Open-pit post-blast dust cloud lightning

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Abstract

Lightning has been observed in dust clouds following open-pit blasting. It is proposed that the occurrence of this phenomenon is related to the physical composition and characterization of the mineral fines that comprise the bulk of the dust cloud. Silicate minerals, which are susceptible to fine fracturing during blasting, generate the initial charge. This is further enhanced by collisions and friction during the turbulent upcast in the post-blast dust cloud. Varying size fractions result in different rates at which these particles drop out of suspension and create a secondary temperature gradient. This results in the creation of two charged zones and increases the potential of developing a discharge in the form of lightning. The ideal prevailing meteorological conditions need to be windless to minimize the effect of particle dissipation and have sufficient moisture to enhance the potential of generating lightning.

Keywords

open pit, blast, dust, cloud, lightning

Introduction

Open-pit blasting results in a dust cloud that is suspended over the area for several minutes. The phenomenon of lightning occurring within these dust clouds has been reported, but not studied or explained. The lightning is only visible for a short period after the initial blast until the dust cloud starts dissipating. Occurrences of lightning in volcanic pyroclastic clouds have been noted over a long historic period. Proposed mechanisms for the creation of lightning within these pyroclastic clouds have been more extensively studied and are used here as a proxy to interpret the formation of lightning in post-blast dust clouds. Lightning has also been observed in fire-induced pyro-cumulus clouds. The instances of post-blast dust cloud lightning are irregular. No instances of damage to mine infrastructure because of these lightning strikes have been reported to date.

Pyroclastic cloud lightning

During the eruption of several volcanoes, lightning was observed in the resulting ash cloud, referred to as a pyroclastic cloud. Dynamic interactions of ash particles within an eruptive plume result in electrical charging and charge separation within the plume, causing the formation of lightning strikes. The plume height plays a role in the potential for volcanic lightning: ash plumes between 7–12 km high concentrate water vapour, which may contribute to lightning activity; smaller ash plumes of 1–4 km have been shown to gain more electric charge from fragmentation of rocks near the vent of the volcano (McNutt, 2008). During eruptive volcanism, large amounts of ash, dust, rock, volatile gases, and lava are expelled in a very short period.

The conditions required for the formation of lightning in volcanic eruptive ash clouds have been summarized by Kaufman (2020). Volcanic ash develops an electric charge due to friction and collisions. This is the process of charge generation by break-up of rock particles. This may create a significant source of charge near the erupting vent. Ionic charges develop due to their difference in mass, resulting in different rates at which the particles drop out of suspension from the ash cloud.

These charges then need to be separated into different regions of the volcano ash plume. In a chaotic plume, this happens naturally as different sized ash particles fall at different velocities, and cause resultant development of a temperature gradient (Siegel, 2018). This creates different zones of charged particles, which can be positively or negatively charged. Two regions of oppositely charged particles develop. The space between them becomes an electric field, which allows electricity to discharge through the air (Siegel, 2018). The maximum currents reached by volcanic lightning are 2 kA and they have an average appearance of 0.1–8 ms; temperatures as high as 12 000–28 000 K are reached by volcanic lightning in the discharge centre (Aizawa et al., 2016; Genareau et al., 2015; Wadsworth et al., 2017).

The electric charge distribution follows the Positive-Negative-Positive (PNP) model proposed by Miura et al. (2002), in which the upper part of the ash cloud is dominated by volcanic gas and aerosols, and has a prevalent positive charge. In contrast, the middle part of the ash cloud mainly comprises negatively charged fine ash particles. The lower part of the ash cloud is dominated by gravitational settling of coarser and positively charged ash particles (Miura et al., 2002).

The fragments are further settled at different rates because of size. In the case of a bimodal size distribution, larger and positively charged particles are confined to the centre of the flow, while smaller and negatively charged particles follow the turbulence in the shear layer with the surrounding atmosphere (Miura et al., 2002). In the case of monodispersed particles, clustering of particles with either prevalent positive or negative charge generates transient electrical dipoles (Miura et al., 2002).

Other factors, such as eruption type and magma composition, do not seem to influence the occurrence of lightning (McNutt & Williams, 2010). It is also suggested that the atmospheric temperature plays a role in the formation of lightning: colder ambient temperatures promote freezing and ice charging within the plume, which leads to more electrical activity (Aplin et al., 2016).

