Wind-remobilisation processes of volcanic ash
Los procesos de resuspensión de cenizas volcánica

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Consensual Document

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Executive summary

Explosive volcanic eruptions can eject large quantities of tephra into the atmosphere that can be dispersed and deposited over wide areas. Whilst the hazardous consequences of primary tephra fallout are well known, subsequent remobilisation of ash by aeolian processes can continue to present an underestimated hazard on timescales of months to even millennia after the eruption. Although wind-remobilisation of ash was first recognised following the 1980 eruption of Mt. St. Helens, USA, ash remobilisation events in recent years, from the deposits of multiple volcanic eruptions (e.g. Grímsvötn, Iceland; Cordón Caulle, Chile; and Mt. Katmai, USA), have highlighted the high frequency of the phenomenon and the potential consequences for human infrastructure and health. Consequently, more than fifty scientists, including staff from volcano observatories and volcanic ash advisory centres (VAACs), and academic researchers from fields such as volcanology, aeolian processes and soil sciences, convened at the Bariloche headquarters of the Argentinian National Institute of Agricultural Technology (INTA) to discuss the current 'state of the art' for monitoring, modelling and understanding ash remobilisation and future issues that need to be addressed. Based on two days of in-depth discussions and a field excursion to examine primary and remobilised deposits and ash-soil interactions, as well as meet a community strongly impacted by ash-remobilisation (Ingeniero Jacobacci, Argentina), the following key findings were determined:

1. *Hazard and impacts.* Remobilisation by wind can resuspend large quantities of ash into the air that presents similar impacts to the primary tephra fallout, e.g. reduced visibility on roads, impacts on human and animal respiratory health and damage to aeroplane engines (through abrasion and melting). In the latter context, ash presents a unique hazard compared to mineral dust due to its high abrasive potential and lower melting temperature. Furthermore, remobilisation deposits, such as ash dunes, can migrate and bury soil and crops, destroying vegetation and contaminating livestock feed. These consequences can continue for years after the cessation of eruptive behaviour.

2. *Driving processes.* The duration and intensity of remobilisation events depends on multiple parameters, the most important of which are:
   - I. Wind friction velocity u^*, which characterises the shear stress that wind exerts on the ground surface. This must exceed a critical threshold u^*_{th} for remobilisation to occur. Limited experiments currently suggest $u^*_{th} \approx 0.4$ m s^{-1}.
   - II. Volume and properties (grain-size distribution, particle density and shape, dust emissivity) of the primary deposit, which is the source of remobilised material.
   - III. Type and distribution of vegetation cover.
   - IV. Effective precipitation, which quantifies the amount of water received by the deposit from direct precipitation (rainfall, snow etc.), surface and groundwater flow.

3. *Need for monitoring.* Following a 2016 VAAC meeting, it was agreed that best practice would be to release a Volcanic Ash Advisory (VAA) for resuspended ash clouds. These VAAs need to be informed by observations. Additionally, information about hazard needs to be provided to local stakeholders.
   - I. *Parameters to monitor.*
     - i. *Before and between events (in preparation for real-time forecasting).* Main priority: location and extent of source areas; secondary importance: precipitation data, vegetation and snow cover.
     - ii. *During events.* Height and extent of resuspended cloud (for data assimilation), visibility and air quality impacts.

II. *Monitoring challenges.*
   i. Distinguishing a remobilisation event from an eruptive emission can be challenging; remobilisation from volcano flanks can look like weak ash plumes. A multi-observation approach combining camera observations, ground- and satellite-based remote sensing and geophysical monitors are needed to constrain the nature of the emission.
   ii. Currently large global variations exist in how, or even if, monitoring of potential source areas for resuspension and subsequent events takes place. For example, not all observatories can measure visibility and the nature of organisations responsible for measuring air quality varies from country to country.

4. *Field characterisation of deposits and processes.*
   I. The distribution, thickness and internal structures and textures of remobilised deposits contain information on remobilisation and subsequent re-sedimentation processes.
   II. Distinguishing between remobilised and primary deposits is not obvious, particularly for syn-eruptive remobilisation.
   III. It is difficult to measure u^* in the field, though it can be approximated from wind-speed measurements across a vertical profile if the surface roughness (including topography and vegetation) is accounted for.
   IV. Active processes can be well-captured using videos, real-time monitors of airborne particulate matter (PM) and sediment traps.

5. *Modelling and forecasting.*
   I. Model results are strongly dependent on horizontal and vertical resolutions, meaning the accuracy of results depends on both the spatial resolution of the input data and computational power.
   II. Source terms in dispersion models are determined through emission schemes which give the vertical mass flux of material. Multiple emission schemes exist of varying complexity and experiments are needed to test them, although limited experimental evidence suggests that all of these schemes may lack accuracy.
   III. Currently, the key input for models is the source area, with the lack of sophistication in emission schemes meaning that model results are currently relatively insensitive to other parameters and specific details of the processes. This may change once emission schemes become more sophisticated.

6. *Hazard communication* The current style and quantity of communication of remobilisation hazard towards the various stakeholders (e.g. population, authorities) varies substantially. Nonetheless, it is important that observatories (according to local needs, capabilities and requirements) consider the implementation of remobilisation monitoring for various reasons:
   I. Ash remobilisation events produce a range of disruptions both proximally and distally (e.g. aviation impact, road visibility, air quality, human and animal health).
   II. Local stakeholders need to be aware if airborne ash originates from a remobilisation event or an eruption.
   III. There is a need to provide input parameters to VAACs.

