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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 to human health

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Abstract. We have carried out a preliminary study on the potential risks caused by the sub-10 µm 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 Southeast 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 and morphological and petrochemical 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, particularly basaltic ash, are readily broken up by traffic and hence remobilized into the air. We believe the impact from ash fallout in the Etnean territory should receive greater attention, especially regarding potential health problems. Simple but effective actions can be implemented to reduce eventual risks, 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. Damby et al., 2013; Hincks et al., 2006; Horwell et al., 2003, 2007, 2010, 2013; Le Blond et al., 2010; Searl et al., 2002; Wilson et al., 2011). The finer particles, especially particulate matter with dimensions $\leq 10\ \mu$m or PM_{10} in aerodynamic equivalent diameter (i.e. the diameter of a spherical particle with density 1000 $\mathrm{kg\,m^{-3}}$ and the same settling velocity as the airborne particle is considered), 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 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). In the first Daughter Directive of the EU Air Quality Framework Directive (EC, 1999), 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 the maximum annual mean concentration. It is worth noting that the EU directive 99/30 (EU, 2008) 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.

Among basaltic volcanoes, Mt. Etna (Italy; Fig. 1) has proved to be a great producer of ash in recent decades. Since 1989, Etna has undergone recurrent explosive activity consisting of more than 200 paroxysmal episodes, and two main long-lasting explosive eruptions in 2001 (Taddeucci et al., 2002; Scollo et al., 2007) and 2002–2003 (Andronico et al., 2009a and reference therein) that produced prolonged ash emissions. Paroxysmal events are characterized 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 tephra (from ash to lapilli to bombs) injected into the atmosphere and dispersed all around the volcano and further, where they may cause light to relatively heavy and serious fallout. In urbanized areas, in fact, paroxysms characterized by a low mass eruption rate (i.e. values of $\sim 2 \times 10^2$ kg s^{-1}; 16 November 2006; Andronico et al., 2009b) have produced deposits prevalently made of ash, while paroxysms with high mass eruption rate (i.e. $4.5 \pm 3.6 \times 10^5$ kg s^{-1}; 23 November 2013; Andronico et al., 2015) have produced lapilli fallout deposits, differing also from a hazard point of view.

Studies on the health effects of particulate matter in the Etnean area have been conducted by Fano et al. (2005), who compared the levels of PM_{10} in the cities of Catania and Acireale (Fig. 1) 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. Such effects on the cardiovascular system have also been documented in non-volcanic areas (WHO, 2006; Delfino et al., 2005). However, a retrospective study by Lombardo et al. (2013) reports, contrary to the results by Fano et al. (2005), on an increase in hospital admissions for cardiovascular morbidity along with a decrease in the rate of admission for respiratory diseases, finding a significantly higher frequency of visits to the emergency department for acute respiratory and cardiovascular diseases, and ocular disturbances during the ash exposure time period in the three main hospitals of Catania in 2002, as compared to the same period of the previous year. Furthermore, Barsotti et al. (2010) simulated the concentration of 10 µm volcanic particles (both in the air and on the ground) in several towns and key infrastructure around the volcano, showing that the remobilization of ash may considerably increase the concentration of the study class of particles in the air.

