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Prospectus for the Characterisation of Airborne Particulates

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Background

The recent increase in cases of Silicosis and Coal Worker's Pneumoconiosis (CWP) in coal mines has brought attention to the management of worker exposure to particulate matter in all mining sectors [1].

While there is already a considerable body of knowledge regarding the impact of particulate matter on human health [2]. There are still significant gaps in our understanding. These gaps pertain to the role of mineralogical constituents in dust, which contribute to adverse health effects [3]. Furthermore, evidence suggests that the size and shape of particulate matter can also influence its potential impact on human health.

At the University of Queensland, we have developed a scanning electron microscopy methodology for characterizing respirable and inhalable dust samples. We have successfully analysed multiple samples from various mining operations, including coal mines, metal mines, and smelters, using this methodology. Through this process, we have been able to identify the mineralogical components and particle size distributions present in different areas of the mines.

Currently, the University of Queensland's Minerals Industry Safety and Health Centre (MISHC) is conducting a research program that utilizes these developed techniques to support ongoing efforts in reducing the adverse effects of particulates on worker health. Figure 1 provides an example of the false colour images of individual particles and their mineralogies, while Figure 6 provides detailed information of the individual particles in the red box.

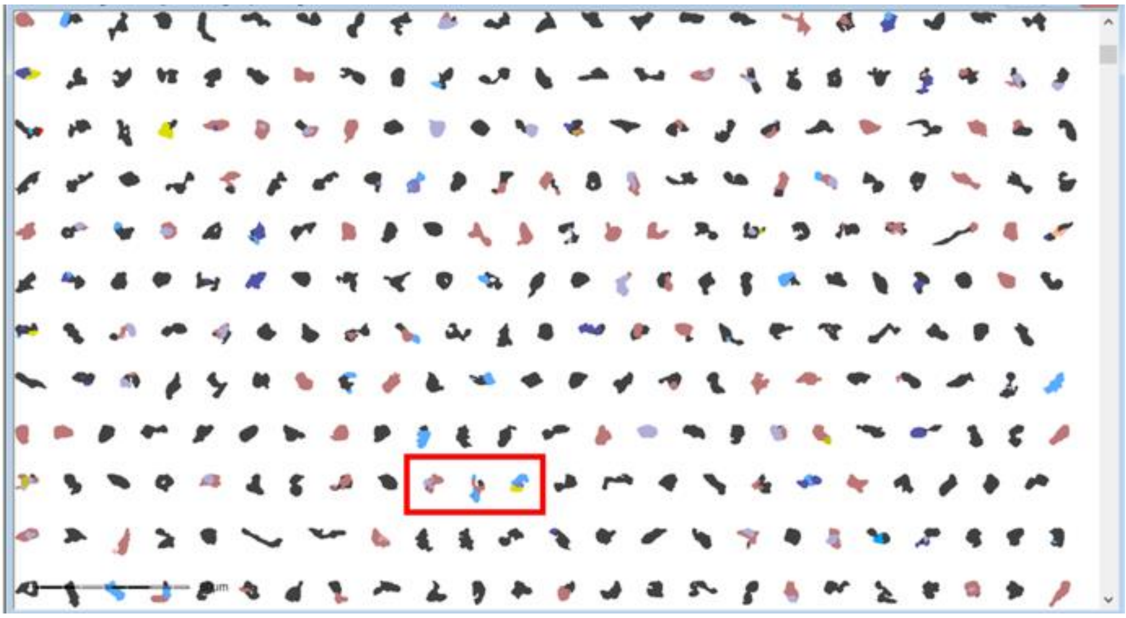


Figure 1- False colour images of particles analysed by the Minerals Liberation Analyser

There is limited understanding among mine workers in open-cut operations (coal, metals, and quarries) regarding their exposure to respirable dust. Only recently have researchers and regulators started collecting industry-wide exposure data to gain a better understanding of the level of risk faced by workers. Furthermore, it is now recognized that discussing particulate matter in general terms is insufficient, as both size and mineralogical content can impact the potential adverse consequences of exposure. In broad terms, four categories of concern have been identified: inhalable dusts, respirable dusts, fine particles (including diesel emissions), and ultrafine particles.

Various mine dust lung diseases are now being diagnosed, including chronic obstructive pulmonary disease (COPD), silicosis, mixed dust pneumoconiosis, coal worker's pneumoconiosis, and Progressive Massive Fibrosis. While some basic characterization work was conducted in the 1980s, significant technological advancements since then have allowed for a much more detailed analysis of the composition of dust and its associated health hazards [4, 5]. The sampling methodology employed by the authors offers two key advantages: sampling respirable dust in real mining conditions and the ability to obtain data on individual particles, rather than just the entire sample.

Sample Collection

The University of Queensland's Minerals Industry Safety and Health Centre (MISHC) offers two options for sample collection: mines can collect the samples themselves using provided instructions, or MISHC staff can visit the mine and collect the samples on-site. The collection process allows for both respirable and inhalable sampling, and a combination of both methods can also be performed. Additionally, paired sampling can be conducted in both the respirable and inhalable fractions to compare the composition of the dust.

Figure 2a presented below, displays four sampling trains mounted inside the sampling frame, while Figure 2b illustrates the sampling frame attached to a piece of equipment for capturing dust generated during mining activities.

