Aeolian Remobilisation of Volcanic Ash: Outcomes of a Workshop in the Argentinian Patagonia

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During explosive volcanic eruptions, large quantities of tephra can be dispersed and deposited over wide areas. Following deposition, subsequent aeolian remobilisation of ash can potentially exacerbate primary impacts on timescales of months to millennia. Recent ash remobilisation events (e.g., following eruptions of Cordón Caulle 2011; Chile, and Eyjafjallajökull 2010, Iceland) have highlighted this to be a recurring phenomenon with consequences for human health, economic sectors, and critical infrastructure. Consequently, scientists from observatories and Volcanic Ash Advisory Centers (VAACs), as well as researchers from fields including volcanology, aeolian processes and soil sciences, convened at the San Carlos de Bariloche headquarters of the Argentinian National Institute of Agricultural Technology to discuss the "state of the art" for field studies of remobilised deposits as well as monitoring, modeling and understanding ash remobilisation. In this article, we identify practices for field characterisation of deposits and active processes, including mapping, particle characterisation and sediment traps. Furthermore, since forecast models currently rely on poorly-constrained dust emission schemes, we call for laboratory and field measurements to better parameterise the flux of volcanic ash as a function of friction velocity. While source area location and extent are currently the primary inputs for dispersion models, once emission schemes become more sophisticated and better constrained, other parameters will also become important (e.g., source material volume and properties, effective precipitation, type and distribution of vegetation cover, friction velocity). Thus, aeolian ash remobilisation hazard and associated impact assessment require systematic monitoring, including the development of a regularly-updated spatial database of resuspension source areas.

Keywords: aeolian processes, volcanic ash, ash remobilisation, field geology, modeling, hazard monitoring, ash resuspension

INTRODUCTION

Explosive volcanic eruptions can disperse significant quantities of ash (diameter <2 mm) over large areas (up to 10^6 km^2; Pyle et al., 2006). Resultant subaerial deposits can consequently be remobilised by different aeolian processes, with larger particles moving by saltation or creep and finer material in suspension (Kok et al., 2012). Regarding ash, remobilisation refers to all aeolian transport mechanisms, whereas resuspension refers only to suspension (Dominguez et al., 2020). Although many sediments undergo aeolian transport, remobilised volcanic ash poses additional hazards to human and animal health and infrastructure (particularly aviation) due to the transient sediment supply, high abrasive potential, low softening temperature and the presence of leachable contaminants.

Impacts from remobilised ash include those shared with, albeit with some differences to, primary ashfall. Airborne particulate matter (PM) threatens human health, contributing to cardiovascular and respiratory diseases (Baxter and Horwell, 2015). Agriculturally, ash can damage crops and contaminate livestock food sources (Craig et al., 2016b; Forte et al., 2018), e.g., fluoride leaching (Cronin et al., 2003). Airborne ash can impact air traffic (Hadley et al., 2004; Elissondo et al., 2016) and also reduce visibility (Weinzierl et al., 2012), threatening transport networks. Remobilisation can extend the temporal and spatial scales of these impacts. Additionally, deposits can form migrating bedforms that further inundate farmland (Wilson et al., 2011). Such structures can inhibit water drainage and become lahar sources. Local meteorology and topography, rather than eruptive style, influence the altitude which resuspended ash reaches. Resuspended ash emitted in September 2013 and April 2017 in Iceland rose up to 2 km due to a temperature inversion (Beckett et al., 2017; Hammond and Beckett, 2019), whereas that from the 2020 Taal eruption, the Philippines (NDRRMC, 2020), and ancient pyroclastic material in the Fiambalá Basin, Argentina (Mingari et al., 2017), have reached 5–6 km. Furthermore, the greater abrasivity and lower softening point of ash ($\geq$700°C) compared to mineral dust (Kueppers et al., 2014) means that ash can potentially damage hot engines more than other remobilised material (Müller et al., 2019; Butwin et al., 2020).