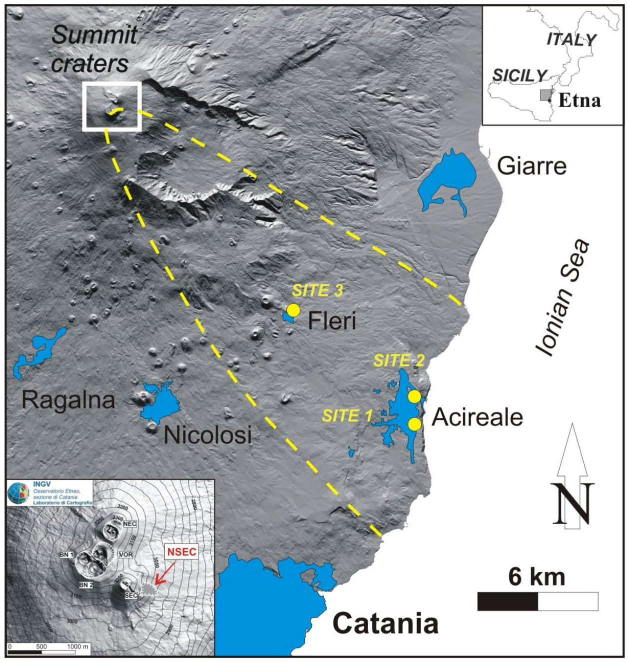

Figure 1. Digital elevation map of Mt. Etna showing the sites (full yellow circles) chosen for PM_{10} measurements and the collected samples (SITE 1, SITE 2 and SITE 3). The white rectangle indicates the summit crater area. The dashed yellow line shows the extent of tephra fallout from the 15 November 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 rectangle) on September 2011 (courtesy of INGV Cartography Laboratory). NEC denotes Northeast Crater, VOR denotes Voragine crater, BN-1 and BN-2 represent Bocca Nuova pit craters, SEC represents Southeast Crater and NSEC represents the New Southeast Crater.

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., 2014a) from the New Southeast Crater (Fig. 1). The problem for human health is potentially large because approximately 900 000 people live on the slopes of Etna, Catania being the largest city with 300 000 inhabitants. The area around Etna comprises another 12 towns, each of which has a population of 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. Sedimentological, morphological and petrochemical 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 Southeast 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, 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 the New Southeast 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 a 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, indicated the downward advancement of a lava flow that had been evident after 06:05 GMT, while discontinuous, low explosions became visible from the upper vent within the new cone after 08:20 GMT (*resumption phase* of Alparone et al., 2003; Fig. 2a). The Strombolian explosions slowly increased in frequency and intensity, also extending along the eruptive fissure, until about 11:15 GMT, when they began to produce almost continuous magma jets up to at least 300 m high (Fig. 2b), forming (since 11:30 GMT) an eruption column up to several kilometres above the volcano (*paroxysmal phase*; Fig. 2c). 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. 2d); 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 southeast 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. 3a). In volcanology, the DT was extensively used in the Caribbean island of Montserrat to evaluate the impact of the ash erupted by the Soufrière 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 1 h. 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 NSEC, 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 roadside 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 operated at a height of 40 cm. The traffic at this site is roughly intermediate in relation to site 1 and site 2. All the measurements were carried out at the same 1 m horizontal distance from the carriageway.

We measured PM_{10} over 10 to 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

