FINAL REPORT

1.0 Cover Page

Grant Number and Title**:** I#0036699 **–** AFC113-11: Connecting Dust Characteristics and Worker Health in Underground Coal Mining

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Full Period of Performance: November 1, 2013 - April 30, 2017

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Abbreviations, Units, and Acronyms

- Coal workers' pneumoconiosis (CWP)
- Central Appalachia (CA)
- South Central Appalachia (SCA)
- Mid-Central Appalachia (MCA)
- Northern Appalachia (NA)
- Thermogravimetric analysis (TGA)
- Scanning Electron Microscopy with Energy Dispersive X-ray (SEM-EDX) Spectroscopy
- Coal Mine Health and Safety Act (CMHSA)
- National Institute for Occupational Safety and Health (NIOSH)
- United Mine Workers of America (UMWA)
- Time weighted average (TWA)
- Forced vital capacity (FVC)
- Forced expiratory volume in 1 second (FEV1)
- Pulmonary function test (PFT)
- Forced expiratory flow 25% to 75% (FEF_{25-75})
- American Thoracic Society (ATS)
- Body mass index (BMI)
- High blood pressure (HBP)
- Tiffeneau-Pinelli (TP)

Executive Summary

Problem Statement and Justification: Recent observations that indicate increased incidence of coal workers' pneumoconiosis or other lung disease, particularly among young miners in Central Appalachia (CA), have raised many questions over both the cause(s) for these concerning trends and potential strategies for combating them. On August 1, 2016, the federal Mine Safety and Health Administration (MSHA) issued the new rule that lowered respirable coal dust concentration limits from 2 mg/m^3 to 1.5 mg/m^3, but this approach has been met with skepticism since factors beyond excessive dust *concentrations* may be contributing to disease. In fact, little is known about the influence of specific dust *characteristics* and associated exposure patterns on lung disease in underground coal miners. Research is urgently needed in this area, as only with a more complete understanding of such relationships can effective mitigation strategies be developed to improve outcomes for miner health.

Research Approach: The specific goal of this study was to comprehensively evaluate characteristics of occupational dust exposures and associate these data with miner lung function. Multiple underground coalmines in the CA and Northern Appalachia (NA) region (between northern WV and southwestern PA) were included to provide access to a range of mining-specific factors of interest and to a cohort of miners. In CA, two distinct sub-regions were included, “Mid-Central Appalachia” (MCA; near Beckley, WV) and “South Central Appalachia” (SCA; near Logan, WV). The two major aims of the three-year project of intensive field study were: 1) comparison of respirable dust exposure characteristics across and within mine regions and between particular sampling locations that represented different working environments in a mine (VT); and 2) associations of lung function (measured by pulmonary function tests (PFT)) and personal risk factors with respirable dust exposure characteristics (UPitt).

Results: 210 area dust samples were analyzed by scanning electron microscope with energy dispersive x-ray (SEM-EDX). The percentages of carbonaceous (i.e., coal) particles were typically low (i.e., 29% on average). Most of the non-coal particles in the dust samples were alumino-silicates (41% on average) and carbonates (23% on average). Alumino-silicates were higher in MCA and SCA than in NA. Conversely, carbonate proportion was higher in NA than in MCA and SCA. The carbonates, particularly those in NA, may be due to rock dusting. 131 miners participated in the health component of the study and 89 had PFTs. These miners had better than expected PFT results among SCA and MCA participants and worse than expected PFT results among NA participants. Because the study relied on volunteer participation, this likely provides evidence of a self-selection bias.

Accomplishments: Major accomplishments of the project include: Recruited cohort of miners and collected large set of respirable dust samples during period of tremendous industry downturn; Developed and applied thermogravimetric analysis and automated SEM-EDX analysis to gain new insights into dust characteristics; Linked lung function data by region and job name to area dust samples; and Identified potential associations between dust characteristics and lung function worthy of further investigation, particularly in regard to specific dust constituents.

Conclusion: While we were able to robustly analyze many underground dust samples and determine important compositional characteristics, our small, non-representative sample, and uncertainty about the relationship between cumulative lung function as measured by PFT and point-in-time exposure as measured by the sampling led to uncertainties about these results. Overall, many of the associations found are likely to be spurious and should be interpreted with considerable caution.

Expected Impact: This project examined associations between dust characteristics in MCA, SCA, and NA mines and worker lung function, allowing us to contrast mining practices and rock and dust characteristics. The knowledge garnered from this study provided useful information about the impact and composition of the dust characteristics and not solely dust concentrations.

Background

Coal Worker's Pneumoconiosis (CWP) is a chronic occupational lung disease caused by long-term inhalation of respirable coal mine dust, which triggers inflammation of the alveoli and eventually results in irreversible lung damage [1]. Respirable dust generally refers to particles below 4-5 μm, which are able to penetrate the upper respiratory system, while inhalable dust, generally not a serious concern for lung function, is in the 5-10 μm range [2, 3]. CWP ranges in severity from "simple" to "advanced," with the most severe form being progressive massive fibrosis (PMF), which is debilitating and often fatal [1]. Silicosis, caused by exposure to crystalline silica dust, is another occupational lung disease that occurs in miners [1, 4]. Because CWP and silicosis have similar symptoms (e.g., increasingly reduced lung capacity) and are difficult to differentiate on x-ray [5], lung disease in patients with coal mining work history is often diagnosed as CWP [5].

To combat coal mine-related lung disease in the US, the Coal Mine Health and Safety Act (CMHSA) of 1969 implemented a surveillance program for assessing prevalence of disease among coal miners and established a federal exposure limit for respirable dust in underground mines at 2 mg/m^3 [6]. Following CMHSA, the prevalence of CWP declined from 11.2% during 1970–1974 to 2.0% during 1995–1999, before increasing unexpectedly in the last decade [7-11]. While rates among coal miners employed for greater than 25 years are still continuing to decline, miners with less than 25 years of employment tenure now seem to show increasing rates of CWP [12]. At least partly in response to this trend, a reduced 1 mg/m^3 exposure limit was proposed [13]. However, because mines across the US are largely already achieving dust concentrations below 1 mg/m^3 [12], many have questioned whether a reduced limit would actually target the root problem(s) [e.g., 14, 15]. On August 1, 2016, the federal Mine Safety and Health Administration (MSHA) issued the new rule that lowered respirable coal dust concentration limits from 2 mg/m^3 to 1.5 mg/m^3 [16]. The new rule also includes changes to respirable dust *sampling and monitoring* protocols (i.e., in terms of equipment, sampling duration and sample compositing), but no changes have been made regarding *dust metrics*. Only total respirable dust concentrations (i.e., mg/m^3) and silica content (i.e., mass % of respirable dust) in applicable samples are measured.