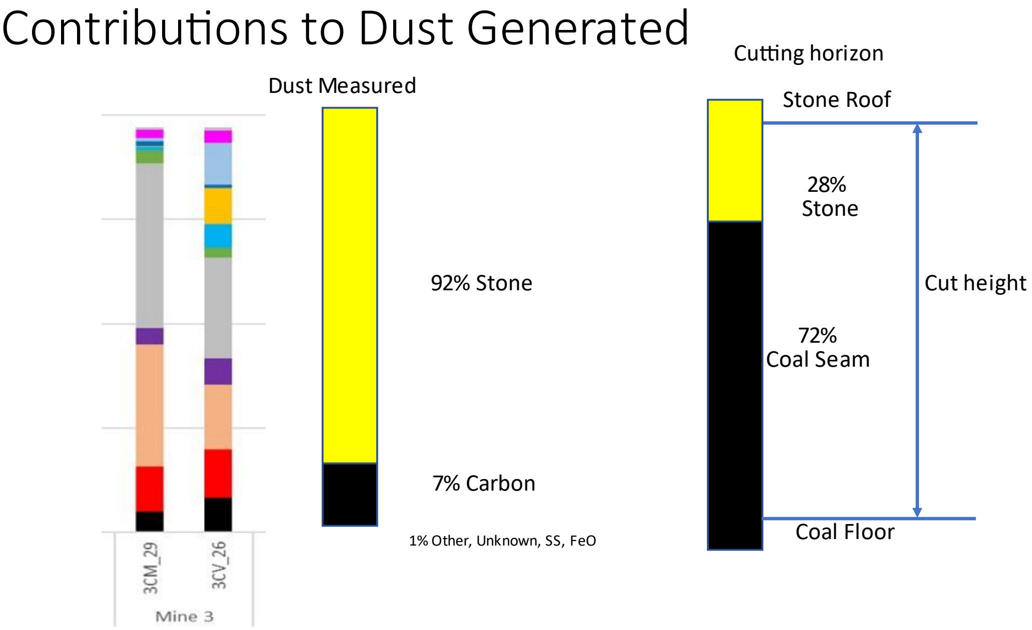
For respirable sampling, MISHC follows the principles outlined in AS2985 [6] and utilizes specialized polycarbonate filters that are well-suited for microscopy analysis instead of the traditional PVC gravimetric filters. Inhalable sampling can be performed using either the IOM sampler or by directly sampling into the polystyrene cassette. Typically, samples are taken at static locations to gather information about the various sources generating the dust. However, personal sampling can also be conducted.

In contrast to historical characterization methods that involved collecting bulk samples from the mines and crushing them for analysis, our approach addresses the challenges encountered in crushing coal to the desired size fraction. This raises an intriguing paradox: if obtaining specific size fractions is difficult, does the rock naturally break up into those size fractions under real-world conditions?

Figure 2- a) Respirable Cyclone Array on Frame b) Cyclone Array Mounted to Continuous Miner [7]

Sampling in Actual Mining Conditions

In coal mines, there are multiple sources of dust besides the cutting of the coal seam. These include vehicle traffic, mining of roof or floor rock, rider seams, stone dusting activities and other mining-related activities such as shovelling. y conducting sampling in actual mining conditions, we capture contributions from all these sources, which can be significant in certain cases.



Sample Locations

Sampling can be conducted in various locations to characterize the primary sources of dust generation. The specific locations will vary depending on the mining method and the desired information from the survey. Here are some examples of potential areas and activities to sample based on different mining types:

Underground Coal Mines: maingate and midface of the longwall, continuous miners, shuttle car, vehicle traffic, conveyors and transfer points, and during secondary recovery activities.

Underground Metals Mines: drilling and blasting activities, around crushers, conveyors and transfer points, return airways, haul roads.

Surface Mines and Quarries: drilling and blasting, overburden removal, haul roads, crushing and screening, stockpiles, storage areas, and loading operations.

Smelters: raw material handling, crushing and grinding, furnace operations, slag handling, material transport and transfer, fugitive dust and cleaning processes.

Engineered Stone Benchtops: cutting, trimming, shaping, profiling, grinding, sanding, polishing, fugitive dust, maintaining dry dust collection systems, workshop clean-up activities.

Filter Loading

The number of particles analysed can vary significantly depending on the amount of dust collected on the filter and the portion of the filter is that is analysed. Figure 3a illustrates different levels of particle loading on the filters. To prevent filter overload, sampling is typically conducted for short durations, usually lasting only an hour or two. Overloading occurs when there is insufficient space between particles to differentiate them under the microscope. Detecting overloading is usually straightforward by examining the overall particle size distribution curve.

To date, we have analysed up to 758,000 particles on a single filter. However, for the sake of time and cost efficiency, representative samples can be obtained by taking smaller punches from the filter, as shown in Figure 3b. This approach allows us to derive valuable insights without analysing the entire filter, saving resources while still maintaining the integrity of the analysis.

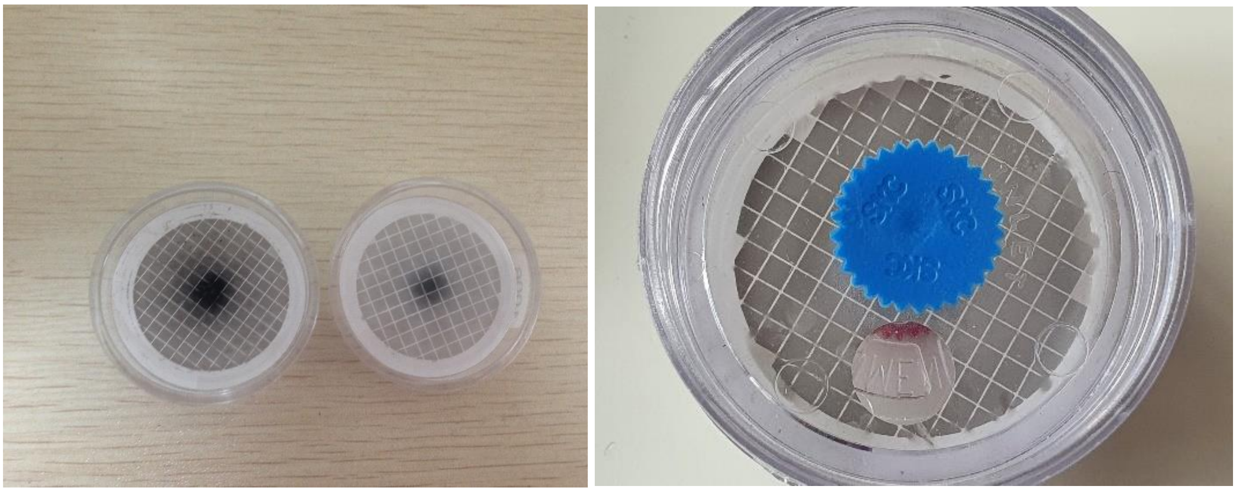


Figure 3- a) Varied Levels of Particle Loading on Filter b) Hole Punched out of Filter for Analysis

Mineral Liberation Analyser Analysis

Several papers have been published documenting the results of the previous sampling campaigns which were analysed on the Mineral Liberation Analyser (MLA) at the Julius Kruttschnitt Mineral Research Centre, at The University of Queensland [8].

