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Eruption early warning at Vesuvius: The A.D. 1631 lesson

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[1] Knowledge of past precursor patterns is crucial for the correct interpretation of monitoring data and reliable volcano forecasting. In the case of Vesuvius, one of the world's riskiest volcanoes, very little information is available about unrest signals following long periods of quiescence. The translation and analysis of three Latin treatises written from eye-witnesses immediately after the A.D. 1631 subplinian eruption allowed us to reconstruct the sequence of precursors. The progression in the signals was remarkably clear starting at least two to three weeks before the event. Widespread gas emission from the ground coupled with deformation was followed by an increase in seismic activity in the eight days before the eruption. Seismicity escalated both in frequency and intensity in the night before the eruption, heralding the opening of fissures on the volcanic cone. The details of phenomena occurring in the medium-term (months before the eruption) are difficult to evaluate, though it is worth noticing that no major tectonic earthquakes were felt in the area of the volcano. Civil protection preparedness plans should be organized in order to complete the evacuation of people in a time span significantly shorter than the duration of expected short-term precursors. **Citation:** Bertagnini, A., R. Cioni, E. Guidoboni, M. Rosi, A. Neri, and E. Boschi (2006), Eruption early warning at Vesuvius: The A.D. 1631 lesson, *Geophys. Res. Lett.*, *33*, L18317, doi:10.1029/2006GL027297.

1. Introduction

[2] The geophysical and geochemical signals that accompany magma rising to the surface show specific patterns in each volcanic system [*Sparks*, 2003; *McNutt et al.*, 2000]. The duration of pre-eruptive crises at different volcanoes is variable (from days to years) and not all volcano unrest results in an eruption. Knowledge of past precursor patterns is thus crucial with high-risk volcanoes, where the decisions of whether to evacuate the population calls for the correct interpretation of monitoring data and reliable volcano forecasting.

[3] In the case of Vesuvius, one of the world's riskiest volcanoes, very little information is available about unrest signals following long–lasting quiescence. Three Latin treatises [*Carafa*, 1632; *Mascolo*, 1633; *Varone*, 1634] describing the 16–17th December 1631 eruption and its precursors help to fill this gap. This most intense and violent eruption of the past 1500 years occurred after a period of quiescence possibly lasting five centuries. This eruption is presently considered the reference for the expected scenario in the case of a reactivation of Vesuvius in the emergency planning of the National Civil Protection. A few papers attempted to reconstruct precursors of this eruption, gathering information through the critical reading of chronicles, books and reports selected from the high number of documents written on the eruption [*Rosi et al.*, 1993; *Rolandi et al.*, 1993; *Nazzaro*, 1998]. However information on precursors given by documents written in Italian and Spanish is rather fragmentary and imprecise. The three texts discussed here, selected through a historical and philological survey of available texts, were not thoroughly examined until now. The three authors, all with a wide cultural insight, were direct eyewitnesses of the eruption and also gathered information from witnesses who they considered trustworthy. Most importantly, they wrote their accounts immediately after the eruption and dedicated entire chapters or even books to describe and analyze pre-eruption phenomena, providing a highly reliable, coherent picture of precursor activity.

[4] The treatises, totaling more than 750 pages were carefully translated from the Latin erudite style of the seventeenth century. The pre-eruptive and eruptive descriptions were analyzed within the cultural and linguistic framework of the period [*Guidoboni*, 2004]. Translation of the passages describing the phenomena was conducted without involvement of volcanologists to avoid preconceptions due to specialist knowledge.

[5] Of particular interest is the treatise by *Varone* [1634]. It is composed of three books the first of which, entitled "Vesuvius Praemonens" (Vesuvius the Admonisher), deals with the direct observations made by the Author himself (he had lived in Portici, only 7 km NW of Vesuvius (Figure 1), since the spring of 1631) and few other "reliable" witnesses of the several anomalous phenomena which preceded the eruption. This book was written with the explicit aim of advising posterity how to read the signs of an impending eruption, and represents a very well detailed, complete description of these phenomena.

2. A.D. 1631 Eruption

[6] The different phases of the eruption are described by *Rosi et al.* [1993] and *Rolandi et al.* [1993], based upon stratigraphic analysis of the deposits and the critical reading of contemporary chronicles.