Modification of ash particles by volcanic lightning strikes has been noted. These are referred to as lightning-induced volcanic spherules (Genareau et al., 2015). Four types of ash particles have been distinguished (Mueller et al., 2018):

Type I – particles that did not undergo lightning-interaction;

Type II – partially melted particles, comprising grains that did interact with the lightning strike, but not sufficiently to melt the entire grain, displayed by remains of a pristine surface or irregular shape of the particle;

Type III – Completely melted particles, which are entirely melted and typically have a spherical shape;

Type IV – Aggregates, which are clusters of up to four amalgamated particles of different types.

A pronounced loss of volatile elements in lightning-affected particles has been noted, showing clear depletion of Na < P and S < Cl < F (Keller, 2020).

Charge generation

The processes regulating the electrification of granular material flows are the composition, size, and kinetics of the solid particles, in conjunction with the ambient conditions (Cimarelli and Genareau, 2022). The main mechanism for generation of a charge during volcanism—and that can be applied to blasting—is fracto-electrification. This process has been observed during fracturing of crystals, rocks, glass, and materials such as metal and ice (Cimarelli and Genareau, 2022). Depending on the type of strained material, fracturing can promote the release of electrons, positive ions, neutral atoms, and electromagnetic radiation, promoting charging of the resulting fragmented particles (Cimarelli and Genareau, 2022).

This phenomenon has been explained in terms of the piezoelectric nature of certain substances, such as quartz, which enhance charge separation at the tip of a propagating fracture and thereby generate large electric fields (Cimarelli and Genareau, 2022). Experiments conducted on pumice clasts that were forced to collide and fracture under vacuum conditions indicated that a net negative charge is held on the solid silicate particles and a net positive charge is either released as ions or carried on a very small proportion of fine particles generated upon collision (Cimarelli and Genareau, 2022). Tribo-electrification (or contact electrification) is the phenomenon of charging by collision and friction between bodies. Eruptive rock fragments that display a high level of heterogeneity in terms of chemical composition and physical characteristics, such as grain size, density, and grain shape, create a favourable environment for charging and redistribution of charge by the collision of these different particles (Cimarelli and Genareau, 2022).

The coexistence of supercooled water droplets and ice crystals in the expanding saturated plume suggests that the mechanism of hydrometeor interaction could be active in volcanic eruptions. Ash particles in the volcanic plume may act as ice nuclei once sufficient altitudes are achieved, promoting ice–ash charging. The eruption column must reach a height coinciding with the local −10°C or −20°C isotherm to achieve volcanogenic ice nucleation (Cimarelli and Genareau, 2022).

Case Study

Lightning has been observed in post-blast dust clouds above the open pits of the iron-ore mines between the towns of Kathu and Postmasburg, in the Northern Cape province of South Africa. The phenomena are noticed more often during the spring and early summer months.

Climate

The climate of the Kalahari in South Africa is described as semi-desert. According to the Köppen and Geiger classification, the Kathu area is classified as BSh. Summer occurs from December to March and winter from June to September. Rainfall mainly occurs during the late summer and autumn months. The months with the highest and lowest relative humidities are April (49.82%) and October (25.41%), respectively (Climate-data.org). Cloud cover varies with the seasons, with least cloud cover during July and most cloud cover during October: overcast weather is present between September and April (weatherspark.com). Most wind is experienced in the period from July to December, dominated by northernly winds, with calmer conditions from January to June (weatherspark.com).

Geological setting and ore mineralogy

The iron-ore mines are developed in the Asbesheuwels Subgroup iron formation on the Maremane Dome, between Sishen and Postmasburg (Smith and Beukes, 2016). High-grade banded-iron formation (BIF)-hosted (> 60 mass%) iron hematite ore deposits developed mainly by supergene and/or hydrothermal leaching of silica from the iron formation host rock under oxidizing conditions. High-grade hematite iron ores only develop in areas where unconformity transects the BIF (Smith and Beukes, 2016). The BIF is a sedimentary deposit that consists of alternating thin layers of iron oxides, mainly hematite and magnetite with silicate chert and subordinate shale.

Open-pit blasting

The open-cast mining method is employed by the iron ore mines in this region. This requires regular drilling and blasting of waste lithologies and ore in the pit. This method fragments the ore and liberates large volumes of dust.