This data obtained from these analyses has revealed that the airborne particles are more complex than originally assumed. The particles look to be agglomerating at this small size producing multiple mineralogies in one particle, termed microagglomerates, not just particles of single mineralogies like was initially thought.

The MLA provides valuable information about the airborne particulates including:

- Mineral abundance: Identifying the types of minerals present in each particle.
- Map of mineral abundance: Locating the different mineralogies within the particles and mapping them.
- Particle size: Measuring the length, width, and equivalent circle diameter of each particle.
- Particle size distribution: Assessing the size distribution of individual mineralogies and overall.
- Particle shape: Analysing the shape of particles, including the aspect ratio.

Relative Mineral Abundance

Figure 4 shows the relative mineral abundance of samples from eight underground coal mines. There are up to 35 different mineralogies identified in the samples, with the top 12 presented here for simplicity. Some mines exhibit high percentages of carbon in their samples. Mine 6 also contains a significant amount of carbon, except for the sample taken at the midface of the longwall. In that specific sample, the mining activities encountered a calcite lens, which became the dominant contributor to the generated respirable dust. The presence of the calcite lens overrides the carbon as the primary mineralogical component in this case.

Mines 3 and 4: Conversely, Mines 3 and 4 demonstrate minimal carbon content but significant amounts of stone, particularly quartz, muscovite, and orthoclase. The bright pink colour represents the presence of pyrite in the seam, while the red represents the silica.

It is noteworthy that the samples with the highest percentages of silica in the seam are derived from mines with a larger proportion of stone. This observation suggests that the stone, rather than the coal itself, is the primary source of silica in these cases.

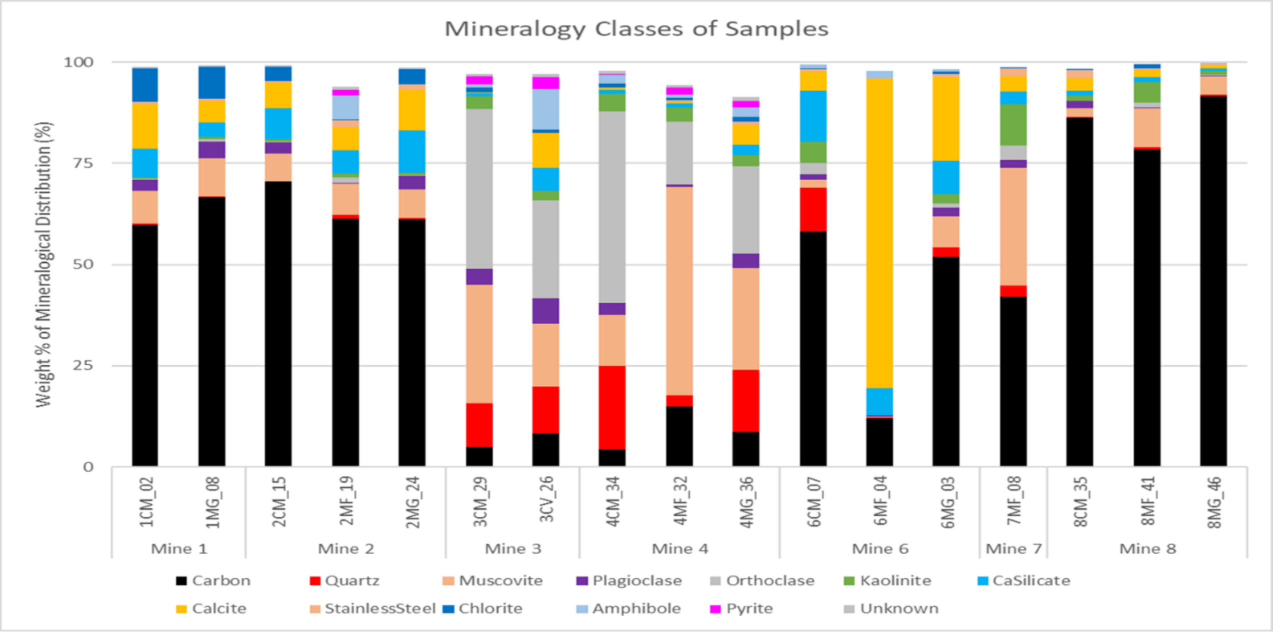


Figure 4- Relative Mineral Abundance of Samples [8]

Relative Contributions to Respirable Dust

To illustrate the contrasting contributions of the coal seam and stone to the respirable dust, let's compare the makeup of Mine 3's seam with the dust being generated. Despite the coal seam occupying 72% of the cut height, the average carbon content in these two samples is only 7%. On the other hand, although stone is being extracted from the roof and represents 28% of the cut height, it accounts for a striking 92% of the dust collected on the filter.

This example highlights the significant disparity in the contributions of the coal seam and stone to the respirable dust. US data from central Appalachia further supports this finding, revealing that, on average across their mines, stone contributes approximately twice as much to the respirable fraction compared to coal.

These observations underscore the importance of considering the specific mineralogical composition of the dust sources, recognizing that stone can play a substantial role in generating respirable dust, even surpassing the contribution from the coal itself.