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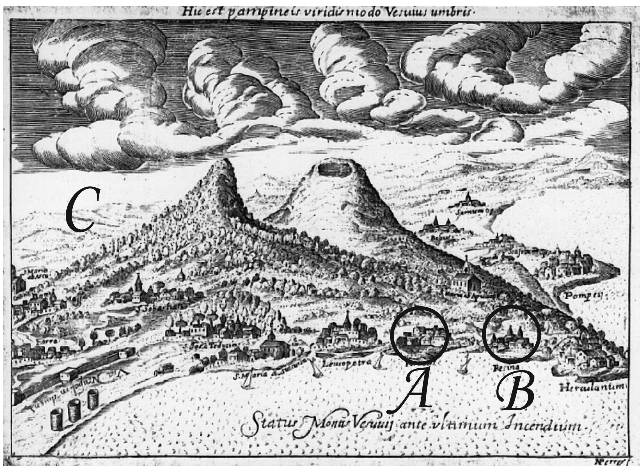

Figure 1. "The state of Mount Vesuvius before its last fire" (engraving from *Mascolo* [1633]). The capital letters indicate the location of the villages cited in the text: A, Portici; B, Resina; C, Ottaviano.

[7] The eruption started at dawn on December 16, 1631, with the opening of an eruptive fissure on the western side of Vesuvius, close to the base of the cone. The first explosions possibly formed cock tail-like clouds, and were followed by a slowly-growing pine-shaped Plinian column, dispersed to the East by the prevailing winds. The convective column was sustained for about eight hours, accompanied by continuous seismic tremor and fallout of lapilli downwind of the volcano. The estimated conservative volume of the plinian deposit is 0.21 km^3 [*Rosi et al.*, 1993] and the column reached a maximum height of about 21 km [*Rosi et al.*, 1993; *Rolandi et al.*, 1993], in the typical range of subplinian eruptions.

[8] The sustained convective column was followed by a pulsating phase characterized by ash showers and extensive rainfalls accompanied by frequent seismic shocks during the whole night between December 16th and 17th, which produced some damage to the buildings.

[9] In the morning of December 17th a violent earthquake occurred, lasting a few minutes. The earthquake was immediately followed by the most violent phase of the eruption, characterized by pyroclastic flow activity. Seven different pyroclastic flows were at this time emplaced toward the western and southern sectors, strongly controlled by the preexisting topography and by the Somma rim.

[10] Most of the casualties are related to this phase of the eruption. The total number of victims varied from 1,000 according to *Varone* [1634], to 3,000 according to *Carafa* [1632] and *Mascolo* [1633], up to 4,000 or 6,000 as estimated respectively by *Rosi et al.* [1993] and *Rolandi et al.* [1993].

[11] The final stages of the eruption were marked by intermittent ash emissions and frequent generation of lahars and floods. These were triggered by the heavy rains which characterized the syn- and post-eruptive periods, starting from the morning of December 17th. Lahars started to form in the night between 16 and 17, reaching their maximum intensity immediately after the pyroclastic flow phase [*Rosi et al.*, 1993]. Lahars and floods occurred for many days after the eruption, devastating the plain at the northern foot of the volcano.

3. Precursors

[12] In order to simplify the analysis, the precursory phenomena described in the three narratives were grouped in 5 different categories: acoustic phenomena, ground deformations and landslides, gas emissions, effects on ground water and seismic activity. In addition, the chronological sequence of the described signals can be easily reconstructed from the chronicles. For each phenomenon we report the source and indicate the number of book (or chapter) and corresponding passage (e.g., Var. 1, 46 corresponds to First book, passage 46 of Varone's report).

3.1. Acoustic Phenomena

[13] Rumblings were heard starting from October until December from the town of Portici (Var. 1, 46), described as thunders during sunny days. Together with rumbles, different sounds were heard in December directly coming from the crater area, in some cases similar to the noise produced by rockfall ["Eight days before there was heard . . . a noise like a great millstone, and the sky, entirely cloudless, thundered, from an unknown direction . . ." (Var. 1, 39). "On 9th December, on the side of the mount facing the sea, they say that there was heard a noise like that of a horn" (Var. 1, 46). "Some days before Vesuvius was rent apart it was heard . . . both day and night, a noise like a great thud coming from the area of the mountain, exploded in a distant and closed place" (Var. 1, 39). "The night before . . . the roar was like that of a turning millstone" (Masc. 1, 8)].