Increased incidence of CWP appears to be particularly significant in the Central Appalachian (CA) region**,** which includes the coalfields of VA, KY and WV, as compared to other coal mining regions (i.e., Northern or Southern Appalachia, Powder River or Illinois basins) [17]. Investigations have found higher than expected rates of CWP and PMF in CA mines, including among young miners with relatively short tenures [18-26]. Results from these reports are not only alarming because of the high CWP incidence, but also because of the age and experience of the miners involved. Recently, Blackley et al [26] reported the presence of CWP and PMF in miners exposed to rock containing high levels of quartz with potential exposure to respirable crystalline silica.

While it has long been suggested that systematic bias in compliance measurements may underestimate actual dust exposures [27-28], a variety of factors should be considered to explain observations of increased CWP incidence in specific regions (e.g., CA). It is possible that such observations may be purely related to differential disease reporting and diagnostics (e.g., more miners are choosing to be screened for lung disease, screening techniques are more sensitive), but geographic clustering indicates that other mining-specific factors are likely at play, which influence particular dust characteristics and exposures. For instance, the structure and mineralogy of both coal and rock layers may impact the quality (i.e., composition) and quantity of dust to which miners are exposed. Operators in CA are exploiting increasingly thin coal seams ("low-seam" coal), which often necessitates mining significant amounts of roof and/or floor rock along with the coal [29], and this could elevate toxicity of mine dusts by contributing more silica and other potentially harmful minerals. Continuous miner operators and roof bolters are occupations likely to have higher silica dust concentrations, but this is variable based on geology and the amount of rock cut. Variations in coal rank and ash minerals (e.g., iron sulfides within the coal seam) may also influence CWP [29-31]. Further, dust concentrations and particle shapes, size distributions, density and moisture content may all be impacted by mining techniques (e.g., cutting or roof bolting methods). The specific surface area of respirable dust plays a key role in how particles are deposited in the lungs [28]. Finally, it is also important to consider that dust exposures may be more dynamic in CA than in other regions due to the relatively small mine sizes and workforces [21, 32, 55]; this may mean that some miners are more frequently working in multiple areas of the mine to perform multiple duties, rather than in a single occupation.

Given the risk for disease progression even after exposure removal, along with few medical treatment options, the need for understanding what characteristics of dust exposure may be leading to increasing risk of CWP is critical. Cohen and others [33-35] hypothesized increased concentrations of respirable silica may be responsible for increased toxicity of coal mine dust. Laney et al. examined found increased prevalence since 1999 of rounded radiographic opacities that are known to be associated with silicosis lung pathology, particularly in miners from Kentucky, Virginia, and West Virginia [35].

Symptoms of cough, sputum and shortness of breath, and wheezing are all associated with cumulative exposure to respirable coal dust, with the prevalence of chronic bronchitis in US miners estimated at 35%. Miners tend to suffer large declines in lung function shortly after beginning work – after which losses continue but at a slower pace [33]. However, exposures to work outside of coal mines and to other activities can also lead to losses in lung function [6]. Any evaluation into coal miner lung function needs to consider these factors outside of the mine as well.

The specific goal of this study was to comprehensively evaluate characteristics of occupational dust exposures and associate these data with miner lung capacity. Multiple underground coalmines in the CA and Northern Appalachia (NA) region (between northern WV and southwestern PA) were included to provide access to a range of mining-specific factors of interest and a cohort of miners. In CA, two distinct sub-regions were included, "Mid-Central Appalachia" (MCA; near Beckley, WV) and "South Central Appalachia" (SCA; near Logan, WV). This research considered dust characteristics related to coal mining seam heights, other mining conditions, and job classes; it also evaluated lung function tests among groups of coal miners in various types of mines and job classes.

Aims

UPitt and VT researchers performed a three-year project of intensive field study to gather and analyze critical data. The two major aims were: 1) comparison of respirable dust exposure characteristics by across and within mine regions and between particular sampling locations that represented different working environments in a mine (VT); and 2) associations of worker lung function, personal risk factors, and occupational history, with respirable dust exposure characteristics (UPitt).

Work scope

We completed a three-year project consisting of an intensive field study to gather and analyze critical data: detailed dust exposure characteristics associated with various areas, and hence occupations, in underground coal mines; and dust exposure and health (i.e., as indicated by associations with lung function) of individuals across a cohort of miners. Data were collected from mines within the MCA, SCA, and NA regions. The MCA and SCA mines were a test bed to study relatively small, "low-seam" operations in the region where CWP appears to be on the rise, while the NA mines provided a control (i.e., larger mines, thicker seams, and lower observed incidence of CWP). Differences in mining methods (i.e., longwall in NA vs. continuous miner in MCA or SCA) also exist between these regions and were included in the study parameters.

The project team partnered with a total of eight underground coal mines in Appalachia to collect dust samples. These mines were located in three distinct sub-regions: mid-central (MCA), south-central (SCA) and northern (NA) Appalachia (Figure 1). General characteristics of each mine are shown in Table 1. MCA and SCA mines were room and pillar operations using continuous miners, and NA mines were longwall operations with continuous miners used in development. Of the three regions, MCA had the smallest mines in terms of production and workforce, and the thinnest seams (i.e., lowest coal to total mining height ratios). In these mines, sandstone was the predominant roof-rock. SCA mines were also relatively small, but were mining somewhat thicker seams – and roof rock was primarily shale. In NA, the mines were extracting thicker coal seams and proportionally less rock. Dust sampling and analysis is described in detail below.