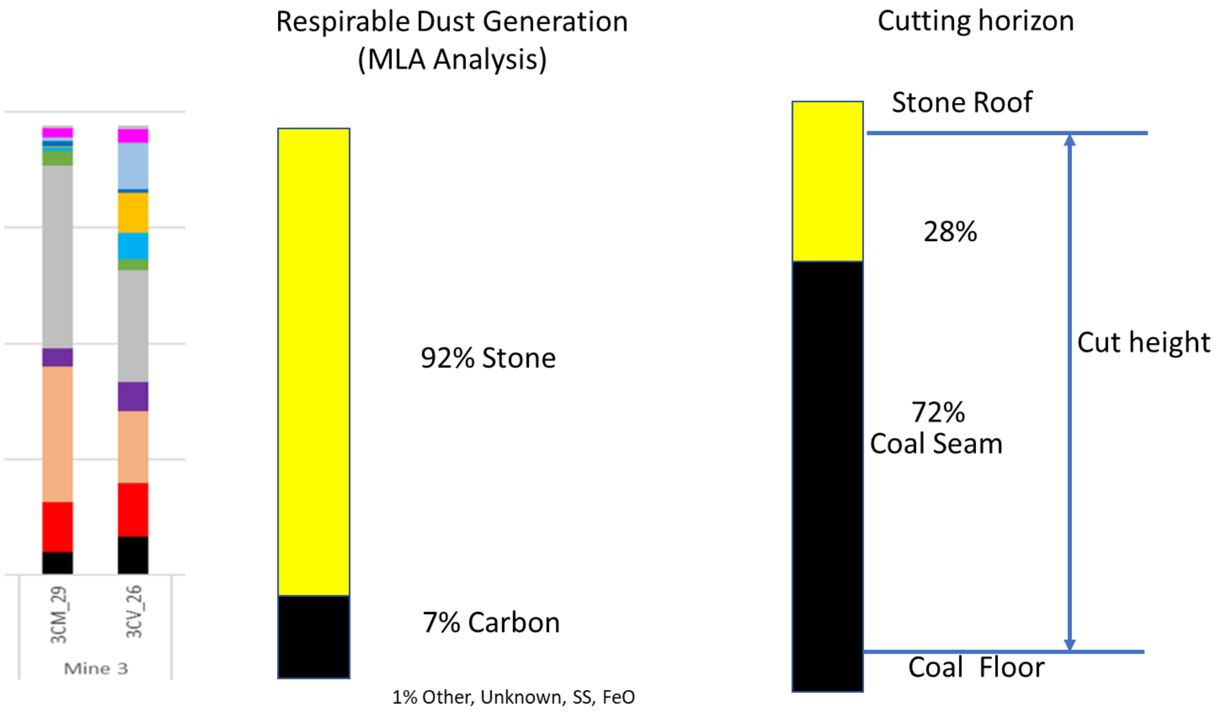
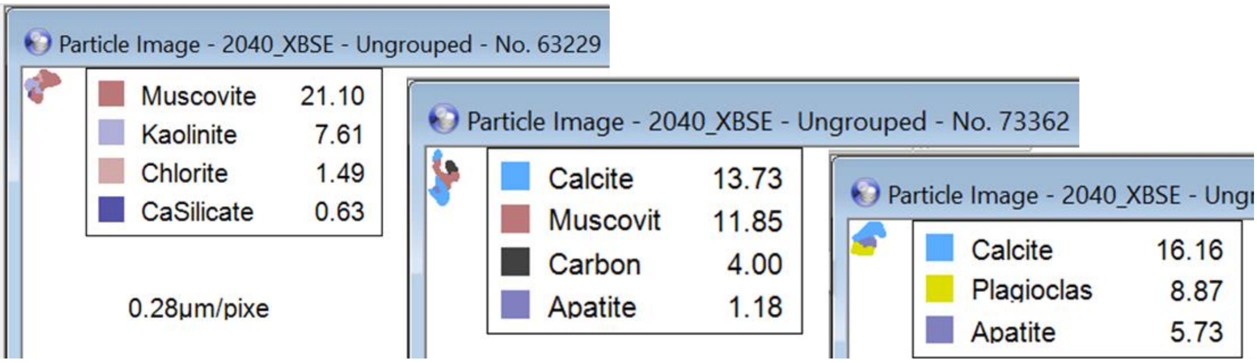


Figure 5- Relative Contributions to Respirable Dust for Mine 3

Map of Mineral Abundance

Figure 6 displays three individual particles within the red box shown in Figure 1. The MLA analysis enables us to identify different portions of the particles corresponding to specific mineralogies and map them accordingly. The numbers next to each mineralogy represent the area of the particle occupied by that particular mineralogy. By applying densities to the various mineralogies, we can calculate the weight of each mineralogy and derive an overall mass for the particle.



Particle Image - 2040_XBSE - Ungrouped - No. 63229

🟥	Muscovite	21.10
🟪	Kaolinite	7.61
🟥	Chlorite	1.49
🟦	CaSilicate	0.63

0.28µm/pixe

Particle Image - 2040_XBSE - Ungrouped - No. 73362

🟦	Calcite	13.73
🟥	Muscovit	11.85
⬛	Carbon	4.00
🟪	Apatite	1.18

Particle Image - 2040_XBSE - Ung

🟦	Calcite	16.16
🟨	Plagioclas	8.87
🟪	Apatite	5.73

Figure 6- Example of MLA data on individual particles on filter

Particle Images Filtered by Mineral Abundance

The MLA data can be filtered to target various mineralogies present in the samples.

Figure 7 illustrates an example of such filtering, focusing on particles containing more than 25% silica. The legend in Figure 8 provides a false-color representation of the particles, with silica highlighted in bright yellow.

Figure 7 showcases the diverse shapes and mineralogies present in the samples, sorted in descending order of particle size. Many silica particles exhibit complex mineralogies as microagglomerates. The modal mineralogy report in Figure 8 reveals that, in this case, carbon is the next most abundant mineral, accounting for 18% of the particles, followed by calcium silicate, kaolinite, and orthoclase, each comprising 4%, 2%, and 2%, respectively.