[14] The account of Carafa of rumbles clearly heard in December from the town of Resina (close to Portici where Varone was living, Figure 1) suggests that the western sector of the volcano was possibly a preferential site for the hearing of acoustic phenomena. ["Some days before rumblings, and roars, from the deep caverns of the mountain around Resina" (Car. 3, 3).]

3.2. Ground Deformations and Landslides

[15] Landslides inside the crater or on the slopes of the cone occurred repeatedly starting some months before the eruption (Masc. 10, 4). Of uncertain timing, but definitely before the eruption, is a landslide on the eastern flank of Somma in the area of Ottaviano (Figure 1). This was described by Carafa as occurring in September, whereas Varone describes a similar event at the beginning of December ["at the beginning of September of that same year, on the slope of the Mount towards Ottaviano, the moved ground had been lowered to a great extent, releasing a landslide" (Car. 3, 4). "Furthermore, from that part of the mount first to be cheered by the light of dawn, a crag of huge dimensions broke away and . . . fell down around the beginning of the month" (Var. 1, 46).]

[16] The landslides inside the cone were responsible for the rise of the crater floor and, as mentioned by Mascolo, this phenomenon and its interpretation (landsliding or uplift) were subject of debate among the contemporary observers ["Vesuvius had swollen some months before, in that summit which dominated the sea below, leveling that chasm which, as I said before, had lowered itself; and this occurred not, as some thought, because the vapors forced

themselves up through the earth . . . but . . . by passing through the crags which, as happens, had fallen there" (Masc. 10, 4)].

[17] A general ground uplift is described by Varone in December, with a maximum located in the western slopes of the volcano ["the mountain not in only one place, in particular in the west, took to swelling more than usual, and, lifting itself up like a great hump"]. Soil fracturing was also observed in December in several places, associated with hot gas emission (Var. 1, 40; Var. 1, 46).

[18] A description of sea recession at the onset of the eruption is given by Varone ["all the sea near the crater, which lay idly across the beach, from the river Sarno up to Pozzuoli, as once at the beach of Cuma, either was thrown back by the force of the mount or attracted by the sun that opened up, in fact all of a sudden the beaches for many paces were dried up, so that for a long time the thirsty sand was without its wave" (Var. 2, 23)]. We can interpret this as a short-term deformation of the area around the volcano immediately preceding the eruption. By using a simple deformation model [*Mogi*, 1958] a vertical deformation of a few centimeters along the shoreline can be related to the pre-rupture pressurization of a 1 km radius spherical magma chamber at a depth of 4 km.

3.3. Gas Emissions

[19] Accounts of the "disappearance" of wild animals from the summit area of the volcano starting from some months before the eruption could be a sign of diffuse gas emission, even though the objective value of these observations is difficult to assess. ["For many months earlier on the slopes of the mountain there was no sight of the rural beasts" (Var. 1, 41).] The description of strange phenomena like those observed on the volcano slopes during the summer preceding the eruption are not of clear interpretation, but could record the occasional occurrence of hot gas emission or, more probably, to be a retrospective interpretation of normal wildfire occurrence ["It is clear above all that Vesuvius once, and a second time, and yet again, lit up the nightly darkness, and rising up like will-o'-the-wisps relieved the darkness. In particular close to Resina there were seen tongues of fire which heralded rather clearly our woes" (Var. 1, 38)].

[20] The first clear indication of diffuse gas emission was reported by Varone, who noticed a droop of local vegetation on Vesuvius by the end of November ["In fact the little flowers . . . were seen to droop just before December, without any wrong having been done to them" (Var. 1, 46)].

[21] Gas emission are unequivocally described in association with fracturing of the cone in the days preceding the eruption ["from the cracks the soil let out red-hot fumes to which livestock succumbed, not without pain" (Var. 1, 40)].

3.4. Variations of Ground Water

[22] Starting from the end of November, the authors also describe phenomena involving the water table, such as muddy well water ["the water of the wells in places close to the mountain had become muddier" (Car. 3, 3)] and muddying and salinity variations in the springs at the foot of Vesuvius ["water from the springs at the foothills of Vesuvius just before the beginning of December flowed . . . corrupted with a muddy aspect, and . . . they had the bitterness of the sea" (Var. 1, 47)].