Resumen Ejecutivo

Las erupciones volcánicas de tipo explosivo tienen la capacidad de expulsar grandes cantidades de tefra a la atmósfera, la cual puede dispersarse y depositarse sobre vastas áreas. Si bien las consecuencias de la caída de tefra primaria son conocidas, la posterior removilización de la ceniza (fracción granulométrica < 2 mm de diámetro) por procesos eólicos es aún un peligro subestimado, ocurriendo en escalas temporales que pueden ir de meses a milenios. Aunque la removilización de ceniza volcánica por acción del viento se documentó por primera vez después de la erupción del Monte Santa Elena (EEUU) en 1980, fueron los eventos observados en los últimos años—asociados a los depósitos de múltiples erupciones volcánicas (por ejemplo, Grímsvötn, Islandia; Cordón Caulle, Chile; y el Monte Katmai, EE. UU.)— los que han resaltado la alta frecuencia del fenómeno y las potenciales consecuencias para la infraestructura humana y la salud. En consideración de esto, alrededor de cincuenta científicos, incluyendo personal de observatorios vulcanológicos y centros de aviso de cenizas volcánicas para la aviación (denominados VAAC por su sigla en inglés) e investigadores especialistas en áreas temáticas relacionadas con la vulcanología, los procesos de erosión eólica y las ciencias del suelo, se reunieron en la sede de Bariloche del Instituto Nacional de Tecnología Agropecuaria de Argentina (INTA) para discutir el 'estado del arte' del monitoreo, modelado y comprensión de la removilización de ceniza volcánica por efecto del viento, a la vez que para delinear los temas que deberían abordarse a futuro. Luego de dos días de intensas discusiones, seguidas por un viaje de campo para examinar depósitos primarios y removilizados, observar las interacciones entre el suelo y las cenizas, y conocer a una comunidad fuertemente impactada por la remoción de cenizas (Ingeniero Jacobacci, Argentina), se llegaron a identificar los siguientes elementos clave:

1. *Peligros e impactos.* La removilización por acción del viento puede resuspender grandes cantidades de ceniza volcánica en el aire, generando impactos similares a los de la caída de tefra primaria (por ej: reducción de visibilidad en rutas, impactos en la salud respiratoria humana y animal, y daños en los motores de los aviones). Con respecto a la aviación, la ceniza volcánica representa un grave peligro en comparación con el polvo mineral, debido a su alto potencial abrasivo y a su baja temperatura de fusión. Por otro lado, los depósitos producto de removilización, como las dunas de cenizas, pueden desplazarse y enterrar suelos, destruyendo la vegetación y los cultivos. Las consecuencias de la removilización pueden extenderse durante años luego de terminado un evento eruptivo.

2. *Procesos.* La duración e intensidad de los eventos de removilización dependen de múltiples parámetros, siendo los más importantes:
   I. La velocidad de fricción del viento (parámetro u^*), que caracteriza el esfuerzo cortante (o de cizalla) que el viento ejerce sobre la superficie del suelo. Esta velocidad debe exceder un umbral crítico (parámetro u^*_{th}) para que ocurra la removilización. Los escasos experimentos realizados hasta la actualidad sugieren un $u^*_{th} \approx 0.4$ m s^{-1}.
   II. El volumen y las propiedades del depósito primario (por ejemplo: distribución de tamaños de grano, densidad y forma de las partículas, emisividad del polvo), el cual constituye la fuente del material removilizado.
   III. Tipo y distribución de la cubierta vegetal.
   IV. Precipitación efectiva, la cual cuantifica la cantidad de agua recibida por el depósito, tanto a partir de precipitación directa (lluvia, nieve, etc.) como del flujo de agua superficial y subterránea.

3. *Necesidades de monitoreo.* Después de la reunión de las VAAC's de 2016, se acordó que la mejor práctica sería emitir un aviso de Ceniza Volcánica (VAA, por sus siglas en inglés) para el caso de nubes de ceniza producto de resuspensión. Para la emisión de los VAA, se requiere de observaciones. Además de los VAAs, se debe proporcionar información sobre este peligro a las autoridades locales y a las instituciones responsables de la toma de decisiones.

I. *Parámetros a monitorear.*
   i. *Antes y entre eventos de removilización de ceniza (para la preparación de pronóstico en tiempo real).* La principal prioridad: ubicación y extensión de los depósitos fuente; en segundo lugar: datos de precipitación (incluyendo cobertura de nieve, si la hay) y de vegetación.
   ii. *Durante los eventos de removilización.* La altura y extensión de la nube de ceniza, la visibilidad y los impactos en la calidad del aire.

II. *Desafíos para el monitoreo.*
   i. Distinguir un evento de removilización de ceniza de una pluma eruptiva puede ser un desafío. La removilización de ceniza desde los flancos de un volcán puede verse como una pluma eruptiva débil. Se necesita un sistema de observación múltiple que combine observaciones desde cámaras terrestres, sensores remotos (satélites) y monitores geofísicos para definir la naturaleza de la emisión.
   ii. Actualmente existe una gran variación a escala global, en cómo (o incluso si) se llevan a cabo el monitoreo de las potenciales áreas fuente para la resuspensión de ceniza y de los eventos posteriores. Por ejemplo, no todos los observatorios pueden medir la visibilidad y, además, los tipos de organizaciones responsables de medir la calidad del aire, varían de un país a otro.

4. *Caracterización en campo de depósitos y procesos.*
   I. La distribución, espesor, estructuras internas y texturas de los depósitos removilizados contienen información sobre los procesos de removilización y posterior re-sedimentación.
   II. La distinción entre depósitos removilizados y primarios no es obvia, particularmente cuando hay procesos de removilización y de emisiones eruptivas de manera sincrónica.
   III. Es difícil medir el parámetro u* en el campo, aunque puede ser aproximado a partir de mediciones de velocidad del viento a través de un perfil vertical, y teniendo en cuenta la rugosidad de la superficie (incluida la topografía y la vegetación).
   IV. Los procesos activos pueden capturarse utilizando videos, monitores en tiempo real de partículas en suspensión en el aire (PM) y trampas de sedimentos.