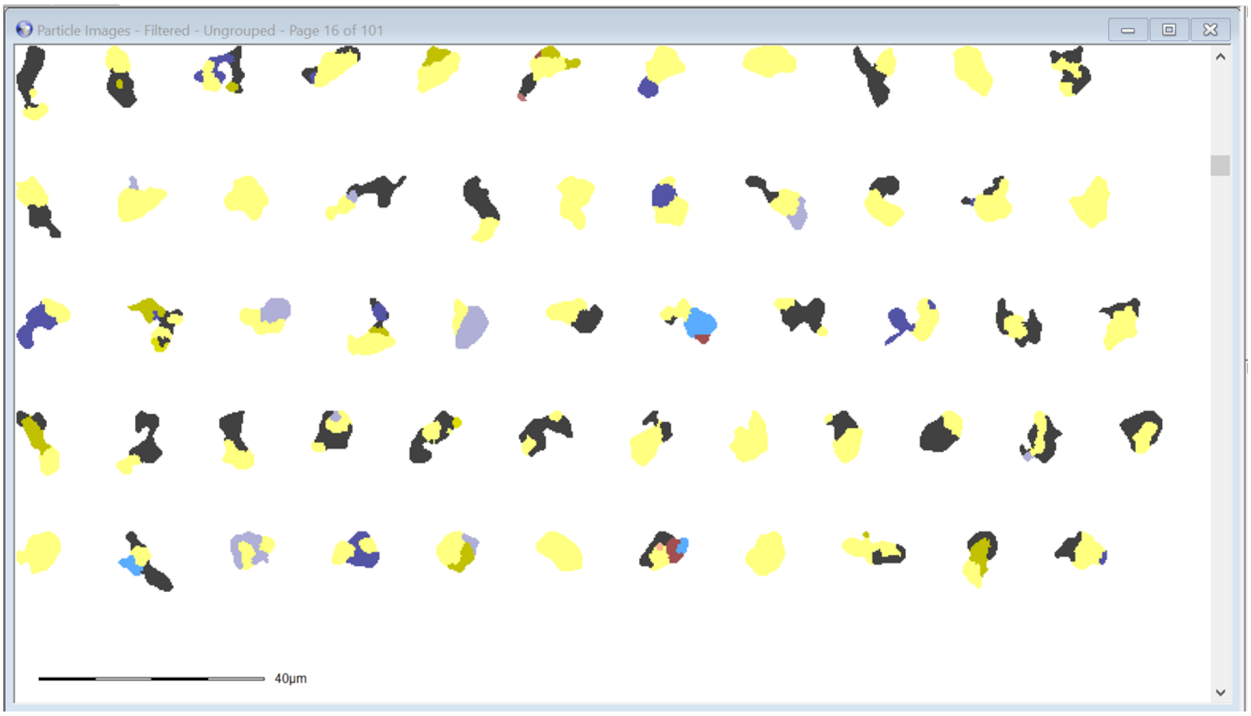
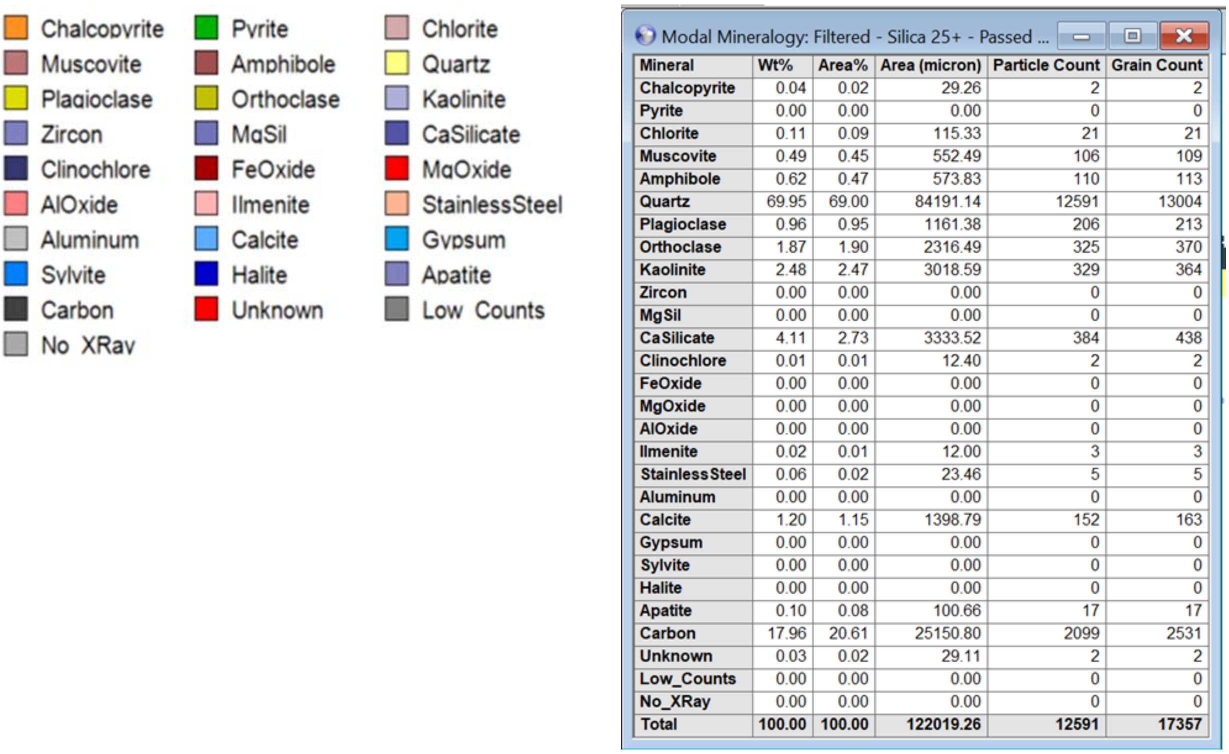


Figure 7- Images Particles containing >25% Silica Generated by the Minerals Liberation Analyser



■ Chalcopyrite
■ Muscovite
■ Plagioclase
■ Zircon
■ Clinochlore
■ AlOxide
■ Aluminum
■ Sylvite
■ Carbon
■ No XRay

■ Pyrite
■ Amphibole
■ Orthoclase
■ MgSil
■ FeOxide
■ Ilmenite
■ Calcite
■ Halite
■ Unknown

■ Chlorite
■ Quartz
■ Kaolinite
■ CaSilicate
■ MgOxide
■ StainlessSteel
■ Gypsum
■ Apatite
■ Low Counts

Modal Mineralogy: Filtered - Silica 25+ - Passed ...