Ash remobilisation was first recorded in 1933, when ash from the 1912 Katmai-Novarupta eruption deposits was observed across northern North America (Alexander, 1934; Miller, 1934). Wider recognition followed the 1980 Mt. St. Helens eruption, USA, where winds around 10 m s^{-1} remobilised fine ash, significantly reducing visibility (Hobbs et al., 1983). More recently, resuspension following eruptions from Eyjafjallajökull (2010) and Grímsvötn (2011), Iceland (Thorsteinsson et al., 2012; Liu et al., 2014; Butwin et al., 2019), and Hudson (Wilson et al., 2011), Cordón Caulle (Craig et al., 2016a; Forte et al., 2018) and Calbuco (Reckziegel et al., 2016), Chile, have highlighted this secondary hazard. Ash remobilisation occurs over widely-varying timescales, from syn-eruptive to millennia post-eruption (Hadley et al., 2004; Mingari et al., 2017). Furthermore, old deposits exposed by anthropogenic activities, e.g., quarrying and deforestation, can become remobilisable (WMO, 2016; Bonadonna et al., 2020).

The recent and recurrent observations of ash remobilisation events highlight the need for increased monitoring, forecasting and research. Additionally, at the 2016 World Meteorological Organization Volcanic Ash Advisory Center (VAAC) "Best Practice" workshop (Buenos Aires), it was decided that "all VAACs treat re-suspended ash as any other ash cloud and would issue a volcanic ash advisory (VAA) to advise users of it" (WMO, 2016). VAACs therefore rely on monitoring of ash source areas and accurate parameterisations for aeolian processes. In order to identify the required objectives and associated challenges of future work on ash remobilisation, a workshop on wind-remobilisation processes of volcanic ash was held in San Carlos de Bariloche, Argentina (https://www.unige.ch/sciences/terre/CERG-C/international-conferences/ash-remobilisation-2019/presentation/; Bonadonna et al., 2020), involving 47 participants from observatories, VAACs and research institutions, across multiple disciplines (volcanology, aeolian processes, soil science) and expertise (field, experimental, numerical modeling). The workshop identified:

- Parameters controlling duration and intensity of remobilisation events
- Input parameters required for modeling ash remobilisation
- Key issues for monitoring and communicating remobilisation hazard
- Research priorities for understanding and characterising ash remobilisation deposits and processes

The detailed outcomes were reported in a consensual document (Bonadonna et al., 2020) while this paper summarises the key findings and provides perspectives for future work.

MECHANISMS OF AEOLIAN REMOBILISATION

Sediment Transport

Grains within a deposit can be remobilised if the friction velocity u_*, a surface shear-stress proxy, exceeds a threshold u_{*t}. This threshold is determined from a force-balance on a surficial grain; wind-drag and aerodynamic lift, which act to entrain the particle, are resisted by gravity and inter-granular cohesion. While various models describe this balance, it is accepted that u_{*t} is typically lowest for diameters ~75–100 μm (Bagnold, 1941; Greeley and Iversen, 1985; Shao and Lu, 2000). For smaller sizes, cohesive forces increase as grainsize decreases so particles can strongly agglomerate and these simple models fail (Fries and Yadigaroglu, 2002). Resuspension of such particles seemingly occurs due to impacts of larger saltating particles (Gillette et al., 1974).

Once mobile, particles can be transported through different modes. Those of diameter ~70–500 μm saltate, following ballistic trajectories (Bagnold, 1941), while larger particles reptate (jumps <1 cm; Ungar & Haff, 1987) or creep (rolling/sliding; Bagnold, 1941). Finer particles become suspended (Nickling and McKenna Neuman, 2009), with those of diameter ≤20 μm entering long-

term (weeks-months) suspension and those in the range 20–70 μm undergoing short-term suspension (≤days).

Controls on Duration and Intensity of Remobilisation Events

The key control on the duration and intensity of a remobilisation event is u_*; as u_* increases so does the quantity of material that can be remobilised. However, u_* is difficult to measure directly in the field without sophisticated instrumentation, e.g., using a sonic anemometer (Bauer and Davidson-Arnott, 2014) or conducting multiple-height wind-speed measurements (Baas and Sherman, 2005). Instead, single-height wind measurements (using anemometers) can be combined with topographic mapping (including roughness elements, e.g., vegetation, rocks) to estimate u_* (Prandtl, 1935; Etyemezian et al., 2019).

