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PM_{10} measurements in urban settlements after lava fountain episodes at Mt Etna, Italy: pilot test to assess volcanic ash hazard on human health

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Abstract

In this paper we focus on the potential risks caused by the sub-10 micron fraction of volcanic ash (particulate matter: PM_{10}) after the basaltic explosive eruptions from Mt Etna volcano (Italy), which have dramatically increased in frequency over the last 20 years. We present results deriving from the study of the ash concentration in the air following the lava fountain episode from the New South-East Crater of Etna on 15 November 2011, which caused tephra fallout over the eastern slope of the volcano. Short-duration tests of PM_{10} measurements were carried out at three different sites using a TSI® DustTrak™ aerosol monitor a few hours after the end of the eruption, and readouts of the air quality were repeated at the same sites a month later without volcanic activity. Furthermore, ash samples were characterized by grain-size, componentry, morphological and petro-chemical analyses.

By comparing PM_{10} levels measured a few hours after the 15 November lava fountain and on 15 December, we found that relatively low amounts (500–1500 $\mathrm{g\,m^{-2}}$) of tephra fallout cause high levels of PM_{10} in the air. This is because the coarse particles, like basaltic ash, are readily broken up by traffic and hence remobilized into the air, due to their intrinsic, physical and morphological features. We believe that in the future the impact from ash fallout in the Etnean territory should receive proper attention in order to avoid potential health problems; this may be achieved by accomplishing simple but effective actions, first and foremost the prompt removal of the ash deposits from the urbanized areas.

1 Introduction

The effects of volcanic ash on people's health have been widely acknowledged and documented in the literature (e.g. Hincks et al., 2006; Horwell et al., 2003, 2006, 2010, 2013; Le Blond et al., 2010; Searl et al., 2002; Wilson et al., 2011). The finer particles, especially particulate matter with dimensions ≤ 10 micron in aerodynamic equivalent diameter (PM_{10}), remain suspended in the air and may be inhaled, causing different degrees of injury depending on the particle size (Horwell and Baxter, 2006). Coarse particles of 4–10 µm aerodynamic diameter (i.e. PM_{10} and PM_4) are also called "thoracic" because they may reach the bronchioles of the lungs via the nose and throat, while fine (< PM_4 and $PM_{2.5}$) particles are called "respirable" since they can more readily penetrate into the lungs, thus involving the alveolar region where the gas-exchanges take place (QUARG, 1996). The limit between thoracic and respirable particles at the sub-4 µm ash fraction also reflects the greater hazard from the fine particles during long-term exposure (Expert Panel on Air Quality Standards, 1995, 2001).

Among basaltic volcanoes, Mt Etna (Italy; Fig. 1) has proved to be a great producer of ash in the last 20 years and more. Indeed, since 1989, Etna has undergone recurrent explosive activity consisting of more than 200 paroxysmal episodes, and two main long-lasting explosive eruptions in 2001 (Scollo et al., 2007) and 2002–2003 (Andronico et al., 2005) that produced prolonged ash emissions (Taddeucci et al., 2002; Andronico et al., 2008, 2009). Paroxysmal events are characterised by explosive activity ranging in style from Strombolian to lava fountains, often as sequences of episodes within periods of weeks to months at the summit craters (Branca and Del Carlo, 2005). Recently, these paroxysmal sequences have been considered single "episodic" eruptions by Andronico and Corsaro (2011). Most of these paroxysms are typically associated with the production of ash injected into the atmosphere and dispersed all around the volcano and further, where they may cause light to relatively heavy and serious fallout.

In this work, we quantitatively evaluate the effects of ash fallout on the air quality during explosive activity from Etna, namely the 2011–2012 and 2013 episodic eruptions (25 and 21 paroxysmal episodes, respectively; Andronico et al., 2014b) from the New-South East Crater (Fig. 1). The problem for human health is potentially considerable because approximately 900 000 inhabitants live on the slopes of Etna, Catania being the largest city with 300 000 inhabitants and comprising another twelve towns each of which numbers more than 20 000.

To this end, we carried out short-duration PM_{10} surveys of particulate matter in the air at three sites with different environmental conditions: (i) within a few hours after ash fallout following the 15 November 2011 lava fountain, and (ii) in similar weather conditions but without any evident air pollution by volcanic ash. Sedimentologic, morphoscophic and petro-chemical analyses were performed on ash samples collected at the measurement sites, in order to determine the grain-size, componentry, shape and composition of particles. Furthermore, we discuss the potential risk caused by tephra fallout in the Etnean urban areas, suggesting simple measures to prevent and mitigate such effects.

