycle. One possible objection to this model is that the height of Etna has not increased significantly in the past century (1864—3,313 m; 1900—3,274 m; 1973—3,316 m). Also, a gradual decrease in leakage rate could be expected to lead to a gradual increase in the magnitude of flank eruptions, rather than an abrupt increase as occurred in the seventeenth century.

Both of these models envisage a uniform rate of input, but another possibility is that the input itself varies with time and was particularly high during the period of high output in the seventeenth century. The eruptions of this period include two (those of 1614–24 and 1651–53) which produced pahoehoe instead of the more normal aa flows of Etna, and these flows probably had an unusually low viscosity. If the low viscosity resulted from a difference in chemical composition then that, and the increased output, could well correlate with changed conditions in the mantle. The large volume of lava which emerged in the 1669 eruption, however, can be related to the unusually low level of the 1669 vents[8].

There is at present no way to choose between these three alternative explanations for the variation in output. Whichever applies, we see signs of a cyclic pattern, each cycle lasting for some hundreds of years and terminated by caldera collapse. There are traces of two calderas (the Valle del Leone and Cratere Ellittico) which existed earlier than that of 1669 (the Cratere del Piano), and the Valle del Bove may be another. There are also lava flows of large volumes, which are older than the seventeenth century.

The discrepancy between the low output (0.26 $m^3 s^{-1}$) of the past 200 yr and the higher output of the most recent period (0.68 $m^3 s^{-1}$) could be attributable to several factors. One possibility is that the latter indicates the onset of another highly voluminous effusive period such as that of the seventeenth century, although there is no other supporting evidence for this.

The base level of Etna varies from below sea level to more than 1,000 m OD. The volume of Etna standing above a horizontal plane 500 m OD is 515 km^3. To this should be added 12 km^3: the volume deficit of the Valle del Bove. The total output since 1535 is of the order of 3.6 km^3, or an average of 0.26 $m^3 s^{-1}$. At this rate Etna could have been constructed in 65,000 yr.

Understanding the mechanism of Etna depends on the availability of good quantitative data. This study demonstrates the importance of making more critical and more frequent measurements of the output.

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