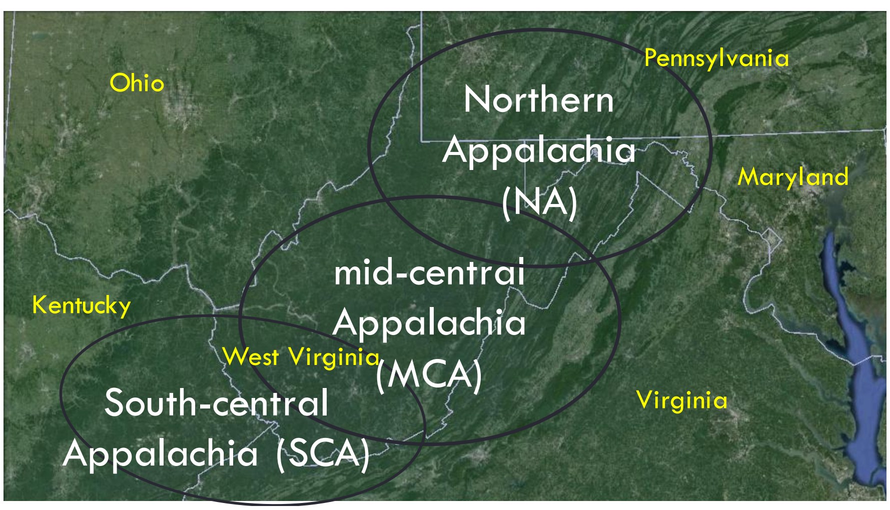

Figure 1. Dust sampling regions for this project.

Table 1. General characteristics of mines where dust samples were collected for this project (taken from Johann-Essex et al., 2017a[36]).

Characteristic	MCA				NA		SCA	
	Mine 1	Mine 2	Mine 3	Mine 4	Mine 5	Mine 6	Mine 7	Mine 8
Primary coal seam	Eagle	Powellton	Peerless	Cedar Grove	Pittsburgh #8	#2 Gas	Alma	
Seam thickness (ft)	3-5	3-4	4.5	2-4	6-8	6.5	5-6	4-4.5
Total mining height (ft)	5	5.5	6	4	8	8	6-7	6
Primary rock strata	sandstone	sandstone	shale and sandstone	sandstone	sandy shale and slate	shale	sandy shale and slate	shale
Number of sections	2 CM	2 CM	2 CM	2 CM	1 LW; 3 CM	1 LW; 5 CM	3 CM	2 CM
Production (10^6 tons/yr)	0.45	0.45	0.84	0.55	2.4	7.5	1.3	0.9
Typical dust conc.[1]	low to moderate	low to moderate	low to moderate	low	low to high	low to moderate	low to moderate	low to moderate
Typical quartz percentage[2]	low to moderate	low to high	low to moderate	low to high	Low	low	low to moderate	low to high

[1]based on operator and inspector mine samples collected between 2013-2016; low = <0.6 mg/m^3, moderate = 0.6-1.8 mg/m^3, high = >1.8 mg/m^3

[2]based on operator and inspector mine samples collected between 2013-2016; low = <5.0%, moderate = 5.0-9.0%, high = >9.0%

For collection of health data, individuals were recruited from the MCA and SCA mines in Table 1, as well as several other small mines operating in close proximity to the MCA mines. Additional individuals were recruited primarily from the NA region by the research team in collaboration with the United Mine Workers of America (UMWA). Participants were asked to complete a survey of occupational and health history; a health assessment (i.e., lung capacity measurements via PFTs); and a personal dust sample. IRB approvals were obtained from UPitt and VT IRBs. Participants were compensated for each component completed. To be eligible, miners must have been actively employed. There were no exclusion criteria.

University of Pittsburgh investigators spent considerable effort on NA recruitment. Outreach included multiple meetings with UMWA representatives, advertising on Craigslist, flyers distributed to and displayed at union meetings and in lunchrooms, recruitment ads in local newspapers, direct email (via Private Industry Council) to miners, and postings on Facebook.

Dust data collection

For this project, both area and personal dust samples were collected. The sampling and dust analysis procedures are summarized here, and have been described in detail elsewhere (see Johann-Essex et al., 2017a; Phillips et al., 2017; Phillips et al., 2018; Johann-Essex et al., 2017b, and Scaggs, 2016[36-40]).

Sampling procedures

Area samples

Area samples were collected by the Virginia Tech research team in various locations of all eight partner mines [36, 38]. These locations were chosen to represent distinct environments with respect to potential dust sources, and an effort was made to sample the same general areas in each mine. All area samples were collected between July of 2014 and July of 2015, during a total of 76 unique sampling events (i.e., sample collection in a particular location of a particular mine). In all, the research team made a total of 11 sampling trips and spent 42 shifts underground.

All samples were collected using Escort ELF pumps (set to 1.7 LPM flowrate) and Dorr-Oliver cyclones. These are the same equipment used to collect respirable dust samples in coal mines for compliance monitoring (i.e., for post-collection gravimetric and crystalline silica analyses). The cyclone removes oversized particles such only those in the respirable range are deposited on the sample filter. At 1.7 LPM, the cyclone produces a d_{50} cut size of about 4 µm.

All samples were collected on 37mm filters housed within two-piece plastic cassettes, which were assembled by the research team. Different filter media were used for different analyses. Polycarbonate (PC) filters were used for particle-level analysis by scanning electron microscope with energy dispersive x-ray (SEM-EDX), which was the primary focus of dust characterization for area samples. For determination of coal and mineral mass fractions by thermogravimetric analysis (TGA), polyvinyl chloride (PVC) or mixed-cellulose ester (MCE) filters were used. Sampling times ranged between 2-4 hours, which was optimal for collecting sufficient dust on the PC filters for the SEM work.

During each of the 76 sampling events, a set of multiple samples were collected simultaneously. In general, the sampling scheme was such that each set had either six or four total filters. For sets with six filters, four were for SEM and two were for TGA (**Figure 2**). Two SEM and both TGA samples were collected side-by-side (i.e., cassette inlets were a few inches from one another and oriented in the same direction), and the other two SEM samples were collected in close proximity (i.e., one was just upwind of the four side-by-side filters, and the other was just downwind). This scheme allowed some analysis of spatial variability in dust characteristics, as is discussed below. For sample sets with four filters, two were for SEM and two were for TGA – and all four were collected side-by-side. On a few occasions, one sample pump was unavailable (i.e., due to a low battery, maintenance need, etc.), and on these occasions only one TGA sample was collected in a set.

The 76 sample sets yielded a total of 210 filters for SEM and 147 for TGA. Table 2 shows the SEM samples collected by mine and sampling location. (TGA samples are not included in Table 2 since all but a few sample sets included two TGA samples.) Sampling locations were grouped into four general categories:

- Intake (I), which included samples in intake airways just outby of the primary production area (including the headgate of a longwall section) and samples collected near the mantrip track;
- Feeder (F), which included samples collected near the feeder breaker or along the main conveyor belt;
- Production (P), which included samples collected near active roof bolters or continuous miner machines, or near the midface of a longwall section; and
- Return (R), which included samples collected in the return airway just outby of the primary production area (including the tailgate of a longwall section), and samples collected near active trickle duster machines in return airways.