2 The 15 November 2011 lava fountain episode

On 11 January 2011, the South-East Crater (SEC; Fig. 1) resumed its eruptive activity that gave rise to a lava fountain episode in the night between 12 and 13 January 2011, being the first of a sequence of 25 events over the next months. The intense activity gradually built up a new cone on the east flank of SEC, named New South-East Crater (hereafter NSEC; Fig. 1; Andronico et al., 2014a, b; Behncke et al., 2014).

The 15 November 2011 episode studied here was the 18th and occurred in partially cloudy conditions around the volcano which prevented full visibility of the eruptive phenomena, in particular of the eruption column. The eruptive activity resumed in the morning around 05:45 GMT (local time: GMT+1). A thermal anomaly was observed by video-recordings from the network of cameras managed by Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania-Osservatorio Etneo (INGV-OE). The anomaly, located on the eruptive fissure cutting the new cone, heralded the downward advancement of a lava flow that was evident since 06:05 GMT, while discontinuous, low explosions began to be visible from the upper vent within the new cone after 08:20 GMT (*resumption phase* of Alparone et al., 2003; Fig. 3a). The Strombolian explosions slowly increased in frequency and intensity, extending also along the eruptive fissure, until to about 11:15 GMT, when they began to produce almost continuous magma jets up to

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at least 300 m high (Fig. 3b), forming (since 11:30 GMT) an eruption column up to several km above the volcano (*paroxysmal phase*; Fig. 3c). This activity lasted with similar intensity and features for more than 1 h; after 12:20 GMT, the lava fountains dramatically dropped in intensity and in a few minutes the activity passed to lower-intensity Strombolian explosions (*conclusive phase*; Fig. 3d); also the eruption column, no longer fed, became exhausted in a few minutes. All the effusive and explosive phenomena ceased completely after 13:00 GMT.

The eruption column was driven eastward by winds blowing above the volcano, causing tephra fallout on the east flank of Etna and further towards the coastline and over the Ionian Sea (Fig. 1).

3 Methods

3.1 DustTrak measurements

PM_{10} measurements were carried out by a TSI® DustTrak™ (hereafter DT) aerosol monitor (Model 8520), a portable laser photometer providing real-time digital readout of airborne particulates (Fig. 2a). In volcanology, the DT was extensively used in the Caribbean island of Montserrat to evaluate the impact of the ash erupted by the Soufriere Hills Volcano between 1996 and 1999 and particularly the exposure of islanders to respiratory hazards (Moore et al., 2002; Searl et al., 2002). These Authors produced guidelines for air quality surveys in volcanic areas characterized by ash fallout in urban settlements. Moore et al. (2002), in particular, provided two strategies for investigating PM_{10} levels in Montserrat: a network of static test sites by which to carry out continuous monitoring and short-duration tests, ranging between 15 min and one hour. In both cases they set the DT for 1 min average recording.

In this work, we measured PM_{10} concentration in the air at three different sites a few hours after the 15 November 2011 lava fountain. The sites were selected on the eastern flank of the volcano in some inhabited areas affected by the ash fallout

(Fig. 1). Short-duration tests were done during the mapping and sampling of the tephra fallout performed soon after the eruption to prevent the removal of the original amount of tephra on the ground.

Site 1 is on the SS114 road linking Acireale with Catania at 21.3 km from the eruptive vent, *site 2* is about 1.5 km north on the same road and 20.4 km from SEC, while *site 3* is on the SP148 within the Fleri village, 12.8 km from NSEC. These sites were selected on the basis of their different features in terms of road traffic. *Site 1* is on a road with "average" but continuous, fairly smooth flowing (both cars and lorries) traffic. Measurements were carried out at the road side at about 1 m of height. *Site 2* is at a main crossroads where cars must stop at the traffic lights. There is more traffic here than at site 1, and the DT operated at 80 cm of height just below a traffic light pole. *Site 3*, finally, is located on a road with regular traffic flow crossed by a secondary, quiet to busy road with a stop sign. The DT measured at 40 cm of height. The traffic at this site is roughly intermediate between site 1 and site 2.