5. *Modelado y predicción.*
   I. Los resultados de los modelos dependen fuertemente de las escalas de resolución horizontal y vertical de los datos, lo que significa que la precisión de los resultados dependerá tanto de la resolución espacial de los datos de entrada, como de la capacidad de computación.
   II. Los parámetros de entrada en los modelos de dispersión se determinan a través de esquemas de emisión que proporcionan el flujo de masa vertical del material. Existen múltiples esquemas de emisión de diversa complejidad y se necesitan experimentos para probarlos, aunque la limitada evidencia experimental sugiere que todos estos esquemas pueden carecer de precisión.
   III. Actualmente, el parámetro de entrada clave para los modelos es el depósito fuente, pero dada la falta de esquemas sofisticados de emisión, los resultados del modelo son relativamente insensibles a otros parámetros y a detalles específicos de los procesos. Esto debería cambiar una vez que los esquemas de emisión se vuelvan más sofisticados.

6. *Comunicacción de los peligros asociados* Las formas de comunicar los peligros de removilización hacia los diversos interesados (por ejemplo, autoridades, población general) varías sustancialmente en la actualidad. Sin embargo, es importante que los observatorios consideren la implementación del monitoreo de la removilización (de acuerdo con las necesidades, capacidades y requisitos locales) por varias razones:
   I. Los eventos de removilización de cenizas producen una variedad de impactos, tanto en proximidad como a distancia (por ejemplo en: la aviación, la visibilidad en rutas, la calidad del aire, la salud humana y animal).
   II. Las autoridades locales e instituciones responsable de la toma de decisiones tienen que conocer si la ceniza en el aire esta originada por un evento de removilización o por una erupción.
   III. Es necesario proporcionar los parámetros de entrada para los VAACs.

1. Introduction

[1] Explosive volcanic eruptions generate large quantities of tephra which can be dispersed and deposited over large areas. The resultant primary tephra-fallout deposit can be remobilised by different wind-driven aeolian processes; larger ash particles might move by saltation or creep along the ground, whilst finer material can be suspended in the atmosphere. Although many sediments are susceptible to aeolian transport processes, the transient sediment supply, highly abrasive potential and other chemical and physical properties of ash mean it poses a unique hazard to human health and infrastructure.

[2] Hazards from remobilised ash include those in common with eruptive hazards, albeit with some different details to eruptive crises. Large quantities of airborne ash can reduce visibility, presenting a hazard on roads, indeed there have been numerous reports of road accidents during remobilisation events. Furthermore, the presence of airborne particulate matter (PM) presents a hazard to human health, contributing to cardiovascular and respiratory diseases (Anderson et al., 2012; Kampa & Castanas, 2007; World Health Organisation, 2013). In rural environments, ash can cover and damage crops and contaminate food sources for livestock. In some environments, these deposits can form dunes and bedforms which can migrate and impinge on further resources. These dunes can also inhibit water drainage, and act as dams. However, during periods of heavy rainfall, these structures can fail leadings to the creation of lahars from remobilised material. Whilst the potential for volcanic ash to disrupt aviation traffic is well known, remobilised ash clouds sometimes have limited altitudes depending on local meteorological conditions e.g. atmospheric temperature inversions have prevented resuspended ash clouds from Iceland rising above a few kilometres (Beckett et al., 2017; Hammond & Beckett, 2018) and so are only likely to affect aircraft landing or taking off locally. However, this is not generally true; resuspended ash from the January 2020 eruption of Taal Volcano, the Philippines, rose to altitudes of 5.8 km (NDRRMC, 2020). Furthermore, the greater abrasivity and lower softening point of volcanic ash compared to mineral dust (Kueppers et al., 2014) means that resuspended ash is potentially more damaging to hot engines than more typically remobilised material (Müller et al., 2019).

[3] Remobilisation of volcanic ash was first recorded in 1933, when "brown snow", consisting of volcanogenic material remobilised from the deposits of the 1912 Novarupta eruption (Hildreth & Fierstein, 2012) was observed across Canada and the northern USA (Alexander, 1934; Miller, 1934). Wider recognition was achieved following the 1980 eruption of Mt. St. Helens, USA, where winds of approximately 1 – 10 m s^{-1} resuspended the finer fraction of the deposit and dangerously reduced visibility (Hobbs et al., 1983). In recent years however, resuspension events after eruptions from Eyjafjallajökull (2010) and Grímsvötn (2011) (Liu et al., 2014) in Iceland, and Hudson (Wilson et al., 2011) and Cordón Caulle (Craig et al., 2016, Forte et al., 2018) volcanoes in Chile, among others, have highlighted the unique hazards associated with these phenomena. Ash remobilisation can occur over hugely varying timescales, from syn-eruptively up to over 1000 years after eruption (Hadley et al., 2004; Mingari et al., 2017). In particular, old tephra-fallout or pyroclastic density current deposits can be exposed by anthropogenic activities, such as quarrying or deforestation, and made available for remobilisation.