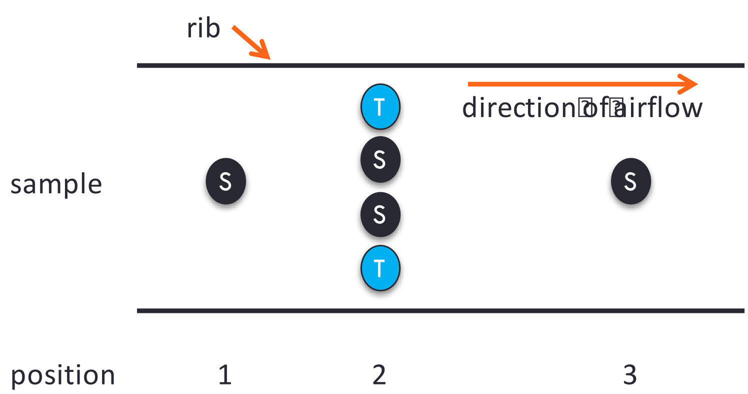

Figure 2. Illustration of area sampling scheme for six-filter sample sets (not to scale). Samples labeled "S" refer to filters collected for SEM analysis and those labeled "T" refer to filters for TGA. In position 2, all samples were collected side-by-side (i.e., inlets positioned just a few inches apart). Relative to position 2 (where position 1 was about 3 m upwind and position 3 was about 6 m downwind. In cases where only four filters were collected in a sample set, these were all collected in position 2.

Table 2. Respirable dust sample collection summary (adapted from Johann-Essex et al., 2017a). Mines are grouped by region: mid-central Appalachia (MCA), northern Appalachia (NA), and south-central Appalachia (SCA). Unless noted, samples were collected as shown in Figure 1 for Mines 1-5, and only as duplicates for Mines 6-8. The four general location categories are divided into their more specific sampling locations: H=longwall headgate, I=intake, TR=track, BD=belt drive, C=conveyor, F=feeder, B=roof bolter, M=continuous miner, MF=longwall midface, R=return, T=longwall tailgate, TD=trickle duster.

Number of Samples/Sample Sets Collected in Specific Location														
Region	**Mine**	**Intake**			**Feeder**			**Production**			**Return**			**Total**
		H	**I**	**TR**	**BD**	**C**	**F**	**B**	**M**	**MF**	**R**	**T**	**TD**	
MCA	1	0/0	4/1	0/0	0/0	0/0	4/1	4/2	6/2	0/0	4/1	0/0	0/0	22
	2	0/0	4/1	0/0	0/0	0/0	4/1	8/2	4/1	0/0	4/1	0/0	0/0	24
	3	0/0	4/1	0/0	0/0	0/0	4/1	4/1	4/1	0/0	4/1	0/0	0/0	20
	4	0/0	4/1	0/0	0/0	0/0	4/1	4/1	0/0	0/0	4/1	0/0	0/0	16
NA	5	3/1	4/1	0/0	0/0	4/1	8/2	4/1	0/0	4/1	8/2	4/1	0/0	39
	6	2/1	8/4	2/1	2/1	0/0	4/2	2/1	2/1	2/1	4/2	2/1	0/0	30
SCA	7	0/0	4/2	0/0	0/0	0/0	6/3	4/2	8/4	0/0	7/3	0/0	0/0	29
	8	0/0	6/3	0/0	0/0	0/0	6/3	4/2	6/3	0/0	6/3	0/0	2/1	30
Total Samples		5	38	2	2	4	40	34	30	6	41	6	2	**210**
Total Sample Sets		2	14	1	1	1	14	12	12	2	14	2	1	**76**
Total Samples in Location Category		**45**			**46**			**70**			**49**			

Personal samples

In addition to the area samples collected by the research team, a total of 59 personal dust samples were collected [40]. For this, 52 volunteers were recruited from four of the mines shown in Table 1 (i.e., mines 2, 3, 7 and 8), and another 7 volunteers were recruited from four more mines in MCA (i.e., only one or two samples from each). Recruitment and consent of these individuals was done in compliance with the University of Pittsburgh and Virginia Tech University Institutional Review Boards. Samples were collected on either PVC or MCE filters, using the same equipment described above. The equipment and pre-assembled filter cassettes were provided by the Virginia Tech research team to each volunteer prior to the start of his work shift, and the sample was collected over his entire shift (i.e., pump was switched on as he was entering the mine and switched off after he returned to the surface). The equipment and samples were retrieved by the research team immediately following sample collection.

Sample analysis

SEM

All 210 area samples collected on PC filters were characterized by SEM-EDX. For each particle analyzed, three primary data were collected: size (i.e., long and perpendicular-to-long dimensions in the plane of view), aspect ratio (i.e., shape feature computed as the ratio of the long and perpendicular-to-long dimensions), and chemistry classification. The size and aspect ratio were measured directly from the SEM image, and the chemistry classification was made from the EDX spectra. Specifically, based on the feedback signals detected when a particle is bombarded with energy, the relative abundances of particular elements can be determined – and these can be interpreted as different mineral types (**Table 3**).

Table 3. Defined chemistry classification categories for dust samples analyzed by SEM-EDX (adapted from Johann-Essex et al., 2017a).

Chemistry category	Carbonaceous (C)	Alumino-Silicate (AS)	Quartz (Q)	Carbonate (CB)	Heavy Mineral (HM)
Example mineralogy or source	coal	clays, feldspars	crystalline silica	rock dust product, native calcite or dolomite	pyrite, Fe/Al/Ti oxides

For this project, a computer-controlled (CC) routine was developed by the Virginia Tech research team to conduct the SEM-EDX work (described in detail by Johann-Essex et al., 2017b [37]). The CC routine is based on a manual method, which was developed earlier by the team to characterize respirable dust particles from coal mines [41]. While the manual method required about an hour to analyze 100 particles per sample, the CC routine typically took just 15-20 minutes to analyze 500 particles or more (i.e., given the filter loading densities achieved by a 2-4 hour sampling time for this project). Based on separate analyses of the same samples (i.e., three independent runs on each of 10 dust samples), the CC routine was shown to produce representative results – meaning that the size, aspect ratio and chemistry class distributions were generally not statistically different between the independent runs[37]. Using analysis of pure and known samples, the CC routine was also found to produce reliable results – meaning that it classifies particles like an experienced manual user.