We measured PM_{10} over 10–16 min periods; the DT was set with a time constant of 10 s, i.e. the display showed readings averaged over the previous 10 s, while the frequency/averaging period was fixed to 1 min, i.e. readings were recorded at 1 min intervals. We observed that just a few hours after the tephra fallout ash was swept laterally by the cars causing remobilization phenomena and accumulation at both sides of the carriageway (Fig. 2b).

We repeated measurements a month later, on 15 December 2011, at the same time and with the same instrument set up and similar weather conditions.

3.2 Sample analyses

A tephra sample (PM_1, PM_2 and PM_3) for each site was collected on a measured surface to evaluate the weight for m^2. PM_2 and PM_3 samples were selected for textural investigation and morphological observation since PM_1 was collected very close to PM_2. At the Laboratory of Sedimentology, INGV-OE, we carried out grain-size analysis by CAMSIZER (Lo Castro and Andronico, 2008) at 1/2-phi intervals (estimating the percentages of different size classes in volume %) and ash componentry characterization under binocular microscope (Nikon SMZ1500). At Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa Laboratory, we performed morphoscopic analyses of clasts and chemical analyses of glass and minerals using a scanning electron microscope Zeiss EVO MA 10 equipped with an Oxford ISIS microanalytical system.

4 Results

The mass per square meter of the samples is significantly different from *sites 1* and *2* with respect to *site 3*. In the most distal and lateral sample (PM_1), the weight amounted to $\sim 490\,g\,m^2$, a value fairly similar to the close sample PM_2 ($\sim 440\,g\,m^2$), while PM_3 was $\sim 1500\,g\,m^2$.

4.1 DustTrak measurements

On 15 November, we measured PM_{10} particulate matter between 2 h (*site 1*) and 5 h (*site 3*) after the end of the lava fountain. All the loggings show a few peaks in the pattern (Fig. 4a–c, blue lines), indicating the significant influence of passing vehicles as observed during the readings.

At *site 1*, the least affected by car traffic, we recorded an average of 0.084, with maximum value of $0.125\,mg\,m^{-3}$. At *site 2*, the average value is considerably higher ($0.642\,mg\,m^{-3}$) and the same is for the maximum value ($1.285\,mg\,m^{-3}$). Remarkably, the minimum value recorded is $0.337\,mg\,m^{-3}$, far higher than the maximum value recorded at *site 1*. Finally, at *site 3* all the statistic values are very high: average at 0.935, minimum at 0.379 and maximum at $1.755\,mg\,m^{-3}$.

Measurements carried out at the same sites a month later gave surprisingly very low values of PM_{10} (Fig. 4a–c, red lines). *Site 1* confirmed the lowest values of particulate matter: average of 0.033, minimum of 0.023 and maximum of $0.045\,mg\,m^{-3}$. These

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values show a very limited variability between these three statistic values. At *site 2* the differential among the statistics is increased though not significantly: average 0.060, minimum 0.026 and maximum 0.149 $mg\,m^{-3}$. *Site 3*, finally, was again the site with the highest PM_{10} values, with an average of 0.081, a minimum of 0.061 and a maximum of 0.192 $mg\,m^{-3}$.

4.2 Grain-size, textural and petro-chemical data

The grain-size distribution of PM_2 and PM_3 samples shows both a Gaussian pattern peaked on 1 and 2 mm, respectively (Fig. 4d). The most proximal sample (PM_3) is obviously coarser, with only 17 % of the collected tephra < 1 mm, with respect to the distal sample (PM_2) which amounts to a good deal more than 60 % of particles below the same size of 1 mm. It should be noted that very fine ash particles (< 0.125 mm) are practically absent in the proximal sample (just 0.1 % of clasts in the range 0.09–0.125 mm), while we measured a higher, even if poorly significant value of 0.9 % between 0.045 and 0.125 mm in sample PM_2.

PM_2 and PM_3 samples are both mainly made up of basaltic sideromelane clasts (ca. 90 %) consisting of light brown, fresh, vesicular clasts with irregular to subrounded shape and smoothed surface (Figs. 5 and 6). The rest of the sample is formed of black, poorly vesicular, blocky clasts (tachylite), rare lithic particles (reworked lavas and scorias) and loose crystals (plagioclase). These morphological characteristics are typical of most of the lava fountain products.