3.5. Seismic Activity

[23] The first seismic activity, only felt along the littoral area, could have occurred during the night between 19th and 20th November, as suggested by a convoluted sentence in Varone ["the shoreline of Vesuvius on that agitated 20th November made fun of the nightly calm" (Var. 1, 46)]. Even more doubtful is the interpretation of the already discussed acoustic phenomena as side effects of minor, low intensity seismic activity.

[24] Earthquakes clearly felt by the population started on December 8th and continued intermittently and with low intensity until December 15th ["The earth trembled around Vesuvius also on 8th December . . .. The earth shook again on 12th and 13th December and again, therefore it was the mere lightness of the movement that made its frequency seem not greatly frightening or prodigious" (Var. 1, 46)]. Shaking could be perceived in a radius of about 8 km from the volcano, while people living in Naples only felt it from the early morning of December 16th ["From the Fourth hour to the Ninth, the earth trembled with frequent shocks, but less violent; in truth around the Ninth . . . also Naples and towns further away shook" (Car. 4, 5)]. Seismic activity escalated during the night between December 15th and 16th, heralding the opening of an eruptive fissure on the western flank of the cone in the morning of December 16th ["And then that night (Night 15th Dec.–Morning 16th Dec.) an earthquake and an underground rumble were repeated almost thirtyfold"(Var. 1, 74; 2, 23). "The night before (Night 15th Dec.) . . . Vesuvius was shaken by more frequent movements" (Masc. 1, 8). "Around the Twelfth hour the earth quaked more violently, jolted by greater vehemence . . . to the point where the flanks of the mount . . . split and tumbled down" (Car. 4, 6)].

[25] Effects of local reduction of the seismic signal are well described by Varone, who indicated minor and less frequent shaking on the southern slopes of Vesuvius ["It was witnessed that the mount, where it looks southwards, trembled more lightly and more rarely" (Var. 1, 46)].

4. Discussion

[26] Based on frequency, temporal correlations and types of the reported phenomena we can distinguish two different periods in the precursory activity: i) the first period, lasting from months before the eruption until the end of November, punctuated by scattered, isolated phenomena of somewhat unclear meaning (medium-term precursors?); ii) a second period represented by the 15–20 days before the eruption, characterized by obvious pre-eruptive signals (gas emission, ground deformation, and seismic activity) that steadily increased in number and intensity and culminated in an important acceleration few hours before the eruption (short-term precursors).

4.1. Medium-Term Precursors

[27] The anomalous phenomena reported before the end of November appear to be of doubtful significance and reliability. Some of these appear to be *a posteriori* reconsiderations of phenomena initially considered normal and clearly conditioned by scientific notions of the time. The

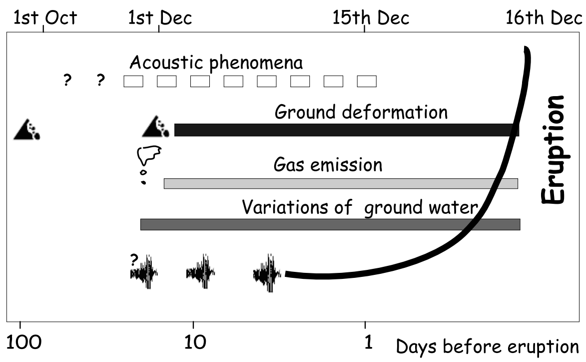

Figure 2. Temporal evolution of the described precursory phenomena of the A.D. 1631 eruption, according to the treatises of *Carafa* [1632], *Mascolo* [1633], and *Varone* [1634].

flames observed on the mountain from August could allude to the triggering of combustion. Rumbles heard from October at first attributed to distant thunderstorms are then regarded as underground noises coming from the mountain, following the notion that an eruption or an earthquake should be heralded by underground noises [“it is uncommon that Mounts Efesti visibly burn without having thundered in secret ”(Var. 1, 39). “It is on the other hand typical of Vesuvius to proclaim the earthquake with a solemn bellow” (Mascolo, Effemeridi…, 22 June 1631). “Never in fact has the sound not preceded the trembling of the earth” (Var. 2, 20)]. Ambiguous reports of rumblings before an eruption, not accompanied by seismic activity clearly felt by the population, are scattered in the volcanological literature [*Benoit and McNutt*, 1996]. A possible explanation for this could be related to the acoustic resonance following low Magnitude (<2–3) seismic activity. Still other observations, such as the fleeing of wild animals from the mountain, are difficult to confirm. Information about landslides both inside and outside the cone appears more reliable, even though the timing, characteristics and location of these phenomena on the northeastern slopes of the volcano are not easy to assess. Landsliding inside the crater could have been due to an incipient deformation or low magnitude, unfelt seismic activity. Indeed, apart from the doubtful earthquake that occurred during the night of November 19th and only felt near the coast, no important seismic activity characterized this period.