[4] The recent observations of ash remobilisation events have highlighted the need for increased monitoring, forecasting and research. In particular, at the 2016 World Meteorological Organization (WMO) VAAC "Best Practice" workshop in 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" (World Meteorological Organization, 2016). In order for VAACs to follow this guidance they rely on monitoring observations of ash source areas and accurate parameterisations for modelling of resuspension and remobilisation processes. In order to identify the required objectives of future work on ash remobilisation and the associated challenges, a workshop on wind-remobilisation processes of volcanic ash was held at the San Carlos de Bariloche headquarters of INTA (https://www.unige.ch/sciences/terre/CERG-C/ash-remobilisation-2019/presentation/), in Argentina. The event brought together 47 participants from volcano observatories, VAACs and academic research institutions, and multiple disciplines (e.g. volcanology, aeolian processes, soil science) with different expertise (e.g. experimental, field, numerical modelling). The objectives of the workshop included:

1. Compilation of best practices for field sampling and characterisation of remobilised volcanic particles.
2. Identifying critical parameters controlling wind remobilisation.
3. Description of the main input parameters required for numerical modelling of ash remobilisation and deposition.

This document summarises the outcomes of two days of oral and poster presentations, break-out sessions and plenary discussions, followed by two days in the field observing deposits of remobilised ash and meeting community members in the town of Ingeniero Jacobacci, a rural community in the Argentinian Patagonia impacted by remobilisation of ash from the 2011 eruption of Cordón Caulle. The list of participants, workshop program and a list of acronyms used in this document can be found in Appendices 1, 2 and 3, respectively. Additional information is also available at our workshop website: http://www.unige.ch/sciences/terre/CERG-C/ash-remobilisation-2019/

2. Mechanisms of remobilisation and resuspension

2.1. Sediment transport

[5] Particles within a deposit can be remobilised if the wind friction velocity u^* exceeds a critical threshold u^*_{th}. The friction velocity is not a true velocity, but a proxy for the shear-stress at the ground surface τ, with $u^* = \sqrt{\tau/\rho}$, where ρ is the density of air. The threshold u^*_{th} is determined from a balance of forces acting on a grain at the surface; wind drag and aerodynamic lift, which act to entrain the particle into the flow, are resisted by gravitational and inter-granular cohesive forces (Bagnold, 1941; Greeley & Iversen, 1985; Shao & Lu, 2000). Whilst various models exist to describe this balance, for sand it is accepted that u^*_{th} is minimised for grain diameters d in the range ($75 \leq d \leq 100$) µm. Below this, cohesive forces increase as grainsize decreases. For particles smaller than sand (<63µm) and especially for dust particles (PM10) cohesive/adhesive effects dominate their behaviour and they are seen to strongly agglomerate / aggregate. Here a simple force balance approach is not seen to work well (e.g. Friess and Yadigaroglu 2002). Conventionally the resuspension of such fine particles is assumed to occur due to impacts of larger saltating sand particles (Gillette et al., 1974). On Earth deposits consisting only of (unconsolidated / uncemented) fine material (in the absence of sand) are not typically found and such deposits have only actively been studied for industrial applications. Water generally has a dominant influence on the generation and transport of such fine materials. Liquid water flows may disperse silt/clay sized particles (which may then

be transported by wind) whilst water can also cause cementation of silt/clay through dissolved salts. Such effects make the transport of dust complex compared to cohesionless sand.

[6] Particles that are successfully removed from a bed can be transported through different modes. Mobilised particles in the range ~70-500 µm will saltate along the surface following ballistic trajectories (Bagnold, 1941). Finer particles have sufficiently small settling velocities that they can become suspended by turbulent fluctuations (Nickling & McKenna Neuman, 2008), with those of diameter ≤ 20 µm entering long-term (weeks-months) suspension and those in the diameter range 20-70 µm undergoing short term suspension. Particles larger than 500 µm can move by reptation (jumps of < 1 cm; Ungar & Haff, 1987) or creep (rolling or sliding; Bagnold, 1941). In this document, we will use the term *remobilisation* to refer to any aeolian transport of ash and use *resuspension* to refer to only the component that is suspended in the atmosphere.

2.2. Controls on duration and intensity of remobilisation events

[7] The key control on duration and intensity of remobilisation events is the wind friction velocity u^*; the greater the value of u^* the greater the quantity of material that can be remobilised. However, u^* is difficult to measure directly in the field without sophisticated instrumentation (e.g. sonic anemometer or multiple height wind speed measurements). Instead, measurements of the wind field (using anemometers) as well as topographic mapping (including roughness elements e.g. vegetation, rocks) can be combined to estimate u^*.

[8] Deposit properties also control remobilisation. In particular, the total volume of erupted material, characterised by the deposit thickness and spatial distribution directly controls the amount of material that is available to be remobilised. For large eruptions, such as the 1912 Novarupta eruption which produced ~28 km^3 of ash and the Valley of the Ten Thousand Smokes (Fierstein & Hildreth, 1992), remobilisation can continue on a timescale of centuries after the eruption (Hadley et al., 2004). For smaller eruptions, the ash can be removed or immobilised on shorter timescales. Other important deposit characteristics include the grainsize distribution (GSD) and the particle density, since these parameters control u^*_{th} and the mode of sediment transport (Section 2.1). Whilst GSD and particle density measurements can be used to make estimates, the only way to accurately determine u^*_{th} for a particular ash deposit is through direct measurements. This can be done by collecting the ash and conducting wind-tunnel experiments (Douillet et al., 2014; Del Bello et al., 2018; Etyemezian et al., 2019) or in-situ by using a calibrated field instrument (Etyemezian et al., 2007). Limited data so far suggests that $u^*_{th} \approx 0.4$ m s^{-1} for ash, and that this threshold remains independent of humidity for relative humidities < 75-90%.