Open-pit post-blast dust cloud lightning

Huang et al. (2019) modelled the post-blast dust particles, showing that these settle at different rates depending on their size. The study found that gases rapidly propel the blast fragments into the air and the dust particles then settle from the dust cloud. The rate of settling of the dust cloud is also affected by the prevailing wind velocity, which causes diffusion over a large surface area. It was found that dust with a particle size of approximately 250 µm reached the ground after about 30 s. Particles with a size range of 60–100 µm settled slowly; those with a particle size below 40 µm settled with difficulty due to disturbance by air flow.

Post-blast dust cloud lightning

It is suggested that the lightning observed in post-blast dust clouds results from a combination of the mineralogical composition of the ore, the fragment sizes and shapes of the suspended dust, and the prevailing weather conditions at the time of the blast.

These mines mainly comprise contrasting ore and gangue minerals, i.e., iron oxides and silicate oxides. Blast fragmentation of the ore produces a dust consisting of the ore mineral fines, driven turbulently upwards by hot blast gases. The resulting fines tend to produce angular fragments, which collide and rub against each other during the upward turbulent movement, resulting in fracto-electrification of the dust particles. The mass difference between the silicate and iron oxide minerals, along with their size difference, results in these particles dropping out of suspension at different rates from the dust cloud. The lighter silicate (chert) tends to develop piezoelectric charges along the sharp edges of the fragments.

It is suggested that the heavier iron oxide and large particles will fall out of suspension faster along the centre of the blast cloud, while the finer material and preferential chert fines fragments will dissipate towards the top and edges of the dust cloud. It is also reasonable to suggest that the post-blast heat-retention capacity difference between the iron oxides and silicates will be sufficient to create a notable temperature gradient.

The more-frequent observation of post-blast dust cloud lightning in the spring and summer months suggests that a minimum moisture content is required and the ambient air temperature needs to be moderate (relative to the extreme cold of winter and heat of summer in the Kalahari) to increase the potential for lightning to develop. The short-lived nature of post-blast dust clouds also preferentially requires a wind-free day to ensure that the dust cloud does not dissipate too quickly.

If all these conditions are favourably combined, a large enough opposite ionic charge difference may develop between the top, centre, and bottom of the post-blast dust cloud, resulting in the development of localized lightning strikes (Figure 1).

Conclusion

The occurrence of post-blast dust cloud lightning is suggested to occur as the result of a combination of three factors. The first is the composition of the mineral species liberated by the blast: the more susceptible the mineral is to generating a charge due to friction, the more likely it is to develop a sufficiently high charge to induce a lightning strike. The second is the size and shape of the fines that are suspended in the air. The third factor is the prevailing meteorological conditions, specifically relating to the presence of moisture in the atmosphere at the altitude of the dust cloud and a lack of wind.

Future work

Future work will focus on collecting settling dust samples from post-blast dust clouds when lightning was observed. The collected samples will be studied to determine the presence or absence of lightning-induced spherules using scanning electron microscopy. The prevailing meteorological conditions on the days that post-blast dust cloud lightning is observed need to be recorded in more detail.

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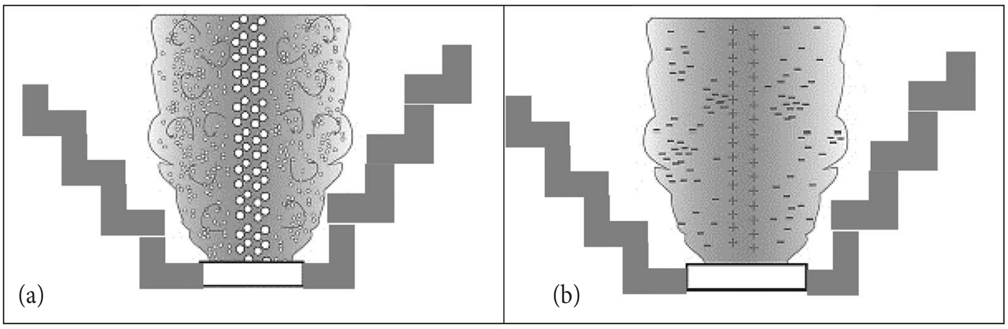

Figure 1—Turbulent post-blast cloud. (a) Heavy fines fragments drop from suspension in the centre of dust cloud and lighter fines fragments dissipate to the edges. (b) Development of positive centre and negative edge charge zones (modified after Cimarelli and Genareau, 2022)

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