Deposit properties also control remobilisation susceptibility. Specifically, the volume of erupted material, deposit thickness and spatial extent directly control the amount of remobilisable material available. For large eruptions in arid landscapes, e.g., the 1912 Novarupta eruption which produced ~28 km^3 of pyroclastic deposit (Fierstein and Hildreth, 1992), remobilisation can continue for centuries post-eruption (Hadley et al., 2004), although re-vegetation in more humid climates can stabilise deposits. Other important deposit characteristics include the surficial grain size distribution (GSD) and particle density, since these largely control u_{*t} and the sediment transport mode. While GSD and particle density measurements can be used to estimate u_{*t}, accurate determination requires direct measurements, either through wind-tunnel experiments on sampled ash (Douillet et al., 2014; Del Bello et al., 2018; Etyemezian et al., 2019) or in-situ with a calibrated field instrument (Etyemezian et al., 2007). Currently, limited data suggests that $u_{*t} \approx 0.4 \, \mathrm{m \, s^{-1}}$ for ash, broadly agreeing with observed aerosol concentrations and wind speeds in Iceland (Leadbetter et al., 2012).

For fine particles, u_{*t} generally increases with the near-surface relative humidity (RH; McKenna Neuman and Sanderson, 2008). However, experiments on ash suggest that u_{*t} is independent of RH for RH <75–90% (Del Bello et al., 2018; Etyemezian et al., 2019). Another control on remobilisation is the amount of effective precipitation. While small amounts of precipitation increase the surficial soil water content, inhibiting remobilisation (Etyemezian et al., 2019), some ash may initially be mobilised through splashing before the soil becomes too wet. Furthermore, significant precipitation can cause surface run-off which erodes the ash into fluvial systems, removing it from the aeolian environment (Forte et al., 2018).

Finally, the amount and type of vegetation onto which ash deposits are also important. Plants can act as sediment traps, whereby ash (primary or remobilised) deposited within and around a plant can be protected from aeolian forcing (Dominguez et al., 2020). The effectiveness of a particular species as a sediment trap depends on its size and structural porosity (Wolfe and Nickling, 1993; Gillies et al., 2002).

FIELD CHARACTERISATION OF REMOBILISATION PROCESSES AND DEPOSITS

Fieldwork characterising remobilisation processes and the resulting deposits is crucial for multiple reasons. Aside from improving our fundamental understanding, measurements pertaining to ash remobilisation allow testing of model parameterisations. Furthermore, field data provide necessary inputs for numerical models, e.g., Fall3D which uses a grainsize-dependent emission scheme (Folch et al., 2014). Thus, to maximise the usefulness of field data for interpretation and use in models, common methodologies are required to allow spatial and temporal comparisons.

Since any exposed sediments are potential sources of transportable material, both primary and remobilised ash deposits require examination. **Table 1** summarises important observations and measurements that should be made concerning deposits. Particularly important are the thickness and spatial distribution of the primary deposit, since these constrain the volume of remobilisable material. Ultimately, deposit features can constrain u_{*t}, which is directly controlled by the GSD and particle density, but also depends on grain morphology, vegetation, surficial soil moisture and the presence of soil aggregates. Of these, soil moisture is particularly difficult to constrain since the mobile surficial layer is thinner (~1–2 cm) than most field techniques, including probes, can resolve (Su et al., 2014). While ground-penetrating radar (Algeo et al., 2018) or satellite methodologies (Petropoulos et al., 2015) could be used, these techniques currently lack sufficient vertical resolution to measure surficial water content.

An initial challenge is distinguishing between primary and remobilised deposits, particularly when syn-eruptive remobilisation occurs, e.g., Sabancaya volcano, Peru, where multiple Vulcanian explosions currently occur daily, depositing ash that is continuously remobilised. Nonetheless, some general features can differentiate between primary and remobilised deposits (Dominguez et al., 2020). Specifically, primary deposit thicknesses decrease with distance from the vent but are typically uniform at a local scale (assuming deposition on a flat surface). Conversely, surface roughness strongly controls the erosion and re-deposition of ash, generating sub-metre variations in remobilised deposit thicknesses and even unconnected deposits. Cross-bedding, resulting from unsteady wind conditions, can also be indicative in remobilised deposits.

Field measurements characterising remobilisation processes can also be performed. Particularly important is characterising u_* (See previous section) while other relevant meteorological parameters include surface temperatures and relative humidities. Solar heating can drive thermal winds and reduce surface moisture, increasing u_* and decreasing u_{*t}, respectively, possibly generating diurnal variations in remobilisation intensity (Mingari et al., 2020). Active remobilisation processes can be constrained using high-resolution videos to identify the source sites and mode of sediment transport, while fluxes can be obtained through the use of sediment traps (Arnalds et al.,

TABLE 1 | Key deposit properties and processes to observe and measure in the field in order to characterise ash remobilisation.