Bulk rock composition of scorias is K-trachybasaltic like the other recent volcanics of Etna (Viccaro et al., 2015). Ash samples are poorly porphyritic with phenocrysts of plagioclase and clinopyroxene, and microphenocrysts of olivine and oxides (titaniferous-magnetite). The groundmass is glassy with large abundance of microlites of plagioclase, clinopyroxene, olivine and oxides (Fig. 7). Composition of glass is more evolved and alkali-rich as we can observe in the Total Alkali Silica diagram (Fig. 8 and Table 1), where the 15 November 2011 samples plot between the basaltic-trachyandesite and the phono-tephrite fields.

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5 Discussion

5.1 The PM_{10} pollution problem and the Etna case

The frequent tephra emissions recorded in recent years at Etna have increased the potential respiratory hazards to the local population, suggesting the need to systematically monitor the PM_{10} concentration produced by explosive activity in order to better understand the real levels of exposure. In the Directive 2001/81/EC (EU, 2001), the European legislation establishes the limit values of PM_{10} concentrations not to be exceeded over 24 h and yearly for the protection of human health, i.e. 0.050 $mg\,m^{-3}$ as the mean measured value over 24 h which must not be exceeded more than 35 times per year and 0.040 $mg\,m^{-3}$ as annual mean concentration. It is worth noting that the EU directive 99/30 had fixed 1 January 2010 as the starting date from which more severe limits would have to be respected, i.e. a limit value of 0.050 $mg\,m^{-3}$ should not be exceeded more than 7 times per year, while 0.020 $mg\,m^{-3}$ was the mean limit value for the calendar year.

A stimulating research on the effects from particulate matter in the Etnean area was previously conducted by Fano et al. (2005), who compared the levels of PM_{10} in the cities of Catania and Acireale during the intense fallout from the 2002–2003 eruption with PM_{10} values measured in the same season but during years without volcanic activity. These Authors concluded that, although a significant increase of PM_{10} in the air was recorded for several days that greatly exceeded the threshold fixed by law at that time (0.050 $mg\,m^{-3}$ over 24 h), there was no evident direct cause of respiratory diseases from the ash fallout. They did note a temporary increase in cardiovascular diseases, particularly among the elderly, which however they assumed to be related uniquely to the stress caused by the eruption. Nonetheless, such effects on the cardiovascular system have also been documented in non-volcanic areas (WHO Air Quality Guidelines Global, 2005; Delfino et al., 2005). More recently, Barsotti et al. (2010) simulated the concentration of 10 µm volcanic particles (both in the air and

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on the ground) in several towns and key infrastructure around the volcano, showing that the re-mobilization of ash may considerably increase the concentration of the study-class of particles in the air.

5.2 The 15 November 2011 PM_{10} pilot test

In good agreement with the latter research, our study shows that the presence of fine-grained tephra in the ground may be highly hazardous in terms of PM_{10} concentrations in the air when not quickly removed. Sites usually characterised by low PM_{10} values proved to be very sensitive after the fallout from lava fountains, because relatively low quantities of tephra deposit per square meter (from ~ 500 to $> 1500\,g\,m^{-2}$) were able to produce significant concentrations of particulate matter in the air.

Measurements carried out a month after the lava fountain have shown that the values of PM_{10} are significantly different than those measured on 15 November 2011, documenting that tephra fallouts on the ground from Etna may significantly pollute the air quality, with PM_{10} levels (at least during the short-duration tests) far exceeding the recommended limit for a 24 h exposure. In particular, PM_{10} values are higher though within the same order of magnitude in *site 1*, the location least affected by vehicular traffic. Conversely, *site 2* and*3* are both characterised by average, maximum and minimum values of PM_{10} 6–13 times higher a few hours after the 15 November lava fountain. Interestingly, *sites 1* and *2*, though affected by similar amounts of tephra, show substantial differences in the production of finer particles and this may be related to the varying intensity of vehicular traffic, higher at *site 2* with respect to *site 1*. Further, Fig. 4 highlights that the 1 min, see-saw averaged line is heavily dependent on the vehicular flow, which by disturbing the tephra deposit is able to raise a clearly visible, irritating cloud of fine particles including a high percentage of PM_{10}.