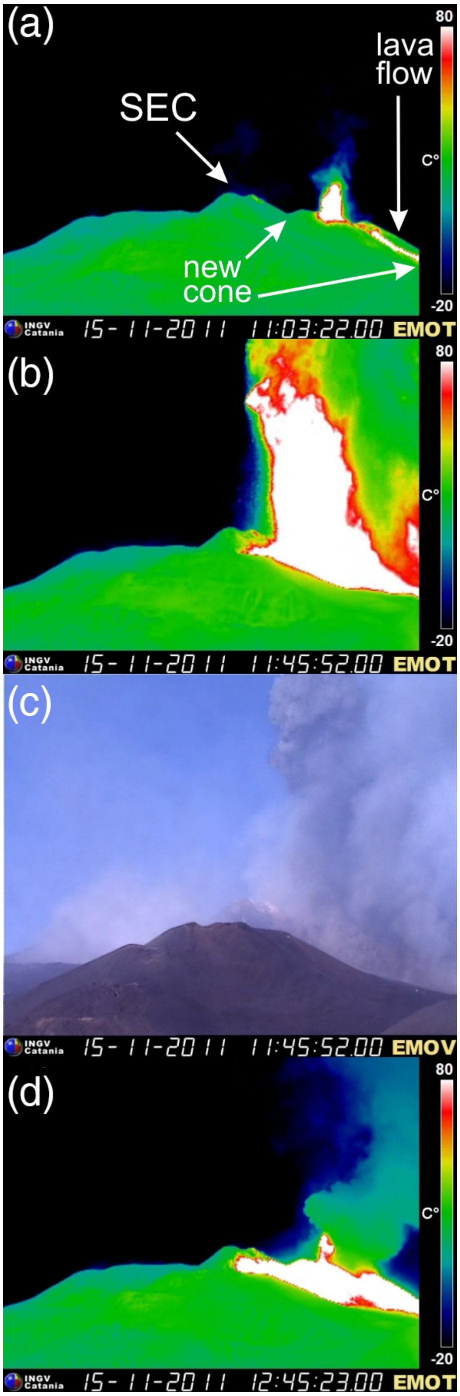

Figure 2. Images extracted from the INGV-OE video camera recordings of the La Montagnola site – **(a, b, d)** by the thermal camera; **(c)** by the true-colour camera, showing the main phases of the 15 November 2011 lava fountain at the new cone on the east flank of the SEC. Panel **(a)** shows the beginning 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 all eruptive phenomena.

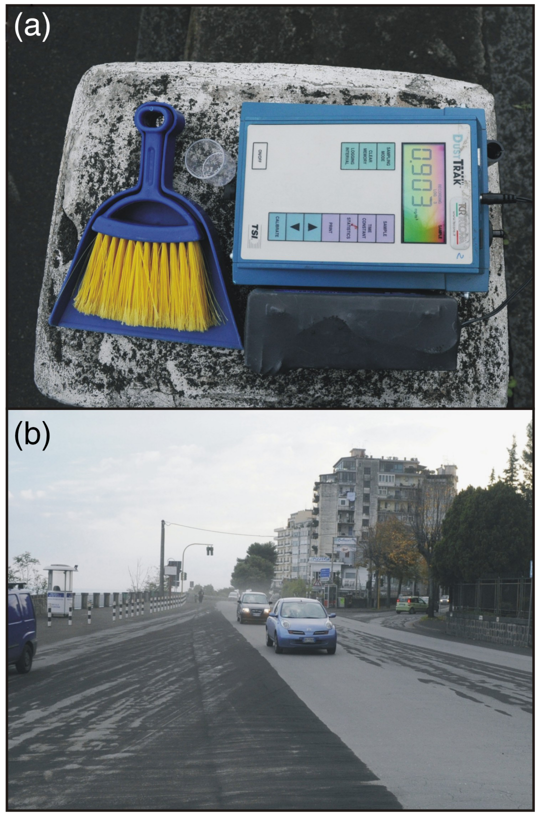

Figure 3. PM_{10} measurement carried out on 15 November 2011 in Acireale at site 2 (SS114 road): **(a)** DustTrak™ in operation; the display shows the averaged reading over the previous 10 s; **(b)** transit of cars at the crossing.

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. 3b).

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.

The methodology used does not entirely follow the exposure guidelines for PM_{10} specifically for volcanic environments. Our focus was primarily on measuring the increase in PM_{10} concentrations during and immediately after tephra fallout. In the future, we plan to undertake more detailed surveys with more attention to a precise procedure. The instrument should be set up at a standard level in all the sites to facilitate comparisons, and the DT set at an appropriate height for human exposure, e.g. 1.5 m, which is considered the "breathing zone" for adults. The duration of measurements should be in 24 h periods for comparison with EU standards. In the future, it might also be helpful to measure the PM_{10} at different heights at the same site to quantify a vertical gradient, thus evaluating if there is any variation in PM_{10} concentration with height.