Mineral	Wt%	Area%	Area (micron)	Particle Count	Grain Count
Chalcopyrite	0.04	0.02	29.26	2	2
Pyrite	0.00	0.00	0.00	0	0
Chlorite	0.11	0.09	115.33	21	21
Muscovite	0.49	0.45	552.49	106	109
Amphibole	0.62	0.47	573.83	110	113
Quartz	69.95	69.00	84191.14	12591	13004
Plagioclase	0.96	0.95	1161.38	206	213
Orthoclase	1.87	1.90	2316.49	325	370
Kaolinite	2.48	2.47	3018.59	329	364
Zircon	0.00	0.00	0.00	0	0
MgSil	0.00	0.00	0.00	0	0
CaSilicate	4.11	2.73	3333.52	384	438
Clinochlore	0.01	0.01	12.40	2	2
FeOxide	0.00	0.00	0.00	0	0
MgOxide	0.00	0.00	0.00	0	0
AlOxide	0.00	0.00	0.00	0	0
Ilmenite	0.02	0.01	12.00	3	3
StainlessSteel	0.06	0.02	23.46	5	5
Aluminum	0.00	0.00	0.00	0	0
Calcite	1.20	1.15	1398.79	152	163
Gypsum	0.00	0.00	0.00	0	0
Sylvite	0.00	0.00	0.00	0	0
Halite	0.00	0.00	0.00	0	0
Apatite	0.10	0.08	100.66	17	17
Carbon	17.96	20.61	25150.80	2099	2531
Unknown	0.03	0.02	29.11	2	2
Low_Counts	0.00	0.00	0.00	0	0
No_XRay	0.00	0.00	0.00	0	0
Total	100.00	100.00	122019.26	12591	17357

Figure 8- Mineralogy Colour Legend and Modal Mineralogy Report for particles >25% Silica

Overall Particle Size Distributions

The MLA analysis enables the calculation of overall size distributions of the dust based on individual particles, with measurements reflecting actual particle diameter rather than aerodynamic equivalent diameter (AED). In the coal mines, a general pattern emerges regarding the particle size distributions across different areas. The midface of the longwall tends to exhibit the finest particle size distribution, while the maingate shows a somewhat coarser distribution, and the continuous miner section displays the coarsest distribution. **Figure *9*** provides an illustrative example of this trend, where SR refers to Secondary Recovery, MG to Maingate, MF to Longwall Midface, and CM to Continuous Miner. These variations in particle size distributions may indicate the number of particles a person would inhale for a given mass of dust. For instance, the longwall section would likely contain a higher number of small particles compared to the continuous miner section. Consequently, the longwall particles would also possess a larger surface area in relation to the coarser particles found in the continuous miner section.

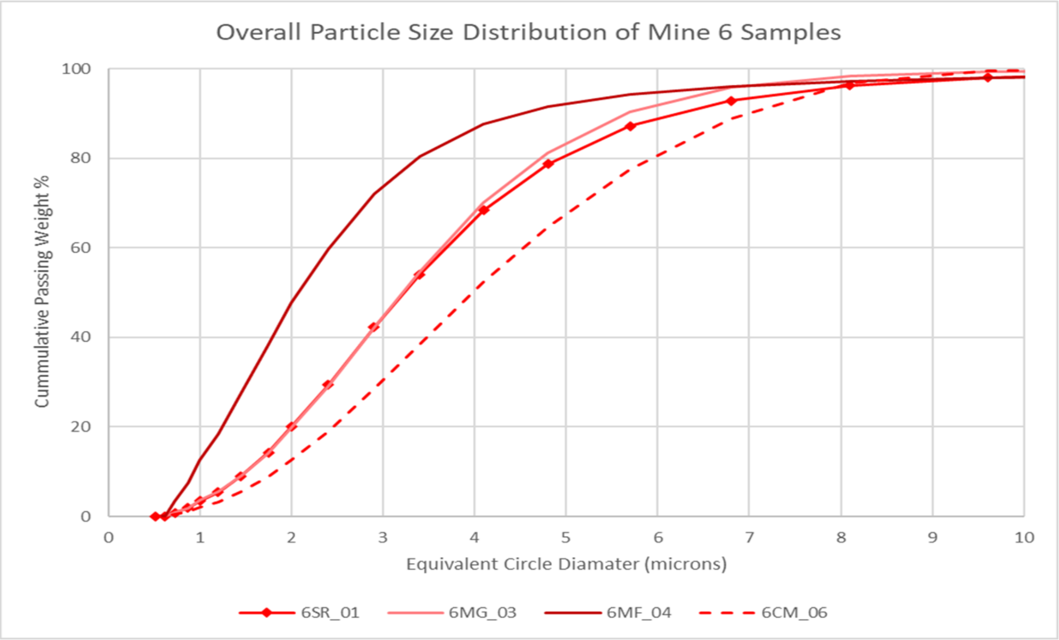


Figure 9- Overall Particle Size Distributions of Samples at Various Locations [8]

(SR= Secondary Recovery, MG= Maingate, MF= Longwall Midface, CM= Continuous Miner)

The MLA characterisation technique offers the advantage of obtaining multiple parameters for individual particles on the filter, surpassing the capabilities of historic characterisation methods. Previous techniques only allowed for the calculation of an overall particle size distribution (PSD) and the determination of the relative abundance of specific minerals. However, with MLA data on individual particles, it becomes possible to calculate PSDs for various mineral components. For instance, the PSD of quartz alone can be assessed *separately.*

Figure *10* showcases the PSDs for eight mineralogies in the sample. Notably, carbon exhibits the coarsest PSD due to the presence of oversize particles on the filter. On the other hand, the particle size distribution of quartz, depicted in red, represents one of the finest distributions in this particular sample.