Given that the local authorities in charge of the territory should take these data into consideration, we think they should reflect especially on: (1) the average PM_{10} value recorded during our tests, which remains well over the 24-H limit ($0.050\,mg\,m^{-3}$) fixed by law at all three sites, i.e. only twice at *site 1* but 13 and 19 times at *sites 2* and

3, respectively, and (2) the minimum values, which, though not so high as at *site 1* (0.49 mg m^{-3}), reached very high readings at *sites 2* and *3* (0.337 and 0.379 mg m^{-3}, respectively), i.e. ~ 7 times the limit fixed to safeguard human health over periods of 24 h.

The study of collected tephra show that their grain-size is 99.8 % (PM_3) and 94.8 % (PM_2) higher than 1 mm, and the total percentage higher than 10 micron. Hence, we infer that the air contamination by PM_{10} is not due to the direct ash fallout but to the breakup of the coarser clasts after mechanical pressure from vehicular transit. The breakage could be enhanced to the fragility of the sideromelane particles, which represent ca. 90 % of the samples.

5.3 Tephra fallout in urban settlements

In the past, high PM_{10} values have been measured by the network of air monitoring stations located in the city of Catania, which have exceeded the EU set threshold even up to some tens of times greater after long-lasting fallout (2002–2003 eruption; Rete di monitoraggio ambientale, 2002) or single paroxysmal events (e.g., July 2011). These data, easily accessible at the web-page maintained by the Environmental Pollution Office of the municipality of Catania, confirm our warning on the potential effects of tephra fallout in the Etna region.

These results are also supported by measurements taken on 6 October 2011 in Ragalna town (Fig. 1), 8 days after the tephra fallout on 28 September 2011 during the lava fountain episode. Here, the tephra cover (96 % of which made up of 0.25–1 mm sized particles) had not been completely swept away from the streets, reaching significant thicknesses (up to several centimetres) in specific points. Also in this case, we measured high PM_{10} peaks up to 0.300 mg m^{-3} correlated with the transit of cars over the ash mounds.

Recently, the villages of Zafferana Etnea and Piedimonte Etneo, located 10 km eastward and 17 km north-eastward of the NSEC, were covered by unusually thick tephra fallout deposits produced by high-energy lava fountain events. These cumulated

$> 7000\,g\,m^{-2}$ at Zafferana on 16 March 2013, and $\sim 6000\,g\,m^{-2}$ at Piedimonte on 23 November 2013, respectively (Lo Castro et al., 2013; Andronico et al., 2013), causing a few days of temporary closure of traffic. Notably, during the removal of the accumulated tephra, a high re-suspension of ash affected the roads causing ash exposure and inevitable inhalation for several days (Fig. 9).

Finally, it should be remembered that physicochemical analyses carried out on ash samples from the 2002–2003 Etna eruption also showed that fine ash particles may generate hydroxyl radicals, an additional source of respiratory toxicity (Horwell et al., 2007), thus increasing the potential health hazard.

6 Conclusions

Tephra fallouts are a source of particulate matter in the air and their high frequency in the east sector of Etna may maintain high levels of PM_{10} for several days in the urban settlements around the volcano. We are aware that the methodology adopted does not entirely follow the EU legislation for urban areas and also exposure guidelines for PM_{10} specifically for volcanic environments. Although our measurements represent preliminary short-duration tests to evaluate the exposure of the community to volcanic ash at Etna, they may nonetheless represent a starting point for future researches.

Our tests urge the adequate planning of the monitoring survey and the assessing of respiratory (and cardiovascular) hazards to the Etnean population during, but above all, after tephra fallout from paroxysmal activity. It is noteworthy that all the sites selected for our PM_{10} measurements (*sites 1*, *2*, *3* and Ragalna) are not located in highly urbanised areas in terms of people passing (whether walking, cycling, motorbiking or driving), so that the risks and thus the effects on the human health could be significantly higher in the town centres. Here the continuous vehicular traffic could lead, on one hand, to the formation of a quasi-permanent PM_{10} cloud within the first 2–3 m of height above the ground, and on the other, to a continuous and marked exceeding of the PM_{10} limits set to protect human health.

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We conclude by hoping that the impact from ash fallout in the Etnean territory and surroundings will not be underestimated but given due attention to avoid potential health diseases from volcanic particulate matter. Although difficult, if not impossible, to prevent exposure to high concentrations of PM_{10} entirely, this goal might be achieved by carrying out simple but effective actions and precautions; first and foremost, the swift and effective removal of the ash deposit in the urbanized areas and public roadways within a few hours from the tephra deposition on the ground, limiting the re-suspension of high amounts of particulate matter into the air.