All SEM work for this project was performed on a FEI Quanta 600 FEG environmental SEM (Hillsboro, OR), equipped with a backscatter electron detector (BSD) and a Bruker Quantax 400 EDX spectroscope (Ewing, NJ). The CC routine was programmed using Bruker's Esprit software (version 1.9.4).

Details on sample preparation, equipment parameters, and particle selection can be found in Johann-Essex et al. [37]. Briefly, a 9-mm subsection was taken from each filter and sputter-coated with Au/Pd. Once in the SEM instrument, which was focused and calibrated, the CC routine commenced by zooming to 1,000x magnification in the center of the sample subsection and capturing an image with the BSD. The image was converted to a binary image and the first 50 particles (moving from left to right and top to bottom) between about 0.94-9 µm were selected for analysis. For each of these particles, its dimensions were measured and its EDX spectra was captured. The relative elemental abundances per the EDX spectra were compared to pre-programmed classification criteria for the defined categories shown in Table 3. Any particles that did not fit within one of these categories, was placed in an additional category called "other". After this process was completed on this first field of view (i.e., at the center of the sample subsection), the microscope automatically moved to the next field and the process was repeated. This continued until at least 500 particles were selected and analyzed, or until 157 frames had been viewed – whichever came first. All data for a sample was exported to MS Excel.

From the CCSEM-EDX results on each filter sample (i.e., for about 500 particles), distributions of particle size, aspect ratio and chemistry classification were computed. These were used to conduct statistical analyses to compare dust characteristics between and within mine regions, and between particular sampling locations – and then they were used in correlational analyses with health data. It should be noted no direct measurement was made of respirable dust concentrations (mg/m^3) or particle densities (particles/m^3) in the sampling environments. However, image analysis from the SEM work was used to make crude estimates of particle densities based on the filter loading density, filter surface area, sampling time and flow rate (see below).

TGA

TGA on area dust samples collected on PVC or MCE filters and all personal samples was completed using a Q500 Thermogravimetric Analyzer (TA Instruments, New Castle, CE). The TGA method was developed for this project and has been described in detail by Scaggs [39] and Phillips et al. [38, 40].

The premise of TGA for respirable dust samples from coal mines is simply that characteristic weight changes with controlled thermal ramping can be correlated to specific dust constituents. Figure 3 shows example thermograms for respirable-sized coal, rock dust (i.e., largely comprised of calcium carbonate) and pulverized shale particles (i.e., largely comprised of alumino-silicates). The coal is oxidized between about 360-480 °C, the rock dust is thermally degraded (i.e., CO_2 is evolved from carbonate) between about 480-750 °C, and the shale is relatively stable across the entire temperature range. Based on these characteristic behaviors, the mass fractions of coal, carbonates, and non-carbonate minerals can be estimated (Figure 4). While imperfect, such estimates may allow a general understanding of the primary sources of respirable dust particles in coal mine samples: in mines where the native geologic strata do not contain much carbonate, the carbonate mass fraction may serve as a surrogate for dust sourced from rock dust products, and the non-carbonate minerals fraction may serve as a surrogate for dust sourced from native rock strata being cut in the mine.

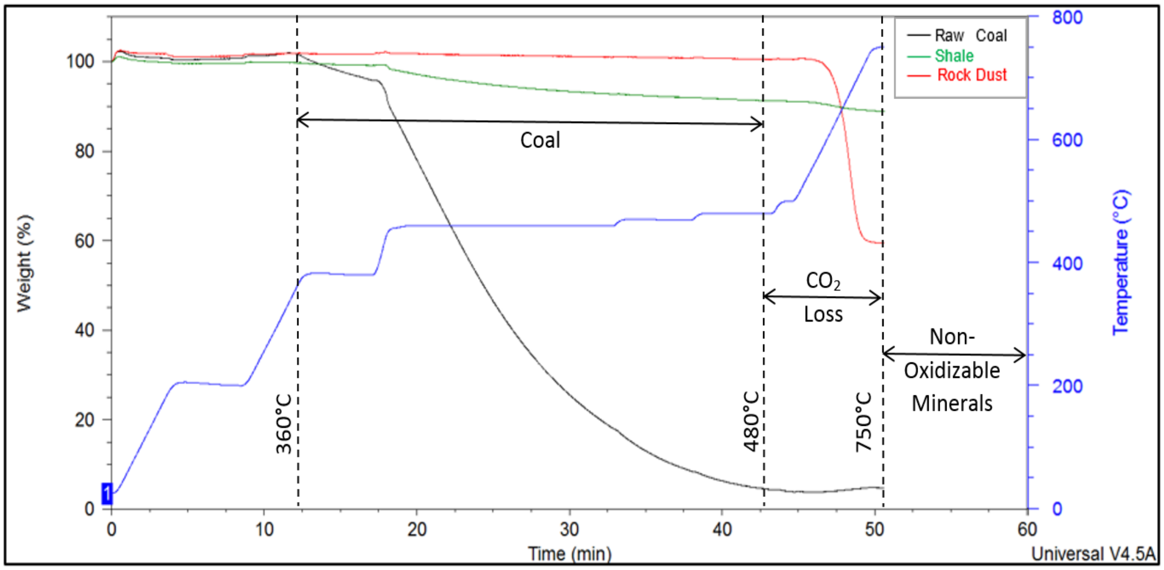

Figure 3. Representative thermograms for respirable samples of raw coal, rock dust and shale (taken from Scaggs, 2016). The entire TGA program is run in high-purity air.

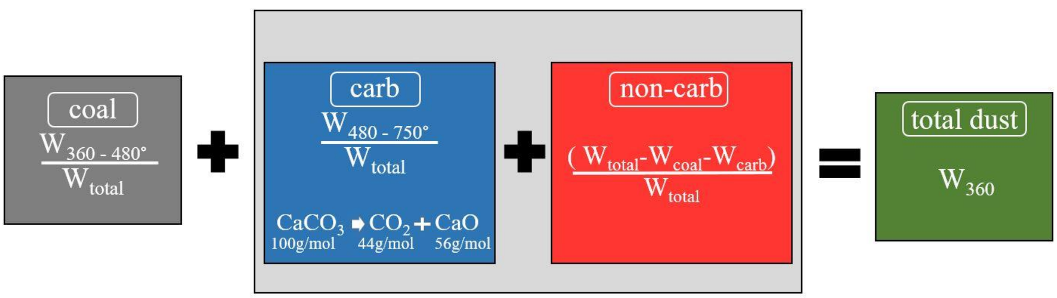

Figure 4. Derivation of coal, carbonate, and non-carbonate mineral mass fractions based on observed weights (W) at specific temperatures during TGA (taken from Phillips et al., 2018). Total dust refers to the dust recovered from the filter sample to the TGA instrument.