Parameter	Methods	Reasoning
Deposit properties		
Thickness and spatial distribution of primary and remobilised deposits	Traditional field mapping, satellite imagery, drone surveying	Can be used to calculate volume of material available for remobilisation, and the extent of the source area
Mapping of roughness elements	Traditional field mapping, satellite imagery, drone surveying	Correlation between distribution of roughness elements and deposits allows identification of natural sediment traps (Dominguez et al., 2020)
Recording of sedimentary structures (cross-bedding, ripples)	Traditional field work	Can be used to distinguish between primary and remobilised deposits (Dominguez et al., 2020), and provide information on the sediment transport processes
Grain size and shape distributions and grain density	Post-fieldwork laboratory analysis	Can be used to estimate u_{*t}, while grain morphology provides insights into what shapes are preferentially remobilised (Dominguez et al., 2020) and the effect of abrasion during transport
Observations of surficial crust and associated cracks	Traditional field work	Provides qualitative information on surficial soil moisture and associated cohesive forces that increase u_{*t}
Size of soil aggregates	Traditional field work	Ash and soil aggregates influence the amount of material available for resuspension; while the aggregates themselves may saltate, they may fragment during impacts, releasing finer, resuspendable material
Arrangement of grains in deposit	In-person observations	Closely packed grains will have more contacts, increasing adhesive forces and u_{*t}
Processes		
Wind field and friction velocity	Sonic anemometer or array of anemometers (Baas and Sherman, 2005)	Can be used to predict particle sizes that should be remobilised and mode of transport e.g., saltation, suspension or bedload
Temperature	Digital thermometer, thermal imaging by drone or satellite	Surface temperature difference can drive thermal winds so there may be a relation between temperature and wind speed that leads to diurnal variations in remobilisation (Mingari et al., 2017)
Humidity	Digital probe	Can correlate changes with temporal variations in remobilised fluxes
Transport mechanism	Digital videos	Can record modes of bedload, saltation or suspension and identify different suspension mechanisms e.g. streamers (Baas and Sherman, 2005), dust-devils (Balme and Greeley, 2006) or ash storms (Wilson et al., 2011)
Remobilisation fluxes	Sediment traps (Wilson and Cooke, 1980; Fryrear, 1986; Greeley et al., 1996; Mendez et al., 2011; Panebianco et al., 2017)	Correlations between fluxes and meteorological conditions can be used to validate models and to study timescales of remobilisation in both the short and long-term
Airborne particle concentrations	Optical particle counters e.g., DustTrak (Wilson et al., 2013, Arnalds et al., 2013; Spanu et al., 2020)	Correlations between concentrations and meteorological conditions can be used to validate models

2013; Panebianco et al., 2017). Airborne ash concentrations can be measured using particle counters (e.g., DustTrak (TSI Inc.) PM10 instrument), which have previously been used during remobilisation events following the Eyjafjallajökull 2010 (Thorsteinsson, 2012) and Cordón Caulle 2011 (Wilson et al., 2013; Elissondo et al., 2016) eruptions. The relation between measured concentrations and fluxes and meteorological conditions is important for modellers.

MODELING AND FORECASTING OF REMOBILISATION

Modeling remobilisation currently focusses on dispersion modeling of resuspended ash clouds, with an emphasis on operational forecasts (Folch et al., 2014), e.g., the United Kingdom Met Office forecasts resuspension on a daily basis in Iceland using NAME (Hammond and Beckett, 2019). The model source terms come from emission schemes that provide the vertical mass flux of material $F(u_*)$, where u_* can be taken from Numerical Weather Prediction data. Multiple emission schemes of varying complexity exist but they are almost universally power–laws, i.e., $F \propto u_*$ or $F \propto (u_* - u_{*t})^n$, where $n > 0$ (Kok et al., 2012). However, empirically-fitted values of n vary from 1.89 to 6.2 (Ishizuka et al., 2014; Etyemezian et al., 2019) and further experimental constraints are required. Operationally-used emission schemes, e.g., $F \propto (u_* - u_{*t})^3$ as implemented in NAME (Leadbetter et al., 2012), are sufficiently simple that the only source deposit parameter that dispersion models vary strongly with is the source area. However, with better parameterisations and constraints, other parameters, including granulometry or soil moisture, will become important. Indeed, some grainsize-dependent schemes already exist (Shao et al., 1993; Marticorena et al., 1997). While operational forecasts of resuspension timing, relative magnitude and height qualitatively agree with observations, absolute values of column mass loading require fitting and uncertainties remain unconstrained (Leadbetter et al., 2012; Beckett et al., 2017). A sensitivity analysis could be used to quantify and identify strategies to reduce these uncertainties (Pianosi et al., 2016).