3.2 Sample analyses

A tephra sample (NSEC1, NSEC2 and NSEC3) for each site was collected on a measured surface to evaluate the mass per square metre. NSEC2 and NSEC3 samples were selected for textural investigation and morphological observation, since NSEC1 was collected very close to NSEC2. At the Laboratory of Sedimentology, INGV-OE, we carried out grain-size analysis by CAMSIZER (Lo Castro and Andronico, 2008) at $1/2-\varphi$ intervals (φ being the $-\log_2 d$, where d is the particle diameter in millimetres), estimating the percentages of different size classes in volume %, and ash componentry characterization under a binocular microscope (Nikon SMZ1500). At Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa Laboratory, we performed morphological analyses of clasts and chemical analyses of glass and minerals using scanning electron microscopy and energy dispersive spectroscopy (SEM-EDS), Zeiss EVO MA 10, equipped with an Oxford ISIS microanalytical system.

4 Results

The mass per square metre of the samples is significantly different from sites 1 and 2 with respect to site 3. In the most distal and lateral sample (NSEC1), the weight amounted to $\sim 490\,\mathrm{g\,m^{-2}}$, a value fairly similar to the close sample NSEC2 ($\sim 440\,\mathrm{g\,m^{-2}}$), while NSEC3 was $\sim 1500\,\mathrm{g\,m^{-2}}$.

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

Measurements carried out at the same sites a month later gave surprisingly low values of PM_{10} (Fig. 4a–c, red lines). Site 1 confirmed the lowest values of particulate matter: average of $0.033\,\mathrm{mg\,m^{-3}}$, minimum of $0.023\,\mathrm{mg\,m^{-3}}$ and maximum of $0.045\,\mathrm{mg\,m^{-3}}$. These 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 $0.060\,\mathrm{mg\,m^{-3}}$, minimum $0.026\,\mathrm{mg\,m^{-3}}$ and maximum $0.149\,\mathrm{mg\,m^{-3}}$. Site 3, finally, was again the site with the highest PM_{10} values, with an average of $0.081\,\mathrm{mg\,m^{-3}}$, a minimum of $0.061\,\mathrm{mg\,m^{-3}}$ and a maximum of $0.192\,\mathrm{mg\,m^{-3}}$.

4.2 Grain-size, textural and petrochemical data

The grain-size distribution of NSEC2 and NSEC3 samples shows both a Gaussian pattern peaked on 1 and 2 mm, respectively (Fig. 4d). The most proximal sample (NSEC3) is obviously coarser, with only 17 % of the collected tephra <1 mm, with respect to the distal sample (NSEC2) 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 (less than 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 NSEC2.

NSEC2 and NSEC3 samples are both mainly made up of basaltic sideromelane clasts (~ 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 scoriae) and loose crystals (plagioclase).

Scanning electron microscope (SEM) analyses of ash indicate that clasts are from highly to moderately vesicular, with elongated or blocky shapes (Fig. 6a–c). Clasts show smoothed surfaces and delicate edges. The finer fraction of the deposit (Fig. 6d) is formed mainly by fragments of larger clasts with similar features. Furthermore, shape parameters obtained by CAMSIZER analyses for NSEC2 and NSEC3 samples give aspect ratios of 0.69 and 0.70, and sphericities of 0.71 and 0.78, respectively, indicating on average that particles are moderately elongated and subrounded. These morphological characteristics are typical of most of the lava fountain products.

Bulk rock composition of scoriae is K-trachybasaltic like the other recent volcanic rocks 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 a 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 are plotted between the basaltic trachyandesite and the phonotephrite fields.

5 Discussion

5.1 The 15 November 2011 PM_{10} test

Measurements carried out shortly after the 15 November 2011 Etna lava fountain have shown that the values of PM_{10} are higher than those measured a month after at the same sites. This survey has documented that tephra fallouts