4.2. Short-Term Precursors

[28] The three weeks that preceded the eruption were characterized by the contemporaneous occurrence of several anomalous phenomena and by their rapid escalation in the days that preceded the eruption. The first precursor to be noticed was an increase in the turbidity and salinity of wells and springs occurred towards the end of November. Groundwater changes before eruptions, both in the level and chemical properties, have been reported [*Newhall et al.*, 2001; *Biagi et al.*, 2004; *Shibata and Akita*, 2001; *Carapezza et al.*, 2004]. At Vesuvius this seems to be a common characteristics as several post-1631 eruptions were preceded and accompanied by marked changes in the water level in wells [*Alfano and Friedlaender*, 1929]. Around the same time, the drying-up of vegetation occurred on the cone suggests an increase of diffuse gas release from the soil. Similar killing of vegetation is described in association with volcanic unrest around the world, like at Vulcano island [*Diliberto et al.*, 2002] and Mammoth Mountain [*Farrar et al.*, 1995] when large amounts of CO_2 are released from the ground. The post-eruption rise in the soil temperature observed after the large 1914 eruption of Sakurajima volcano had a similar effect on vegetation [*Newhall et al.*, 2001]. Perceptible earthquakes started on December 8th. Seismic activity was intermittent and of low intensity and, until the morning of the eruption was practically unfelt in Naples (about 12 km from the volcano). Intensity and frequency of the seismic activity markedly increased only during the night of December 15th, 8 hours before the beginning of the eruption. The described seismic activity does not fit the “generic volcanic earthquake swarm model” presented by *McNutt* [1996, 2000] because there was no “relative quiescence” immediately preceding the eruption. In the case of 1631, the eruption possibly occurred at the peak of seismic activity, both in terms of number and intensity. Vice versa the 8-days duration of the precursory seismic activity is practically coincident with the median calculated by *Benoit and McNutt* [1996] for 385 volcanic swarms all over the world. The rapid increase of the seismic activity in the eight hours preceding the eruption is consistent with the model proposed by *Kilburn* [2003] who identifies a final acceleration of short-term pre-eruptive volcano-tectonic seismicity, when the dominant crack mechanism changes from crack nucleation to crack growth. This final acceleration generally evolves over intervals of 1–10 days and is often dominated by events occurring around the volcano axis. An exponential runaway increase leading right up to the point of the eruption was also described at other volcanoes [*Endo et al.*, 1996; *Voight*, 1988]. The pattern of widespread gas emission from the ground and the geochemical variations was thus followed by rapid escalation of phenomena involving widespread deformations at the scale of the entire volcano, fracturing, hot gas emission and seismic activity in the ten days before the eruption. This fact is indicative of a fairly rapid rise of magma to the surface. Such a rise eventually accelerated until its climax the day before the eruption proper. Rapid magma ascent appears to be in agreement with the absence of precursory phreatic explosions. Steam explosions often characterize long-lasting unrest, when slow magma ascent allows time to heat the surface aquifers by conduction or magmatic volatile release produced by decompression [*Barberi et al.*, 1992].

5. Conclusions

[29] The pattern of precursors preceding onset of the 1631 eruption of Vesuvius is remarkably clear, starting at least two to three weeks before the event (Figure 2). The description of the progression of the signals is unmistakable and comparable with modern pre-eruptive crises all over the world. The details of phenomena occurring in the months before the eruption are impossible to evaluate with any reliability, though it is worth noticing that no major tectonic earthquakes were felt in the area of the volcano. Even if duration of precursors is not always constant, knowledge of past precursor pattern is of invaluable importance at Vesu-

vius where the civil protection preparedness plans should be organized in order to complete the evacuation of people in a time span significantly shorter than the duration of expected short-term precursors.

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