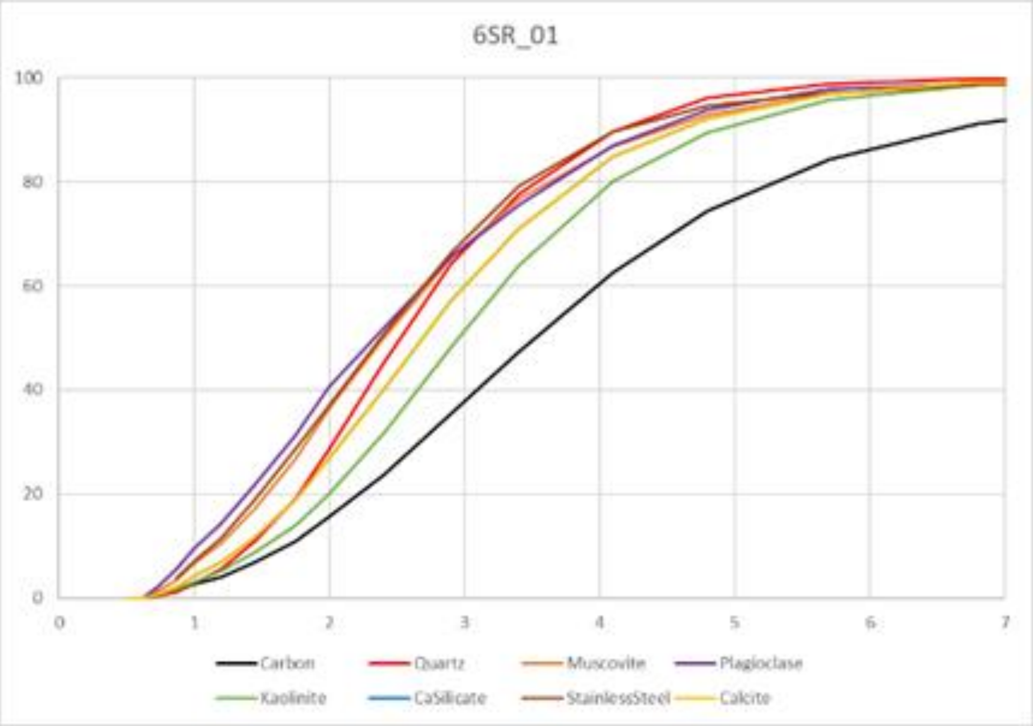


Figure 10- Particle Size Distribution of Various Mineralogies in Sample [8]

Dust Suppression Effectiveness and Particle Size Distribution

Figure 11 demonstrates a trial conducted to assess the efficacy of dust suppression measures in a metals mine. The dashed lines represent the particle size distribution of dust generated by the crusher without any dust suppression employed. The black dashed line represents the overall particle size distribution, while the red line specifically indicates the particle size distribution of silica. Subsequently, additional measurements were taken while implementing dust suppression to evaluate its impact. In this case, the overall particle size distribution exhibited a slight coarsening, as depicted by the solid black line. Notably, the dust suppression system effectively reduced the presence of fine quartz particles, resulting in a coarser quartz fraction. Through MLA analysis, this assessment can be extended to various mineralogies, enabling a comprehensive evaluation of dust suppression effectiveness.

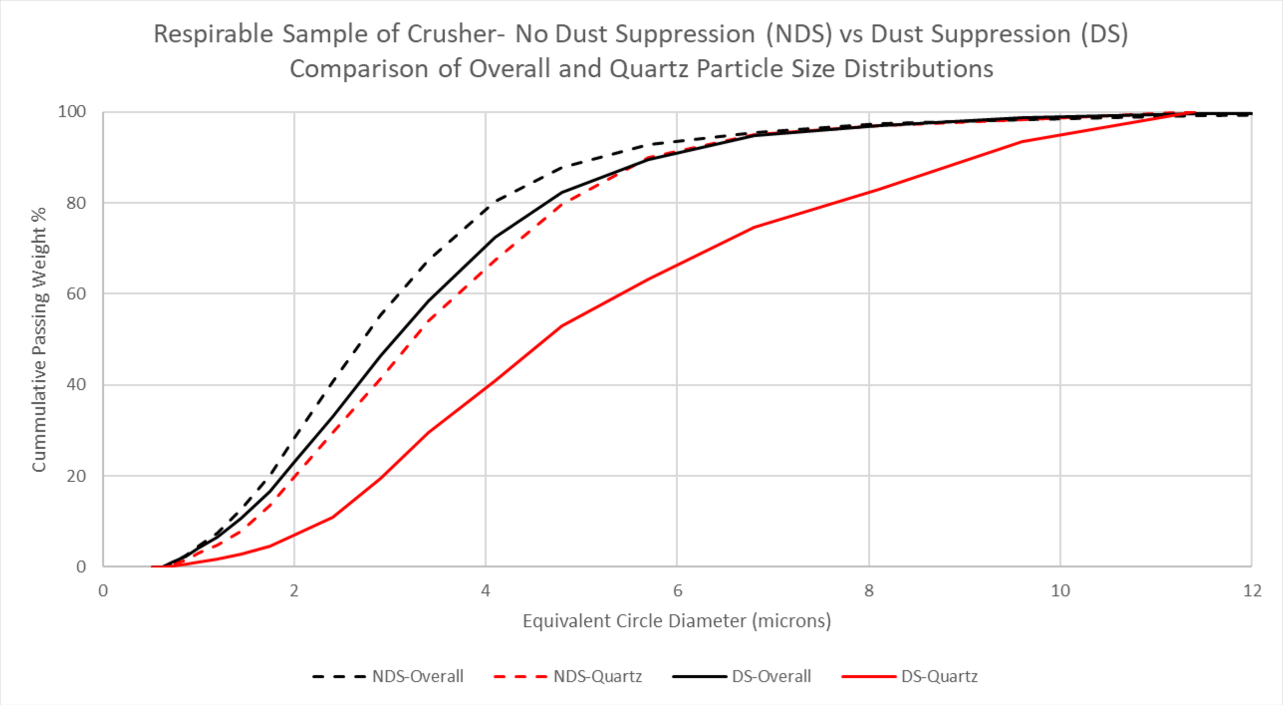


Figure 11- Change in Overall and Silica Particle Size Distribution due to Dust Suppression

Why Characterisation?

The significance of dust characterization goes beyond simple gravimetric sampling in determining the associated health hazard. A mass measurement alone fails to account for the potential risks posed by dust particles with smaller particle size distributions (PSDs) and greater surface areas, which can penetrate deeper into the lungs. Conversely, a dust sample with a larger PSD would contain fewer particles, less surface area, and reduced lung penetration.