[9] Another control on remobilisation is the amount and type of vegetation cover onto which the ash has deposited. Plants can act as sediment traps, whereby ash can deposit within and both immediately upwind and downwind of a plant and be protected from aeolian forcing. This can occur for primarily deposited ash as well as remobilised ash that consequently becomes trapped and is effectively removed from the available budget for remobilisation. The effectiveness of a particular plant species as a sediment trap depends on its size and permeability. Finally, the amount of effective precipitation is also important. Whilst small amounts of precipitation can increase the soil water content at the surface, generally inhibiting remobilisation, some ash may initially be released into the atmosphere through a splashing process before the soil becomes too wet. Large amounts of precipitation can lead to surface run-off which erodes the ash into fluvial systems, removing it from the aeolian environment. Such a process may have occurred in 2014, when a large precipitation event led

to a reduction in frequency of remobilisation events originating from the 2011 Cordón Caulle primary fall deposit (Forte, 2018).

3. Field characterisation of remobilisation processes and deposits

[10] Fieldwork carried out with the intention of characterising both remobilisation processes and the resulting deposits is vital for multiple reasons. Firstly, making measurements of quantities related to the erosion, transport and deposition of volcanic ash allows testing of parameterisations used in models. Secondly, field campaigns can be used to collect input data for numerical models, e.g. Fall 3D which uses a grainsize-dependent emission scheme (Folch et al., 2014). In order to maximise the usefulness of field data for interpretation and use in models, it is desirable to develop some "best practices" so that data from different field sites and at different times is comparable. In this section, we present some of the challenges associated with the field characterisation of ash remobilisation and suggest some key parameters that should be measured.

3.1. Challenges of field characterisation

[11] An initial difficulty is that the distinction between primary and remobilised deposits is not always obvious. This is particularly true when syn-eruptive remobilisation takes place, such as at Sabancaya volcano, Peru, where multiple small Vulcanian explosions occur per day, depositing ash that is continuously being transported by the wind. Despite this, some general deposit features can be used to distinguish between primary fallout and remobilised deposits. In particular, primary fallout deposits will have a uniform thickness at the local scale (assuming deposition on a flat surface), whilst the thickness typically decreases with distance from the vent. However, surface roughness can have a strong control on the erosion and deposition of remobilised ash, meaning remobilised deposits can strongly vary in thickness on sub-metre length scales. Specifically, in environments with a prevailing wind, ash deposition will exceed erosion in shadow zones downwind of roughness elements such as plants, rocks or topographic highs. If erosion occurs in the space between roughness elements, this can lead to unconnected deposits. A further identifying feature of remobilised deposits includes the presence of cross-bedding, which results from unsteady wind conditions and is expected to be absent from primary fallout deposits.

3.2. Important parameters to be measured in the field: deposit features

[12] It is necessary to measure properties of both the primary and the remobilised tephra deposits. In general, any exposed sediments are potential sources of transportable material and, therefore, need to be examined. Of particular importance are the thickness and spatial distribution of the primary deposit since these can be used to estimate the volume of material available for remobilisation. Combining the spatial distribution of the deposited remobilised material with maps of roughness elements can also provide insights on which parts of the landscape act as sediment traps. Structures within the deposit (cross-bedding, ripples) can provide information on the transport processes.

[13] Aside from the volume, other features of the primary deposit can provide information on the remobilisation potential of the material. In the absence of direct measurements, the GSD and particle density can be used to provide estimates of u^*_{th}, whilst the presence of soil moisture in the very surficial layer can inhibit erosion by increasing u^*_{th}. Although evidence of surficial soil moisture is commonly observed through the existence of a crust and associated

cracks on the deposit surface, since this layer is very thin (~1-2 cm) it is difficult to measure and quantify the water content. Sedimentary structures may allow for conclusions on duration, stability or dynamical variations of atmospheric conditions during remobilisation and eventual re-sedimentation. Whilst radar or satellite methodologies could perhaps be developed to attempt measurements, these techniques do not currently exist and the ability to measure surficial water content in the field remains lacking. A further important feature is the size of aggregates and their constituent parts within the surficial layer. These aggregates are likely to be a mixture of volcanic ash and other sediments. They have implications for the available supply of resuspendable material as even though they may be in the size range for saltation, they may fragment on impact with the ground or other saltators, releasing resuspendable material. Hence, a characterisation of the relative quantity of aggregates within the deposit can provide information on the manner of remobilisation expected.

[14] Textural analysis of the remobilised deposit should be carried out, with measurements of the GSD, sorting and grain morphology being performed. By comparing these quantities with the corresponding measurements in the primary deposit, researchers can identify which particles, if any, are preferentially remobilised, as well as the effect of abrasion during transport on particle shape.

3.3. Important properties to measure in the field: process features

[15] Field measurements characterising the processes of remobilisation can also be performed. Of particular importance is characterisation of the wind field and the wind friction velocity. As described in Section 2.2, measurement of u^* requires substantial instrumentation. For example it can be estimated from a vertical profile of wind speeds obtained from an array of anemometers (Baas & Sherman, 2005) or by using a sonic anemometer at approximately 10 m above ground level (higher if roughness elements are very large). Surface roughness exerts a strong control on u^*, and is normally characterised through the roughness length z_0 and treated as a fitting parameter. The precise value depends on the size and spatial distribution of roughness elements where they are present, and on the grain size in open, flat areas. A characterisation of roughness elements could be obtained from satellite imagery, drone surveying or traditional mapping depending on the scale and available tools.

[16] Aside from wind speed, other meteorological parameters that should also be recorded include the temperature and relative humidity. In many arid regions that are affected by remobilisation of ash, such as the Patagonian steppe or the Altiplano, winds are driven by solar heating of the ground surface. A relationship between temperature and wind speed therefore exists which means the temperature can exert a control on the amount of remobilised material. This generates a diurnal variation in the frequency of remobilisation events with the majority of events occurring in the afternoon once the ground has been sufficiently heated (Mingari et al., 2017). This variability is reinforced by the associated changes in soil moisture. As such, measurements of the temperature and relative humidity are important as they describe, in part, the weather conditions that drive remobilisation.