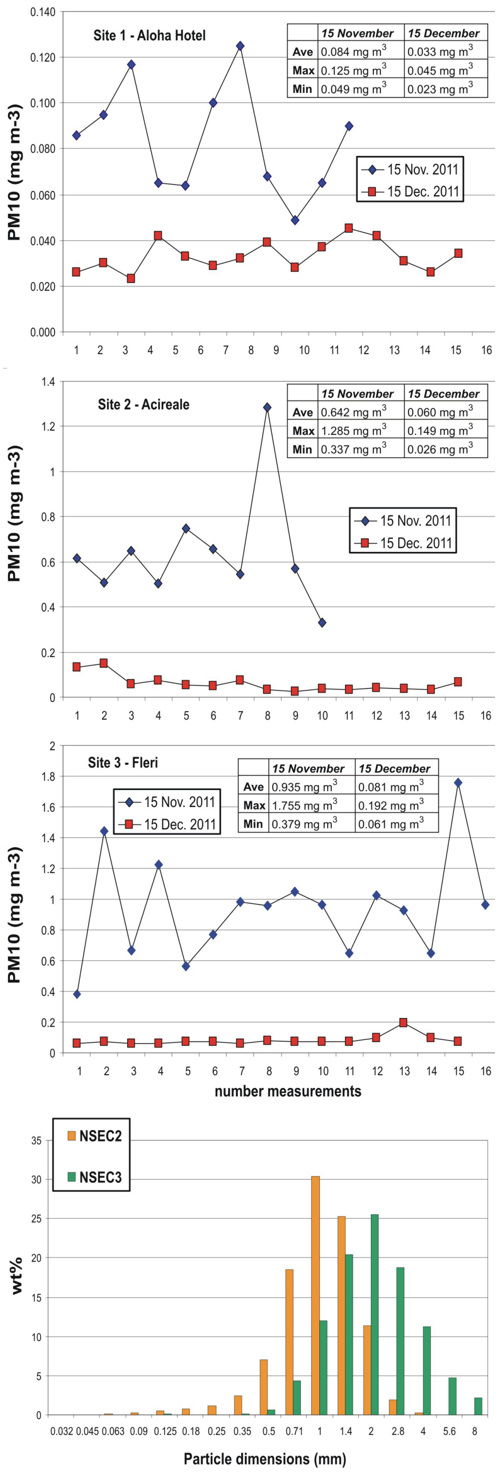

Figure 4. Panels **(a, b, c)** show PM$_{10}$ measurements in three studied sites: **(a)** site 1, Aloha Hotel; **(b)** site 2, Acireale; **(c)** site 3, Fleri. The time interval of the number measurements is 1 min. Blue lines and diamonds represent values measured in the afternoon of 15 November 2011, a few hours after the tephra fallout; red lines and squares represent values measured on 15 December 2011, in absence of a volcanic event. At the side of each plot the main PM$_{10}$ statistics data are reported. Ave is the average value; Max is the maximum value; Min is the minimum value. **(d)** Grain-size histograms concerning samples NSEC2 and NSEC3.

Figure 5. Binocular microscope images showing different morphological types of ash particles from NSEC2 **(a, b)** and NSEC3 **(c)** samples.