Dispersion model results for ash resuspension strongly depend on the horizontal and vertical resolution of meteorological and topography data and the dispersion model. In the operational setup of NAME, source regions are represented at a horizontal resolution of 0.01° × 0.01° (Leadbetter et al., 2012) while meteorological and topographical fields have a horizontal resolution of ~10 km (at mid-latitudes). Sufficiently fine horizontal resolutions are required to capture topographic effects on u_*; otherwise $F(u_*)$ can be underestimated (Mingari et al., 2017). Furthermore, the predicted heights of resuspended clouds require the vertical resolution be sufficiently fine to accurately parameterise vertical convection in the near-surface planetary boundary layer (Banks et al., 2016; Mingari et al., 2017). Thus, operationally, a compromise exists between computational time and the greater accuracy achieved through high-resolution simulations.

MONITORING AND COMMUNICATING REMOBILISATION HAZARD AND MITIGATING IMPACT

Ash remobilisation can impact local and regional stakeholders (e.g., damage to livestock and crops, air quality alteration, air traffic disruption). It is therefore important that observatories can monitor such processes and provide useful information. Locally, communities may observe ash and be concerned that an eruption is occurring, meaning observatories require the ability to identify the source of the ash (eruptive or aeolian) and communicate this to local stakeholders. Promising techniques for distinguishing between primary and remobilised ash clouds include satellite observations (e.g., cloud location, water content estimates; Toyos et al., 2017) in combination with ground-based cameras and geophysical monitors. No single method is likely to be definitive, thus data from different sources requires synthesis, presenting a challenge for poorly-monitored volcanoes.

Regionally, a 2016 VAAC meeting (Buenos Aires) agreed that best practice would be to release a VAA for resuspension clouds if there are supporting observations (WMO, 2016), with low-altitude ash being a hazard near airports. Forecasting by VAACs, therefore, relies on updated monitoring data being provided by observatories. Despite this, monitoring and communication strategies vary globally. Even though the nine observatories involved in the workshop (Supplementary Material) confirmed that ash remobilisation is a common and concerning phenomenon, only four of these routinely monitor and/or report it. This lack of consistency makes providing usable information to VAACs difficult, something that could be alleviated with standardised protocols for data collection and communication. However, timely and precise monitoring of resuspension is challenging.

Table 2 lists parameters relevant to ash remobilisation that need monitoring and is separated into those that require regular recording in preparation for remobilisation episodes, and those to be recorded during events. Those requiring regular recording can evolve periodically (diurnally, seasonally) or monotonically (e.g., source material volume reduces with time). These quantities should ideally be recorded in a continuously-updated database of input parameters to be available for forecast modeling. Ultimately though, this relies on observatories being aware of possible source areas.

During resuspension events, cloud height and extent need to be monitored so that forecast modeling can use assimilated data (Schmehl et al., 2011). A readily-available data source comes from satellite images, which could, for example, be automatically processed in real-time using the VOLCAT program (Pavolonis et al., 2015a; Pavolonis et al., 2015b; Pavolonis et al., 2018). For eruptive clouds, ash detection in satellite images typically uses the brightness temperature difference (BTD) between the 11 and 12 μm channels (Watson et al., 2004), with a negative BTD indicating the presence of ash at high-altitude (Prata, 1989). However, this method is unsuitable for resuspended clouds that remain at altitudes <2 km (Beckett et al., 2017). In these cases, a positive BTD can instead be used to detect ash (Beckett et al., 2017). Satellite imagery is thus an essential resource for

TABLE 2 | Parameters to be monitored during and in between remobilisation events.