Following preliminary work to determine the efficacy of direct-on-filter TGA, it was determined that a dust-only method is required for the typical filter sizes and media available for respirable dust sample collection – and given the typical dust weights that can be collected on a single filter over several hours [39]. These circumstances effectively mean that the sample filters are relatively heavy compared to the dust, and their thermal behavior can cause interference with interpretation of the dust behavior. Thus, as part of the TGA method, a sample preparation procedure was devised to remove dust from a filter by sonication in deionized water (DI). However, this procedure can be inefficient for the PVC and MCE filters, meaning that recovery of dust mass from the sample filter to the TGA instrument can be low. (Notably, recent work by the Virginia Tech research team has shown that PTFE filter media may be a favorable alternative to the PVC or MCE used on this project – and work is ongoing to adapt and demonstrate the TGA method used here with PTFE filters.)

Since TGA is mass-based, sample mass affects the accuracy of results. The TGA method developed for this project was evaluated using composite respirable dust samples generated in the laboratory [39]. Briefly, the lab-generated samples were made with known weights (i.e., measured by microbalance) of known materials (i.e., characterized independently by TGA) on both PVC and MCE filter media. The TGA results (i.e., mass fractions of coal, carbonates and non-carbonate minerals) on these composite samples were compared with the expected results based on the measured weights of each dust material. For samples with 50 µg or more of dust recovered, the TGA-derived coal fraction results were generally within 25% of the expected results.

Unfortunately, many of the area dust samples collected for this project did not have enough recovered dust mass to complete the TGA. Of 147 samples, only 106 were viable in this regard. For these, the TGA results could be compared with SEM-derived results since all samples were collected in sets [38]. To make this comparison, the SEM data had to be translated into mass fractions to correspond with the TGA data, which was done by assuming spherical particles and specific gravity values for each chemistry classification. This comparative analysis yielded 86 samples that had TGA- and SEM-derived coal mass fractions within 25% of one another; and 47 samples where the carbonate mass fractions were also within 25%. This approach to verifying the TGA results allowed some valuable analysis of dust constituents by mine regions, mines and sampling locations. However, given that a greater number of SEM (versus TGA) area samples were collected for this project, greater confidence is associated with the SEM results, and SEM provides more detailed characterization of the dust, it was decided that only the SEM results would be used for correlational analysis between area dust sample characteristics and health data.

Since the personal dust samples were collected on PVC or MCE filters, only TGA could be conducted on these. Enough dust could be recovered from all samples to conduct the TGA, although dust masses were very low in most cases [40]. Thus, these results must be viewed with some caution, and discussion with respect to verified area sample results collected in the same mines may provide some perspective.

Heath data collection

Health Component Cohort Recruitment

As indicated above, miners were recruited from MCA, SCA, and NA on site at the mines and in collaboration with the United Mine Workers of America (UMWA) in a series of 6 recruitment visits over almost 2 years. The health component consisted of two main parts: a survey of occupational and health history, and a health assessment (i.e., a pulmonary function test (PFT)). Miners were also asked to participate in the collection of a personal dust sample (described above). Participants provided written informed consent to investigators; the study was approved by the University of Pittsburgh and Virginia Tech Institutional Review Boards.

Health survey

Telephone interviews assessing occupational and health history were conducted at participants' convenience. Surveys lasted no more than 30 minutes and consisted of questions regarding prior work experience in coalmines, work experience in non-coal mines, exposure to potential lung contaminants (e.g., quarrying, sandblasting, or occupations associated with diesel exposure). Personal medical history, including respiratory symptoms, and behavioral and lifestyle factors (e.g., smoking habits) were also asked [43]; this more detailed survey was considered the long survey. A shorter survey was administered at the time of the pulmonary function test to assess conditions or injuries that may affect lung function (e.g., history of pneumonia).

Pulmonary function tests

A mobile-health services contractor was used for the PFT tests. The mobile van traveled onsite to mine locations or a local central location (e.g., local hotel parking lot). Testing was scheduled as times convenient to participants, including overnight and on weekends. PFTs were administered according to American Thoracic Society (ATS) guidelines, either before a participant's work shift or at least 10 hours post-shift to eliminate the direct, short-term effects of exposure. At least three maximum expiratory maneuvers were performed, and the best maximal effort was selected from those producing a technically satisfactory tracing [42-43].

Measures of lung volume and airflow, via PFT, were used to assess lung function and determine the degree of damage to the lungs. Results of lung function tests were used to associate lung capacity with a variety of mining occupations of interest (e.g., continuous miner and longwall miner operators, roof bolters, rock dusters, shuttle car operators) and those with regular movement to different areas (e.g., maintenance workers, foremen) in MCA, SCA, and NA mines.

PFTs produce several measures of lung function. For this study, we considered: Forced vital capacity (FVC), or the amount of air exhaled forcefully and quickly after inhaling as much as possible; Forced expiratory volume (FEV), or the amount of air expired during the first, second, and third seconds of the FVC test; and Forced expiratory flow (FEF_{25-75}), or the average rate of flow during the middle half of the FVC test. FVC, FEV_1, and FEF_{25-75} from the selected effort were recorded as well as age (years), body mass index (BMI), and blood pressure.

Blood pressure was categorized into four groups:

Systolic (mm Hg)	Diastolic(mm Hg)	Category
Below 120	and Below 80	Normal blood pressure
Between 120-139	or Between 80-89	Prehypertension
Between 140-159	or Between 90-99	Stage 1 hypertension
160 or higher	or 100 or higher	Stage 2 hypertension

Detailed smoking information was asked in the long survey (type of tobacco, amount years); ever-never smoking was assessed in the short survey. BMI >30 was considered obese.

Data Analysis

Statistical analyses were performed using STATA v13, and R. Statistical significance was assessed at $p<0.05$. There were no corrections made for multiple comparisons.

Translation of CCSEM results into TWAs for specific occupations

Individuals were placed into a standardized job name category based on self-reported current job at the time of data collection. Area dust sample characteristics, based on CCSEM, were assigned to miners based on 23 standardized job name and region. A matrix of percent time in four areas of the mine (Intake, Feeder, Return, or Production) was developed for each standardized job name using expert judgement (**Table 4**).