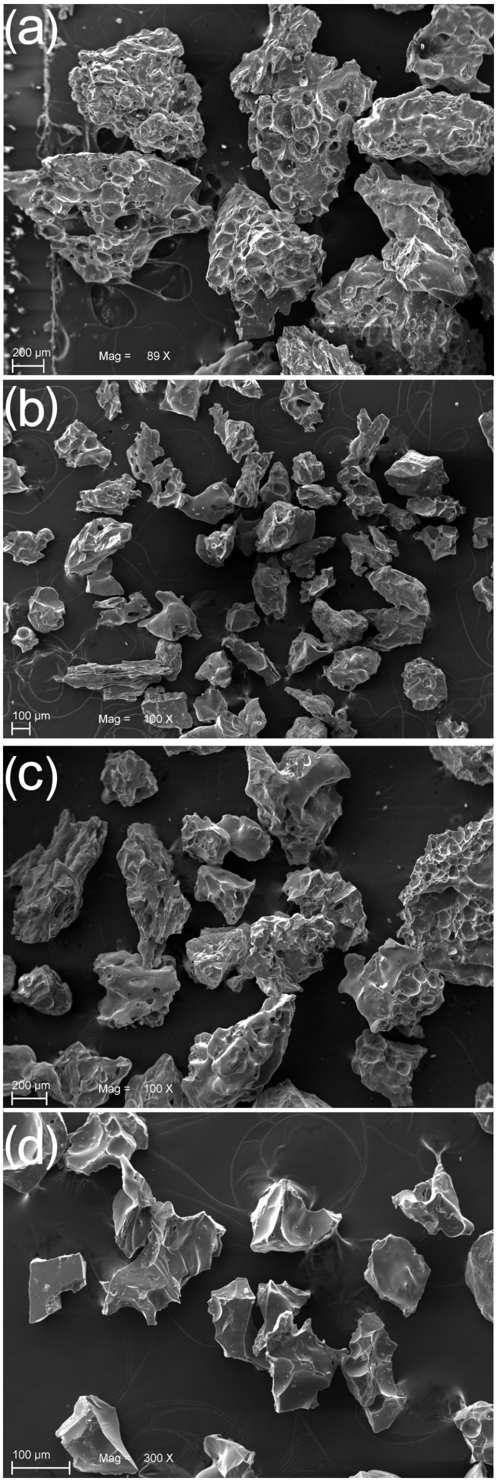

Figure 6. Scanning electron microscope secondary electrons (SEM-SE) images representative of the textures identified in studied tephra, showing moderately vesicular, glassy scoriaceous fragments with fluidal texture (sideromelane) and scarce poorly vesicular, blocky clasts (tachylite). **(a, b)** NSEC3 sample at Fleri; **(c, d)** NSEC2 sample at Acireale.

Table 1. SEM-EDS analyses of major elements in glass of 15 November 2011 ash fragments (weight % average value); no. denotes the number of analyses; SD denotes standard deviation value.

	No. 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	

on the ground may 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 characterized 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 the following: (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. Sites usually characterized by low PM_{10} values proved very sensitive after the fallout from lava fountains, because relatively low quantities of tephra deposit per square metre (from ~ 500 to $> 1500\,g\,m^{-2}$) were able to produce significant concentrations of particulate matter in the air.

The grain-size distributions of collected tephra show that 99.8 and 94.8 % of the volume for samples NSEC3 and NSEC2 (respectively) is coarser than 1 mm, and all the samples are composed of particles coarser than 10 µm. Hence,

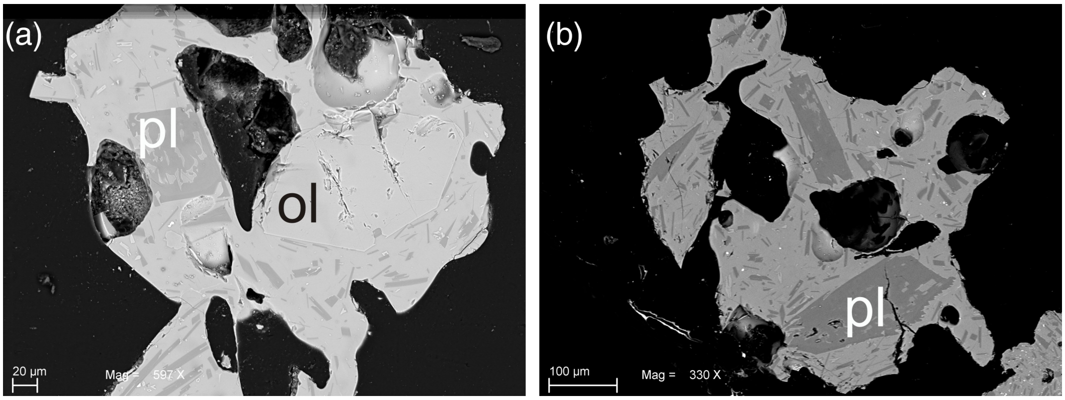

Figure 7. Scanning electron microscope secondary electrons (SEM-SE) images representative of textures identified in the 15 November 2015 ash; pl denote plagioclase; ol denotes olivine.