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Table 1. SEM-EDS analyses of major elements in glass of 15 November 2011 ash fragments (wt % average value); # number of analyses; SD: standard deviation value.

	# 10	SD
SiO_2	49.29	0.72
TiO_2	2.19	0.22
Al_2O_3	16.11	0.40
FeO	10.13	0.37
MgO	3.68	0.22
MnO	0.26	0.10
CaO	7.56	0.30
Na_2O	4.59	0.15
K_2O	3.32	0.15
P_2O_5	0.82	0.20
Total	98.06	

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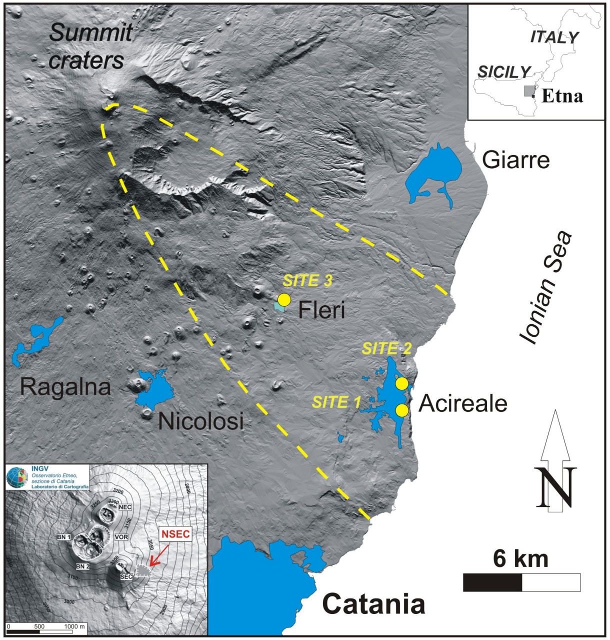

Figure 1. Digital elevation map of Mt Etna showing the sites (full yellow circles) chosen for PM_{10} measurements and the collected samples (site 1, site 2 and site 3). The broken yellow line shows the extent of tephra fallout from the 15 November 2011 lava fountain. Blue areas represent the main cities in this volcano sector, especially those reported in the text. Right-top inset: location of Sicily. Left-bottom inset: map of the summit craters *(white rectangular represented in a)* on September 2011 (courtesy of INGV – Cartography Laboratory): NEC Northeast Crater, VOR Voragine, BN-1 and BN-2 Bocca Nuova pit-craters, SEC Southeast Crater, NSEC New Southeast Crater.

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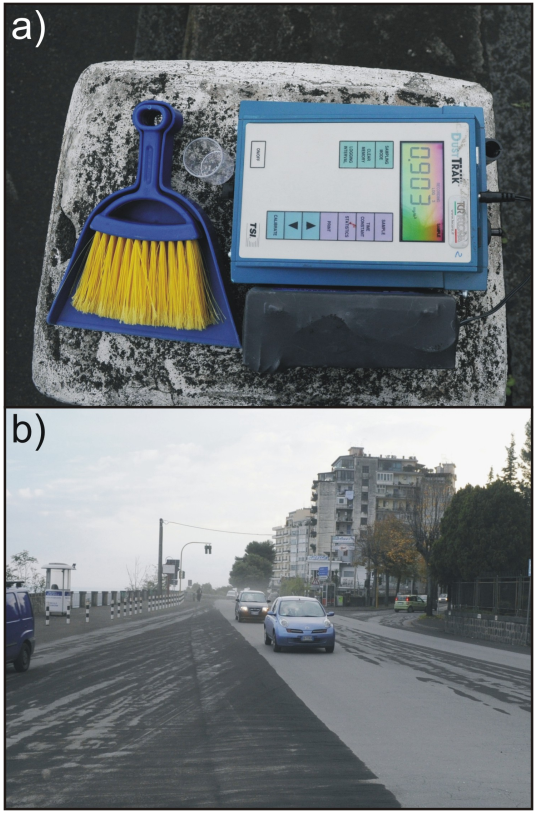

Figure 2. PM_{10} measurement carried out on 15 November 2011 in Acireale at site 2 (SS114 road): **(a)** DustTrak working; the display shows the averaged reading over the previous 10 s; **(b)** transit of cars at the crossing.