Table 4. Percent Time Spent in Mine Areas by Standardized Job Names

Job Type	Mine Type	Feeder	Intake	Production	Return	Outside
Beltman		5	90	0	0	5
Bolter		0	15	80	0	5
Continuous Miner Operator		0	15	80	0	5
Electrician	Longwall	5	55	25	5	10
Electrician	CM	7.5	40	40	2.5	10
Fireboss	Longwall	1	42	6	31	20
Fireboss	CM	1	43	4	32	20
General Laborer		0	75	0	10	15
Lift Operator		10	75	0	5	10
Longwall Laborer		0	45	25	25	5
Longwall Mechanic		0	60	25	10	5
Maintenance Foreman		7.5	40	40	2.5	10
Mason		0	70	0	25	5
Mechanic Welder	Longwall	5	40	30	5	20
Mechanic Welder	CM	10	30	40	0	20
Mine Foreman	Longwall	1	51	15	3	30
Mine Foreman	CM	2.5	35	30	2.5	30
Motor Man		0	70	0	0	30
Move crew		0	85	0	0	15
Outby Worker		0	85	0	5	10
Outside Mine Worker		0	0	0	0	100
Rock Dust Crew		0	70	0	15	15
Safety Representative		0	50	0	0	50
Scoop Operator		15	70	5	5	5
Shearer Operator		0	25	65	5	5
Shuttle Car Operator		15	55	25	0	5
Superintendent		0	10	0	0	90
Surveyor		0	55	0	5	40

It is pretty well established that sampling airborne particulates with closed face cassettes can result in non-uniform deposition such that deposition is heavier toward the center of the filter (i.e., due to the airflow pattern through the cassette). Due to this, it is likely that the subsection of each filter with the highest particle densities was used. These results should not be used to compare with dust mass concentrations obtained from gravimetric samples. Our purpose with the particle concentrations was to compare study samples (all gathered using the exact same procedure) to one another, not to calculate the mass fraction of the samples.

A time weighted average (TWA) was formed for each job name to estimate total particle concentration and particle concentration in any specific dust characteristic category (i.e., particle size, aspect ratio or chemistry classification). An example of how the TWA was calculated for each job name is illustrated below:

Sample Calculation for Aspect Ratio <1.5 for Beltman in MCA

Step 1: Total part conc for beltman = (part conc in feeder * time % in feeder) + (part conc in intake * time % in intake) + (part conc in production * time % in production) + (part conc in return * time % in return) + (part conc outside * time % outside)

Feeder	Intake	Production	Return	Outside

4,987,693.40*0.05 + 1,834,861.41*0.90 + 52,448,122.39*0.00 + 42,871,808.19*0.00 + 0*0.00

= 1900759.943 Beltman specific particle concentration

Step 2: Apply job-name specific particle concentration to percent particles in aspect ratio <1.5

Conc of >1.5 AS particles for beltman = (part conc in feeder * % particles >1.5 AS in feeder * time % in feeder) + (part conc in intake * % particles >1.5 AS in intake * time % in intake) + (part conc in production * % particles >1.5 AS in production * time % in production) + (part conc in return * % particles >1.5 AS in return * time % in return) + (part conc outside * % particles >1.5 AS outside * time % outside)

= 904549.2662 particles of aspect ratio <1.5 per cubic meter

Because samples were collected in the Production area specifically for bolter and continuous miner, we applied those particle concentrations directly for those job names and did not use the average for the whole “P” area in MCA and SCA. The P average was used to calculate TWA for all other job names.

Survey results

Comparison of frequencies of long survey responses, short survey responses, and PFT results between MCA, SCA, and NA coal miners were made with chi-square test (or Fisher's exact test of probability) for categorical variables and with ANOVA for continuous variables. ANOVAs were performed for overall statistical significance as a predictor and for pairwise comparisons between regions. Comparisons were also made for certain characteristics (age, smoking, BMI) among those who did and did not complete pulmonary function tests to ascertain any response bias.

Health data

The ratio of FEV1/FVC, also known as the Tiffeneau-Pinelli (T-P) index, was the primary PFT result of interest in the analyses. This index is used in the identification of obstructive lung disease and represents the proportion of a person's vital capacity that they are able to expire in the first second of forced expiration to the full vital capacity. FEV1/FVC ratio was considered both as a continuous variable and was dichotomized (<80) as normal or abnormal.

Centered logratio transformation

The dust characteristics are compositional data (the parts sum to unity) and therefore have collinearity among the measurements. The centered logratio transformation was used to transform the compositional data into a form in which the contribution of each component could be assessed independently from the other components. Because the centered logratio requires the parts to sum to 1, only those participants with dust exposure to their occupation could be included (i.e., those who worked outside the mine were excluded). This method then accurately captures the independent association between each specific dust characteristic and lung function *among those with dust exposure*.

Mathematically, the transformation was used to minimize collinearity between compositional parts that, for all groups, sum to some constant by subtracting the geometric mean of parts from each individual log-transformed element. A D-dimensional centered log transformation can be written:

$$\mathrm{clr}(x_i) = \log(x_i) - \frac{1}{D}\sum_{j=1}^{D}\log(x_j), \text{ for } i = 1,\ldots D$$

Association of CCSEM results with health data

The univariable and correlational analyses used the transformed variables to identify relationships between compositional dust characteristics and demographic details acquired by survey. Seven miners with PFTs were not included in these associations because of work outside the mine or missing job names, leaving 82 miners in the analyses.

Univariable linear regression analyses were performed to assess the relationship between each of the dust characteristics and FEV1/FVC. Correlation coefficients were calculated overall and by region for each dust characteristic for FEV1/FVC. Correlation coefficients were evaluated as:

Coefficient Value	**Strength of Association**
$\|r\| < .1$	no correlation
$0.1 < \| r \| < .3$	weak correlation
$0.3 < \| r \| < .7$	moderate correlation
$\| r \| > .7$	strong correlation

Correlation of personal dust sample results with health data
Dust characteristics (from TGA) for individuals that collected personal dust samples were applied directly to these individuals. Correlation coefficients were calculated overall and by region for each dust characteristic for continuous forms of FEV1/FVC. Personal dust samples were only available for miners in MCA and SCA, not for those in NA.

Multivariate Modeling
Multivariable models based on the results of the univariable and correlational analyses were planned. However, the lack of robust findings from these steps precluded our ability to perform any multivariate modeling.