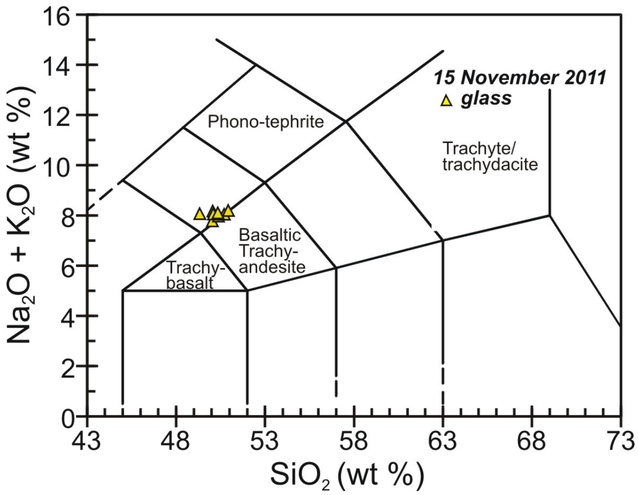

Figure 8. Total alkali–silica classification diagram of Le Bas et al. (1986).

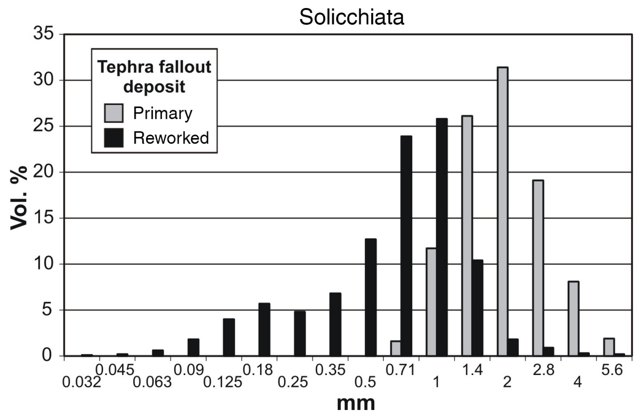

Figure 9. Comparison between the grain-size distribution of two samples collected at the same site in Solicchiata village (14 km northeast of the vent): primary (grey) and reworked (black) tephra fallout deposit after grinding by passing cars.

we infer that the air contamination by PM_{10} is not due to the direct ash fallout but to the break-up 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 as morphological and component analyses indicate.

5.2 Quantitative estimation of the tephra grinding by car passage

The passage of the cars on the roads covered by tephra fallout causes the grinding of the original tephra on the ground itself and its accumulation along the edge of the carriageway (Fig. 3b). This simple as well as reiterated observation suggested we evaluate the phenomenon quantitatively to understand if the original grain size of the tephra on the ground could be significantly modified.

We tested this observation following the lava fountain at SEC on 23–24 November 2007 (Andronico et al., 2007). The paroxysmal episode produced tephra fallout more than 80 km NE away from Etna, reaching the Calabria region. At 14 km from the vent along the dispersal axis (Solicchiata village), we collected two distinct samples, one unaltered ($\sim 1120\,g\,m^{-2}$) and another one from the edge of the carriageway, clearly related to the passage of the cars which had ground down and accumulated a macroscopically finer deposit.

The comparison between the grain-size distribution of the two samples (Fig. 9) shows that the mode of the "ground" sample is at least one-phi shifted toward finer classes with respect to the original deposit (from 1.4–2 to 0.71–1 mm). What is more striking, however, is that while the grain-size distribution of the original sample indicates that only 1.6 % was lower than 1 mm, the "ground" sample was formed by more than 60 % of particles with dimensions < 1 mm.