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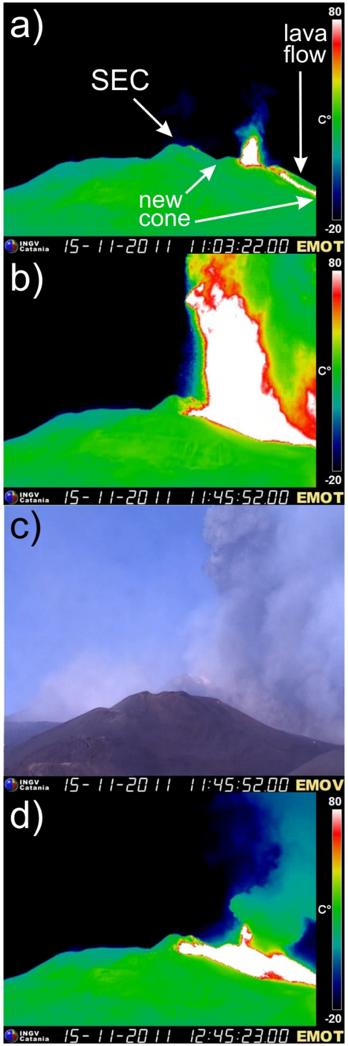

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Figure 3. Images extracted from the INGV-OE video-camera recordings of La Montagnola site (**a**, **b**, **d**: thermal camera; **c**: true-colour camera) showing the main phases of the 15 November 2011 lava fountain at the new cone of SEC: **(a)** the beginning of the explosive and effusive activity in the upper vent and eruptive fissure of the new cone, respectively; **(b)** lava fountains from the eruptive fissure; **(c)** the eruption column formed above; **(d)** the last explosions before the cessation of each eruptive phenomena.

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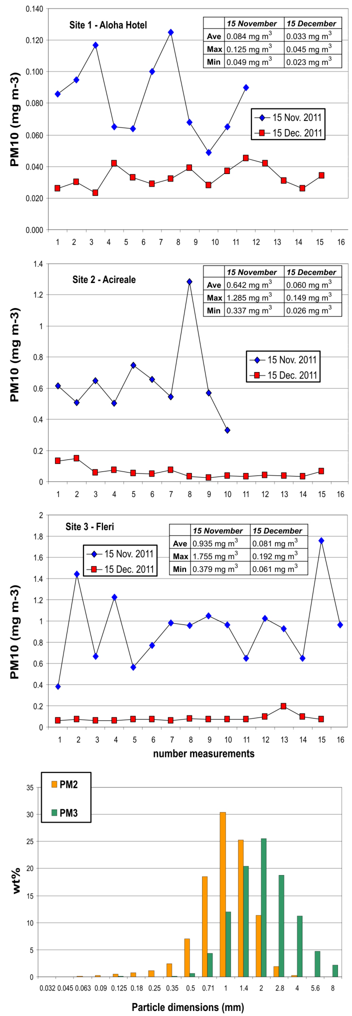

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Figure 4. (a–c) Plots showing PM_{10} measurements in three studied sites: **(a)** site 1, Hotel Aloha; **(b)** site 2, Acireale; **(c)** site 3, Fleri. The time interval of the number measurements is 1 min. Blue lines and diamonds: values measured in the afternoon of 15 November 2011, a few hours after the tephra fallout; red lines and squares: values measured on 15 December 2011, in absence of volcanic event. At the side of each plot are reported the main PM_{10} statistics data: Ave = average value; Max = maximum value; Min = minimum value. **(d)** Grain-size histograms concerning samples PM_2 and PM_3.

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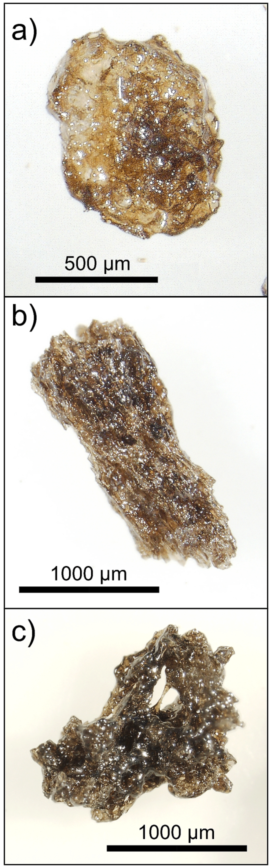

Figure 5. Binocular microscope images showing different morphological types of ash particles from PM_2 **(a, b)** and PM_3 **(c)** samples.