[17] It is also important to capture data on active remobilisation processes. This can be achieved using videos to identify the source sites and the mode of sediment transport (i.e. bedload, saltation or suspension). Furthermore, such images can also be used to distinguish between different mechanisms through which particles become suspended including streamers (Baas & Sherman, 2005), dust-devils (Balme & Greeley, 2006) or ash storms (Wilson et al., 2011). Further information can be obtained through the use of traps to capture actively moving material. Different traps exist that can be used to measure the horizontal and vertical

fluxes of both the saltating and suspended material. The Big Spring Number Eight (BSNE) collector is commonly used to measure horizontal saltation flux (Fryrear, 1986), and has been used to measure the horizontal flux of remobilised volcanic material (Panebianco et al., 2017). Other devices such as the Modified Wilson and Cooke (MWAC) collector (Wilson & Cooke, 1980) are also commonly used in aeolian studies (Mendez et al., 2011). Vertical fluxes from saltation can be obtained from collectors which are buried in the surface and capture saltating particles as a function of their horizontal travel distance (Greeley et al., 1996). Measuring the vertical mass flux of suspended material in the field is very difficult although measurements of the airborne concentration can be made using optical particle counters, such as a DustTrak, as has previously been used during ash remobilisation events following the 2011 eruption of Cordón Caulle (Wilson et al., 2013). Correlations between the measured concentrations and fluxes and the meteorological conditions will provide useful information for modellers.

4. Monitoring remobilisation

[18] Both local and regional stakeholders can be impacted by remobilisation events, creating a need for monitoring remobilisation source areas and the associated phenomena. Local communities may observe airborne or sedimenting ash and be concerned that an eruption is taking place. It is therefore important that observatories can identify whether the ash has an eruptive or aeolian source, and communicate this information locally. On a larger scale, a 2016 VAAC meeting agreed that it would be best practice to release a VAA for resuspension clouds if there are observations to support the presence of a remobilised ash cloud. Although discussion is still ongoing as to how this should be implemented, VAACs therefore need to receive monitoring data to inform dispersion modelling.

[19] Despite these needs, there are currently, large global variations in how, or even if, monitoring of resuspension events takes place. Some observatories, such as INSIVUMEH in Guatemala include resuspension events in daily reports, whilst others, such as the Alaska Volcano Observatory (AVO) primarily monitor resuspension for internal purposes, but also issue public reports to be consistent with agencies reporting on dust events. In many other locations no monitoring of remobilisation occurs. Furthermore, since resuspension can be considered an air quality, as opposed to a volcanological, issue, agencies other than volcano observatories may have responsibility for monitoring resuspension clouds. This lack of consistency makes it difficult to provide usable information to VAACs.

[20] An initial challenge can be identifying a resuspension event from an eruptive emission, especially for resuspension from the summit or flank of a volcano. For example, on 14th December 2018 and 2nd January 2019, ash plumes were observed from the summit area of Nevado del Ruiz, Colombia, with ashfall occurring some distance from the volcano. These visual observations were initially reported as an eruption, but no geophysical signals that would be expected for an eruptive event were detected. Thus, although an eruptive event cannot be entirely discounted, it seems likely that the ash was remobilised from the volcano summit and flank by high wind speeds. Promising techniques for distinguishing between primary and remobilised ash clouds include satellite observations (e.g. Brightness Temperature Difference (BTD), water content estimates) in combination with ground-based cameras and geophysical monitors that would detect an eruption and constrain the source. However, the lower altitude of resuspension clouds relative to eruptive clouds complicates satellite measurements. It is also likely that no single method would be definitive, so synthesis of different data sources is required.

[21] Parameters relevant to ash remobilisation that need to be monitored can be separated into two types: those that need to be recorded continuously in preparation for remobilisation episodes, and those that need to be recorded during an event. Those that need to be recorded periodically include (in order of importance):

1. Location and extent of source area
2. Wind velocity field
3. Volume and properties (GSD, particle density, dust emissivity) of source material
4. Effective precipitation (sum of direct precipitation and input from ground and surface flow)
5. Type and distribution of vegetation cover

[22] All of these parameters can change with time in either a periodic fashion (diurnally or seasonally) or monotonically (e.g. the volume of source material reduces with time). Therefore, it would be ideal if these quantities could be recorded in a continuously updated database of input parameters to be available for forecast modelling. These parameters are also those that need to be measured during field characterisations of remobilisation processes (Section 3), highlighting that this could be a fruitful area of collaboration between researchers and observatories.

[23] During a resuspension event, it is important that the extent and height of the cloud are monitored so that forecast modelling can make use of assimilated data. Such measurements can be obtained from visible camera observations, as well as satellite- and ground-based remote sensing techniques. Typically, detection of ash in satellite images uses the brightness temperature difference (BTD) between two different wavelength channels (Watson et al., 2004). For high altitude clouds, a negative BTD can indicate the presence of ash (Prata & Grant, 2001). Whilst this method is suitable for eruptive clouds, this often fails for resuspended clouds that do not rise sufficiently high. In particular, resuspended ash clouds from Iceland have had maximum altitudes of less than 2 km above sea level (Beckett et al., 2017) due to a tropospheric temperature inversion. One alternative method involves combining the minimum brightness temperature of the cloud at 11 µm, as detected by satellite, with radiosonde data (Toyos et al., 2017), whilst it has also been shown that a positive BTD can also be used to indicate the presence of ash at low altitudes (Beckett et al., 2017). Other technologies such as solar photometers and lidar can also be used.