Further, to better quantify the finer particles, the fraction < 2 mm (i.e. 96.8 % of the total sample) was analysed using the CILAS laser diffraction analyser (http://www.cilas.com/granulometrie.html) at the University of Geneva; the cumulative grain-size distribution curve shows that it contains 2.8 % of particles with a dimension of < 8 µm. In other terms, for each 100 g m^{-2}, the grinding produced ∼ 2.5 g m^{-2} of PM_{10} particles in the ground deposit. This is indeed a high percentage of potentially dangerous particles for human exposure directly produced by passing cars.

5.3 Tephra fallout in urban settlements

In the past, high PM_{10} values have been measured by a 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 the 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 the town of Ragalna (Fig. 1), 8 days after the tephra fallout on 28 September 2011 during the lava fountain episode. Here, the tephra cover (96 % of which was made up of 0.25–1 mm sized particles) had not been completely swept from the streets, reaching significant thicknesses (up to several centimetres) at 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. In other terms, as occurred during our measurements following the 15 November 2011 lava fountain, the grinding by car passage was able (a week after the end of the tephra fallout) to cause the remobilization of volcanic particulate matter and its resuspension in the air, the effects of which have been quantified by the high PM_{10} concentrations measured by DT.

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 (2–3 cm depth) produced by high-energy lava fountain events. These cumulated > 7000 g m^{-2} at Zafferana on 16 March 2013, and ∼ 6000 g m^{-2} at Piedimonte on 23 November 2013, respectively (Lo Castro et al., 2013; Andronico et al., 2015), causing a few days of temporary closure of traffic. Notably, both during the removal of the accumulated tephra and the remobilization by car traffic, a high resuspension of ash affected the roads, causing the formation of a PM_{10} cloud, thus increasing the ash exposure and inevitable inhalation for several days (Fig. 10).

This is also demonstrated by Thorsteinsson et al. (2012), who reported that ash resuspension near the ground was able to generate levels of particulate matter similar to those caused by direct tephra fallout during the 2010 Eyjafjallajökull eruption in Iceland. The wind erosion due to strong storm episodes remobilized the ash deposited during this eruption, generating resuspension events with higher concentration of PM_{10} also several tens of kilometres away from the deposit (Leadbetter et al., 2012; Arnalds et al., 2013). Furthermore, the sweeping of tephra from the road several days after the fallout had also increased the resuspension effects (Leadbetter et al., 2012).

Figure 10. The remobilization of ash in the air after the 16 March 2013 tephra fallout at Zafferana Etnea.

Studies by Hincks et al. (2006) and Barsotti et al. (2010) also linked the resuspension to the amount of tephra cover and showed the direct correlation between the thickness of tephra deposit to the higher concentrations of PM_{10} and 10 µm volcanic particles, respectively.

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. Our study, in particular, suggests that the presence of fine-grained tephra on the ground may be hazardous in terms of PM_{10} concentrations in the air when not quickly removed, and matches well with a medical study on acute health effects due to volcanic ash exposure during the 2002 Etna eruption.

Although our measurements represent preliminary short-duration tests to evaluate eventual exposure to volcanic ash at Etna, they may nonetheless represent a starting point for future research. Data showed that after the 15 November 2011 lava fountain, the PM_{10} concentrations exceeded the EU limit of 0.050 mg m^{-3} (fixed over 24 h) 91, 90 and 94 % of the time in the three investigated sites. Our tests urge the planning of a systematic monitoring of the PM_{10} concentrations, especially after tephra fallout from paroxysmal activity. Measuring and assessing the real levels of exposure needs to be done to understand eventual respiratory (and cardiovascular) hazards to the Etnean population.

It is noteworthy that all the sites selected for our PM_{10} measurements (sites 1, 2, 3 and Ragalna) are not located in highly urbanized 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 the 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 hand, to a continuous and marked exceedance of the PM_{10} limits set to protect human health.

We conclude by hoping that the impact from ash fallout in the Etnean territory will not be underestimated but given due attention to avoid potential health risks. 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 resuspension of high amounts of particulate matter into the air as well the grinding of tephra by passing cars.

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