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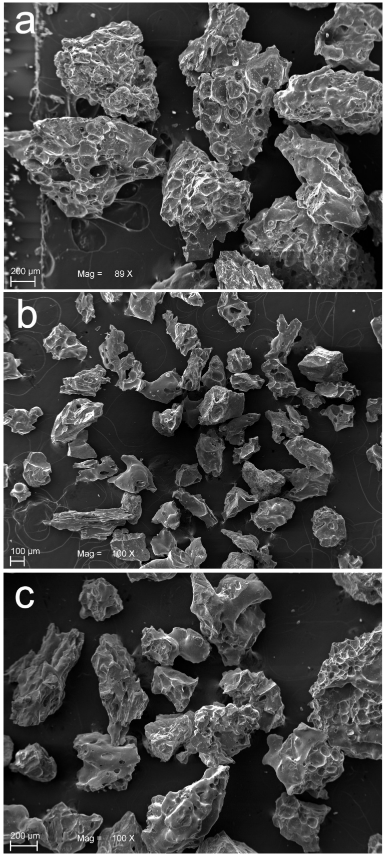

Figure 6. Scanning electron microscope secondary electrons (SEM-SE) images representative of the textures identified in studied tephra showing moderately vesicular, glassy scoriaceous fragments with fluidal texture (sideromelane) and scarce poorly vesicular, blocky clasts (tachylite). (**a** and **b**) PM_1 sample at Fleri; **(c)** PM_2 sample at Acireale.

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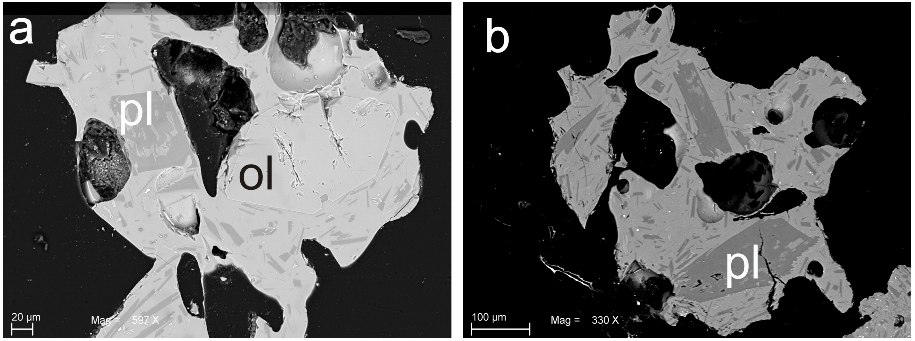

Figure 7. Scanning electron microscope secondary electrons (SEM-BSD) images representative of textures identified in the 15 November 2015 ash; pl: plagioclase; ol: olivine.

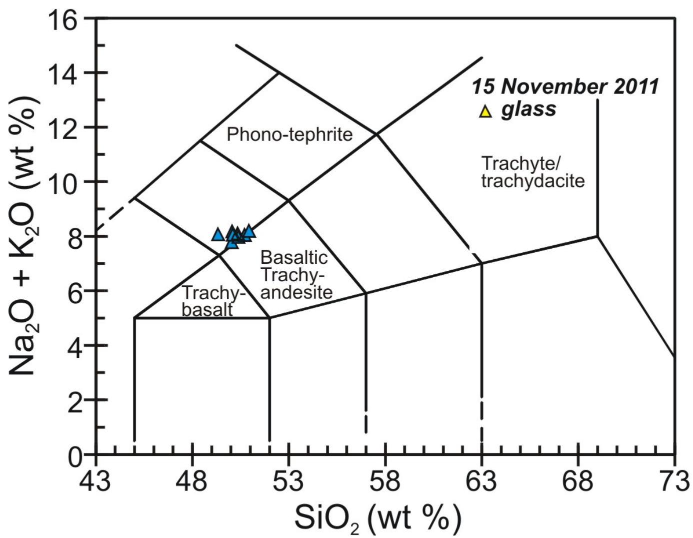

Figure 8. Total alkali-silica classification diagram of Le Bas et al. (1986).

Figure 9. The remobilization of ash in the air after the 16 March 2013 tephra fallout at Zafferana Etnea.

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