Parameter	Methods	Reasoning
Continuous or periodic measurements (in between remobilisation events)		
Source area location, extent and thickness	Traditional field mapping, satellite imagery, drone surveying	Necessary for the calculation of the volume of material available for remobilisation
Wind velocity field	Anemometry	Necessary for the determination of u_* and the amount and grain size of material that can be remobilised
GSD, particle density and emissivity of source material	Laboratory analysis using dynamic image analysis or laser diffraction, wind tunnel or *in-situ* experiments	Necessary for the determination of the potential of the source for remobilisation and the possible PM threats
Effective precipitation (direct precipitation + ground/surface flow)	Rain gauges	Necessary for the determination of u_{*t}, which is increased by the cohesiveness of material and therefore the amount of available water
Type and distribution of vegetation cover	Satellite imagery, drone surveying or traditional mapping	Plants can strongly affect u_* and thus can act as sediment traps and immobilise material
Measurements during remobilisation events		
Extent and height of cloud	Visible camera observations, satellite- and ground-based remote sensing, e.g., radiosonde, solar photometer, lidar, ceilometer	Provides data for use in modeling
Air quality (PM concentration)	Optical particle counters e.g., DustTrak	Fine PM, such as PM10 and PM2.5, is a respiratory threat to humans and animals
Visibility	Visibility sensor	To inform road and aviation users of air visibility

forecast modeling, while height estimates are also obtainable by combining satellite observations with radiosonde data (Toyos et al., 2017).

Air quality and visibility present threats during remobilisation events and need to be monitored, but not all observatories can measure these parameters. Variations can also be extremely local and thus go undetected. Furthermore, organisations other than volcano observatories are normally responsible for measuring air quality. Therefore, monitoring strategies need to be tailored to each observatory's specific needs and capabilities.

Assessing and monitoring ash remobilisation hazards can identify priority mitigation measures for reducing adverse impacts. Following the 2011 Cordón Caulle eruption, short-to medium-term mitigations included road and town clean-ups, livestock refuges, greenhouse cultivation and windbreaks (Wilson et al., 2013). However, the cleaned-up ash is itself remobilisable (Wilson et al., 2011) and longer-term mitigations regarding storage and stabilisation must be considered. The same eruption also demonstrated the importance of prompt livestock relocation to secure refuges or areas. When possible (e.g., in case of detected unrest), this should occur prior to eruption onset.

CONCLUDING REMARKS AND RESEARCH PRIORITIES

Volcanic ash remobilisation threatens human and animal health, various economic sectors, and critical infrastructure. In recent years, progress has been made characterising field deposits, understanding and modeling remobilisation processes, and monitoring remobilisation phenomena. However, progress remains to be made. Further field observations (e.g., spatial distribution and granulometry of ash deposits) are needed to provide valuable input data for remobilisation forecasts while observations of active remobilisation processes, e.g., using sediment traps and PM instruments, can validate models. Operational forecast models of resuspended ash clouds include emission schemes that relate the vertical flux of resuspended material to the wind friction velocity. Such schemes, however, currently neglect deposit properties and further constraints are needed. To address these issues, the workshop participants identified the following research priorities:

- Practices need to be developed for field characterisation. Methodologies should include: mapping of primary and remobilised deposits and roughness elements; textural, GSD and ash morphology measurements; and observations of active remobilisation processes through videos, sediment traps and PM monitors.
- New techniques are needed to better quantify surficial soil moisture, possibly involving ground-penetrating radar or satellite technologies.
- It is necessary to determine controls on u_{*t}, needed for initialisation of emissions.

- Laboratory and field measurements are needed to better constrain the relations among u_*, deposit properties (e.g., granulometry and surface moisture), and vertical mass fluxes, and thus improve ash emission schemes, e.g., better constrain the exponent n.
- A regularly updated spatial database of resuspension source areas needs to be available for real-time forecast modeling, including information on areal extents, material properties, effective precipitation and vegetation cover.
- Ad-hoc impact mitigation measures should be identified in preparation for emergencies, including livestock refuges, greenhouse cultivations, clean-up operations and tephra deposit stabilisation.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors attended the 2019 workshop on Wind-remobilisation processes of volcanic ash in San Carlos de Bariloche and Ingeniero Jacobacci, Argentina. CB, LD, CF, PJ, PF, and DB were members of the workshop organizing committee. PJ drafted the manuscript and all authors contributed to the content, style and structure.

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SUPPLEMENTARY MATERIAL

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