[24] Air quality is also an important consideration and is typically quantified through the concentration of PM. Visibility can also be monitored during a remobilisation event. Large quantities of fine PM pose a significant health hazard to human and animal health whilst low visibilities present a hazard for road traffic and air travel. As described in section 3.2, PM concentrations can be measured using optical particle counters whilst sensors for visibility also exist. However, not all observatories are equipped to measure these parameters whilst variations can also be extremely local so may be missed by detectors. Furthermore, organisations other than volcano observatories, such as meteorological agencies, are responsible for measuring air quality in some locations. Therefore, strategies for monitoring air quality and visibility need to be tailored to the specific needs and capabilities of local observatories.

5. Modelling and forecasting remobilisation

[25] Modelling of remobilisation processes currently strongly focusses on dispersion modelling of resuspended ash clouds, with an emphasis on operational forecasts (Folch, 2014; Hammond & Beckett, 2019). The source terms for these models are determined through emission schemes which provide the vertical mass flux of material *F* as a function of the wind friction velocity $u*$, which operationally can be taken from Numerical Weather Prediction (NWP) data available from the National Oceanic and Atmospheric Administration (NOAA). Multiple emission schemes of varying complexity exist but essentially these schemes are almost universally power law relationships of the form $F \alpha u*^{n}$, where *n* is some positive exponent (Kok et al., 2012). These expressions are theoretical scalings derived by assuming suspension is saltation-driven, and then considering the kinetic energy balance between the horizontal saltation flux, and the vertical suspension flux (Gillette 1979). Some schemes also consider factors to account for grainsize dependence (Shao et al., 1993; Marticorena et al., 1997). However, empirically fitted values of *n* vary from 1.89 to 6.2 (Ishizuka et al., 2014; Etyemezian et al., 2019) and there remain a lack of experimental validation for these relationships. It is therefore possible that the simplicity of these parameterisations fails to accurately predict vertical mass fluxes. Further experimental and theoretical research is required before models will be able to implement more sophisticated emission schemes, although some schemes are grainsize dependent (Folch et al., 2014). The current simplicity of emission schemes means that the only source deposit parameter that dispersion models are strongly sensitive to is the source area, with some sensitivity to grainsize for grainsize dependent schemes. However, once emission schemes becomes more sophisticated and better constrained, parameters other than source area will become important.

[26] Dispersion model results are strongly dependent on horizontal and vertical resolutions. Sufficiently high horizontal resolutions are required to capture topographic effects on the friction velocity u*, with coarse parameterisations of the ground surface leading to an under-estimate of the vertical flux of material in emission schemes (Mingari et al., 2017). Furthermore, the vertical resolution must be fine enough to accurately parameterise vertical convection in the near-surface planetary boundary layer (Banks et al., 2016). Such convection is required to lift remobilised ash into the atmosphere and the predicted height of the ash cloud depends on reliable modelling of these processes (Mingari et al., 2017). This is less of an issue for models of primary ash plumes, which are injected at greater altitudes and are less sensitive to near-surface effects. For resuspended clouds however, the resolution requirements mean that the accuracy of dispersion modelling is constrained by the available computational power.

6. Communicating remobilisation hazard

[27] The style and quantity of communication of remobilisation hazard to different stakeholders varies substantially between localities. Events of ash remobilisation produce a range of impacts in both proximal and distal areas; these include disruption to both road and aviation traffic due to poor visibility, damage to crops and livestock in agricultural communities, and health issues relating to particulate air pollution. Therefore, both local communities and VAACs need to receive relevant information for the assessment of risk.

[28] Local communities need to be informed about visibility and air quality degradation and the potential for ashfall. Limited visibility during ash storms have contributed to the

occurrence of road traffic accidents whilst the PM concentration in air is a health threat for both humans and animals. However, as described in Section 4, in some locations, organisations other than volcano observatories, such as meteorological agencies, are responsible for measuring air quality in some locations. This means that local communication of hazard due to remobilised ash needs to be tailored to the needs of specific communities.

[29] The current styles of communication concerning resuspended ash clouds to VAACs also vary considerably. As an example, some observatories within the coverage area of the Buenos Aires VAAC (i.e. central and southern part of South America) may issue a Volcano Observatory Notice for Aviation (VONA) for resuspension events, whereas the Alaska Volcano Observatory (AVO) does not issue a VONA in such circumstances, but instead includes information of ash remobilisation within a formal Information Statement that goes to civil protection but not to the Anchorage VAAC (although direct communication with the VAAC is made by phone). Since multiple observatories fall within the coverage area of an individual VAAC, the standardization of resuspension hazard communication is currently under discussion, to better enable VAACs to forecast ash resuspension in real time.

7. Research priorities

[30] Following the workshop, the following research priorities have been identified:

1. There is a need to develop some "good practices" for field characterisation of ash deposits which are the sources of remobilisable material, as well as those deposits that result from aeolian transport of ash. This will enable comparisons between different field sites and across different time scales. Recommended methodologies should allow for: mapping of primary and remobilised deposits in combination with roughness elements, textural, GSD and ash morphology measurements and observations of active remobilisation processes through the use of videos, sediment traps or real-time PM monitors.
2. New technologies, possibly involving radar or satellite technologies, need to be developed to better quantify surficial soil moisture measurements.
3. A database of source areas for resuspension needs to be compiled, with regularly updated information on source area extents, source material properties, effective precipitation and vegetation cover. This information needs to be readily available for real-time forecast modelling.
4. Experimental and field measurements are needed to better constrain the relationship between wind friction velocity, deposit properties and vertical mass fluxes, and thus improve ash emission schemes for use in forecast modelling.
5. Observatories and VAACs need to collaborate to develop a consistent communication protocol that allows VAACs to release VAAs for resuspension events.
6. Where necessary, observatories and local agencies need to collaborate to assess visibility and air quality during resuspension events, and develop communication protocols for local stakeholders.