Moreover, it is crucial to recognize that certain mineralogies exhibit higher toxicity levels than others. While silica content is typically the only mineralogy tracked separately in coal mines,

Figure 7 highlights the intricate nature of silica particles, which can form complex microagglomerates and may be associated with diesel particulate matter (DPM) and various other mineralogies.

The United States has extensively documented regional disparities in the prevalence of coal worker's pneumoconiosis (CWP). Graph A, in Figure 12, illustrates the overall CWP rates across the entire US, while Graph B focuses specifically on central Appalachia (comprising Kentucky, Virginia, and West Virginia). Notably, CWP rates have been on the rise in central Appalachia, with the third graph depicting the US excluding this region, showing only a slight increase among the cohort. Underground miners in central Appalachia experience a four-fold higher prevalence of CWP compared to long tenured underground miners elsewhere in the US. Alarmingly, one in 20 long tenured miners in central Appalachia has progressed to progressive massive fibrosis (PMF), despite adherence to the 1.5 mg/m³ exposure standard and the use of continuous personal dust monitoring technology underground [9].

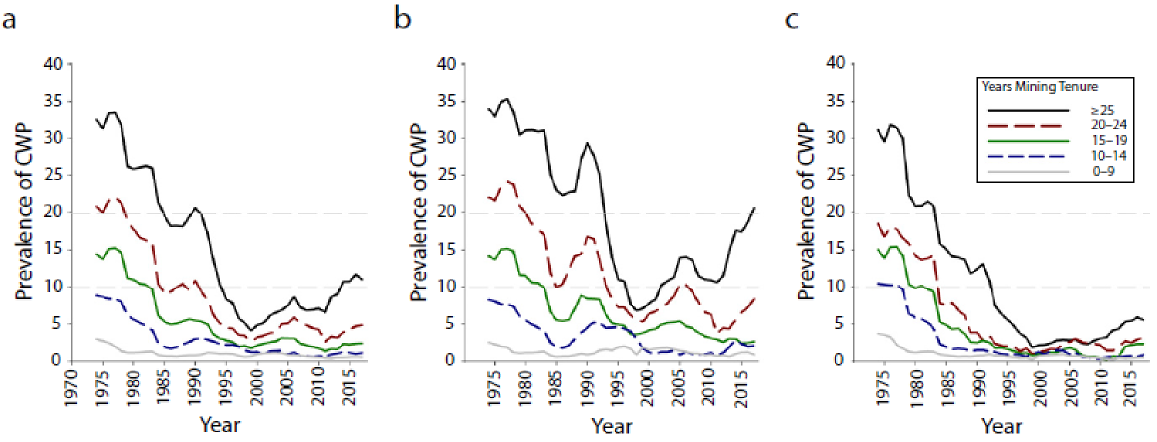


Figure 12: Prevalence of coal workers pneumoconiosis in the US by region a: All US b: Central Appalachia only c: All US less Central Appalachia [9]

These regional discrepancies emphasize that different coals present varying health hazards and that simplistic gravimetric sampling may fall short in monitoring and mitigating future health risks. A comprehensive understanding of dust characterization and its correlation with health hazards is imperative. Ongoing studies are currently exploring the relationship between dust characterization and its impact on lung tissue through extensive research.

Recognizing the limitations of gravimetric sampling, the future of dust monitoring demands more detailed analysis of dust exposures to enhance worker protection. Comprehensive characterizations encompassing the size, shape, and chemical composition of dust particles can provide valuable insights into the associated health hazards. Establishing a comprehensive database of exposure characterizations is essential across industries with high dust hazards, including coal mines, metal mines, quarries, engineered stone facilities, and construction sites. This data-driven approach will contribute to improved hazard assessment and enable the development of more effective preventive measures.

The Research Team

The multidisciplinary team comprising key personnel from The University of Queensland's Minerals Industry Safety and Health Centre (MISHC) are well placed to deliver this type of research. The University of Queensland is a research-intensive institution in the top 50 universities worldwide. It employs well regarded academics and researchers including the project team. Project personnel will include the following researchers who have specific expertise in this field:

Nikky LaBranche – BSc (Mining Engineering) MBA, PMP, PE RPEQ is a Research Fellow in the Minerals Industry Safety and Health Centre, Sustainable Minerals Institute, University of Queensland. She brings prior research experience from previous roles at the National Institute for Occupational Safety and Health (NIOSH, US) and Simtars. Ms LaBranche is currently pursuing her PhD entitled "Characterising the Impact of Dust on the Respiratory Health of Coal Mine Workers" where she is looking at the chemical composition, particle size distribution and shape of dust particles including RCS. She has been awarded the prestigious AusIMM Education Endowment Fund Post-graduate scholarship for the duration of her degree. She also has experience running comparative trials of real-time monitoring devices for respirable dust. Ms LaBranche will be responsible for the sample collection and reporting for this project.

Dr Kelly Johnstone, PhD – MSc (OHP), BAppSc (OHS) (Honours), is a Senior Lecturer in the School of the Environment, Faculty of Science, The University of Queensland. Dr Johnstone is a certified occupational hygienist (COH®) with the AIOH and certified chartered occupational health safety professional (ChOHSP) with the AIHS. She is actively involved with both professional societies (AIOH and AIHS) and has served in several roles including her current appointments as member of the AIOH Professional Development and Education Committee and AIHS representative on the Australian OHS Education and Accreditation Board (AOHSEAB). She brings to the team over 20 years of industry and academic experience in the fields of occupational hygiene and occupational health and safety science. Dr Johnstone has experience across a number of industry sectors including construction, manufacturing, agriculture, energy and resources.

Dr David Cliff, PhD – Professor of Occupational Health and Safety in Mining, Minerals Industry Safety and Health Centre, Sustainable Minerals Institute, University of Queensland. Dr Cliff brings considerable Australian and international expertise to the project. Dr Cliff has extensive knowledge of data sets regarding exposures and occupational risks through his work at the Sustainable Minerals Institute and his membership in numerous professional organizations.

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