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Appendix 2: Workshop Program

23 October – Day 1

8:00 – 8:30	**REGISTRATION**
8:30 – 9:00	Welcome and Workshop Opening (Mauro Sarasola – INTA and Costanza Bonadonna – UNIGE)
	THEME 1: Physical description I: examples from Argentina
9:00 – 10:00	➢ **9:00-9:20** M. Elissondo and J. Kaufman (SEGEMAR, AR) "Sources of remobilized pyroclastic material associated with the volcanism of the Argentine-Chilean Andes" ➢ **9:20-9:40** M. Easdale (INTA, AR) "Assessments and responses of INTA Bariloche to the volcanic ash fall from the Cordon Caulle eruption" ➢ **9:40-10:00** L. Dominguez (UNIGE, CH) "Aeolian transport and deposition mechanisms of tephra remobilisation"
10:00-10:30	*Coffee Break*
10:30-11:50	➢ **10:30-10:50** P. Forte (UBA, AR) "Wind remobilization impact associated with the Cordon Caulle eruption" ➢ **10:50-11:10** C. Stewart (University of Canterbury, NZ) "Wind remobilization impact in Argentina" ➢ **11:10-11:30** G. Toyos (CONAE, AR) "Wind resuspension of volcanic ash from space" ➢ **11:30-11:50** E. Wolfram (CEILAP-UNIDEF, AR) "New insights into wind remobilisation from surface remote sensing"
11:50 – 13:10	*Lunch*
	THEME 2: Physical description II: examples from other regions
13:10 – 14:50	➢ **13:10-13:30** N. Varley (Universidad De Colima, MX) "Wind remobilisation in Mexico" ➢ **13:30-13:50** M. Encalada (IGEPN, EC) "Wind remobilisation in Ecuador" ➢ **13:50-14:10** C. Chun (INSIVUMEH, GT) "Wind remobilisation in Guatemala" ➢ **14:10-14:30** R. Aguilar (INGEMMET, PE) "Wind remobilisation in Peru" **14:30-14:50** A. Saballos (INETER, NI) "Wind remobilisation in Nicaragua"
14:50 – 15:20	*Coffee Break*
15:20 – 17:00	➢ **15:20-15:40** ML Monsalve (SGC, CO) "Wind remobilisation in Colombia" ➢ **15:40-16:00** C. Jorquera (SERNAGEOMIN, CL) "Wind remobilisation in Chile" ➢ **16:00 -16:20** M. Butwin (IMO, IS) "Wind remobilisation in Iceland" ➢ **16:20-16:40** K. Wallace (USGS, USA) "Wind remobilisation in Alaska" ➢ **16:40-17:00** K. Wallace (USGS, USA) "An overview of efforts toward standardization of tephra collection, analysis and reporting"
17:00 – 18:00	Poster presentation

24 October – Day 2

THEME 3: Dynamics of wind remobilisation	
8:40 – 10:00	➢ **8:40-9:00** J. Merrison (Aarhus University, DK) "Dynamics of wind remobilisation" ➢ **9:00-9:20** J. Gillies (DRI, USA) "Laboratory experiments of volcanic ash resuspension" ➢ **9:20-9:40** E. Del Bello (INGV Roma, IT) "Experimental and field studies of the resuspension of volcanic ash by wind" ➢ **9:40-10:00** A. Folch (BSC, ES) "Theory and numerical modelling of ash remobilisation" (SKYPE)
10:00 – 10:30	*Coffee Break*
10:30 – 11:45	Breakout sessions
11:45 – 12:45	Plenary discussion
12:45– 13:45	*Lunch*
THEME 4: Modelling wind remobilisation	
14:00 – 15:20	➢ **14:00-14:20** F. Beckett (UK-MetOffice, UK) "Forecasting remobilised ash clouds at the London VAAC" (SKYPE) ➢ **14:20-14:40** M. S. Osores (VAAC-BA, AR) "Ash remobilisation observations and forecasting for BA-VAAC operations" ➢ **14:40-15:00** H. Schwaiger (USGS, USA) "Operational forecasts of the resuspension of volcanic ash deposits from the 1912 Novarupta eruption" ➢ **15:00-15:20** L. Mingari (BSC, ES) "Numerical simulations of ash resuspension using the WRF-ARW/FALL3D modelling system"
15:20 – 15:45	*Coffee Break*
15:45 – 17:00	Breakout sessions
17:00 – 18:00	Plenary discussion
18:00 – 18:15	Workshop Closing
18:15 – 18:30	Field trip logistics

25-26 October – FIELD TRIP TO INGENIERO JACOBACCI

- *Visit to wind-induced ash-remobilised deposits associated with the 2011 CC eruption*
- *Meeting with the population of Ingeniero Jacobacci impacted by the 2011 CC eruption*

Appendix 3: List of acronyms

BGS	British Geological Survey
BSNE	Big Spring Number Eight
BTD	Brightness Temperature Difference
GSD	Grain-Size Distribution
INTA	Argentinian National Institute of Agricultural Technology (Instituto Nacional de Tecnología Agropecuaria)
MWAC	Modified Wilson and Cooke
NAME	Numerical Atmospheric-dispersion Modelling Environment
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
PM	Particular Matter
USGS	United States Geological Survey
VAA	Volcanic Ash Advisory
VAAC	Volcanic Ash Advisory Centre
VONA	Volcanic Observatory Notice for Aviation