Results

Dust characteristics

Prior to conducting correlational analysis between the dust and health data gathered for this project, the results of the area and personal dust samples were presented and discussed on their own (see Johann-Essex et al., 2017a; Phillips et al., 2017; and Phillips et al., 2018). The following sections summarize the key findings from the dust characterization work.

Area Samples

All 210 area dust samples were analyzed by the CCSEM-EDX routine described above [36]. For seven samples, fewer than 300 particles were analyzed – so these samples were not included in further analysis. The data gathered from the CCSEM-EDX work allowed number distributions of particle size, aspect ratio and chemistry classification to be determined for each sample. Since size and aspect ratio are continuous metrics, these data were binned into three respective categories.

Particle size (i.e., measured as the long dimension) was binned into 0.94-2.0 um, 2.0-3.0 um, or 3.0-9.0 um, and aspect ratio was binned as < 1.5, 1.5-3.0, or > 3.0. Chemistry classifications were binned into the five predefined categories (**Table 3**) or "other". Table A1 in the Appendix shows the binned particle distributions for all 203 samples included in subsequent analyses.

Across the entire dataset, some important observations could be made about the relative abundances of different particle types. First, the percentages of carbonaceous (i.e., coal) particles were typically low (i.e., 29% on average for all 203 samples); and this observation was supported by the TGA results, where available [38]). Except for a few instances (i.e., samples collected in F locations in MCA mines, and samples collected in P locations in NA mines), carbonaceous particles were generally less than 40% [36]. While finding relatively small percentages of coal in most samples may seem somewhat surprising, it should be noted that some historical data compiled by the IARC [44] does show that the mass fraction of coal in respirable mine dusts can vary considerably. However, no data are available for direct comparison to that collected for this project (i.e., gathered recently in the same mine regions and analyzed to determine fractions of specific dust constituents other than quartz).

From the SEM data (**Table 3**), it was also observed that most of the non-coal particles in the dust samples fell into one of two categories: alumino-silicates (41% on average) and carbonates (23% on average). In some cases, carbonates may be associated with the rock strata being cut in the mine. For example, several samples collected near active roof bolters did exhibit high carbonate content [38]. However, most carbonate in the mines sampled for this project is believed to be sourced from rock dust products[1] based on general knowledge of the native

[1] Rock dusting refers to application of fine, inert dust to coal surfaces, and is required in underground coal mines to mitigate explosibility hazards [45]. Rock dust products are most

geologic strata and field observations of rock dust application. Prior to implementation of the new dust rule, there were some concerns with respect to the contribution of rock dust to the total respirable fraction of dust in coal mines (i.e., since the new rule lowered the permissible exposure limit on total respirable dust, and meanwhile mine operators have also been encouraged to apply more rock dust in the interest of mitigating explosibility hazards). Compliance rates with the new dust rule [16] appear to indicate that proper rock dusting can generally be done without increasing the total respirable dust over the compliance limit. However, the finding of relatively high carbonate percentages in the samples collected for this project seems to suggest that rock dust products can indeed contribute significantly to respirable dust levels.

The finding of relatively high alumino-silicates percentages, on the other hand, suggests that cutting of rock strata is perhaps the most significant source of respirable dust particles. To examine this further, the near-face samples (i.e., those collected on active continuous miners or at the longwall midface) were looked at independently [36]. For this, the SEM-derived particle chemistry distributions were normalized by removing carbonate particles – which might conservatively be assumed to be completely sourced from rock dusting products, while all other particles could be assumed to be generated from cutting at the face. Then, the normalized percentage of carbonaceous (i.e., coal) particles in the respirable dust was compared to the percentage of coal seam height within the total mining height (i.e., based on values in **Table 1**). This analysis was done for all mines except mine 4, since no continuous miner samples could be collected in that mine.

Other than in mine 6, the percentage of coal in the respirable dust was less than expected based on the coal seam thickness as a percentage of the total mining height – and, in many cases, much less (**Figure 5**). These results seem to indicate that cutting rock strata (as opposed to coal strata) can produce an inordinate amount of respirable dust particles. Some possible explanations may stem from differences between the geotechnical properties of rock and coal materials, which control their propensity to generate dust particles; or the relative efficacy of dust controls at the cutting face for limiting aerosolization of dust from different strata or face heights.

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often comprised of high quality limestone or dolomite (i.e., calcium and/or magnesium carbonate minerals), as was the case for the products used by the mines sampled for this project.

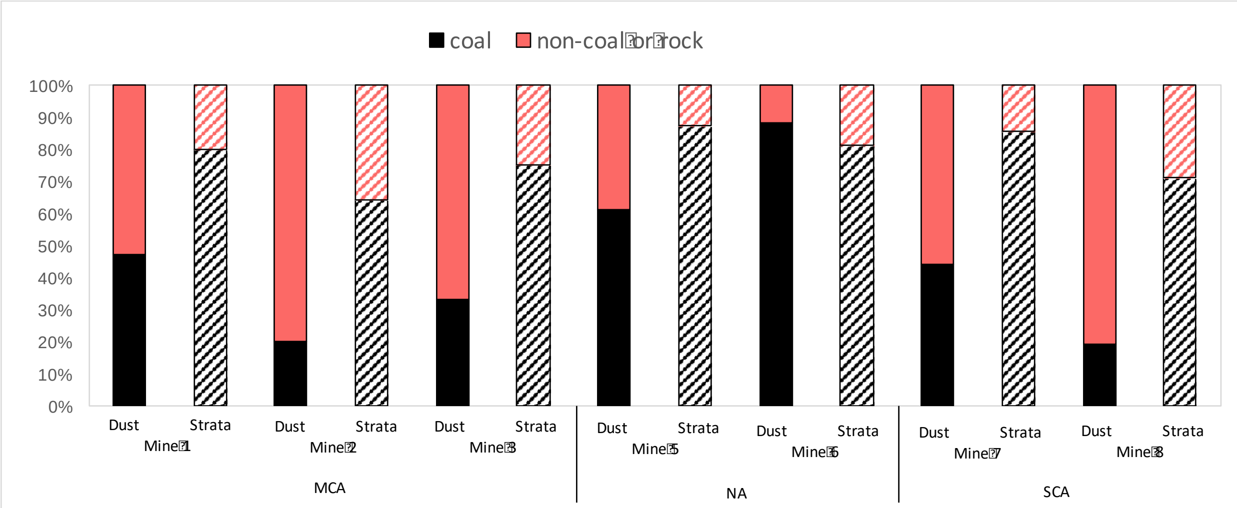

Figure 5. Normalized percentages of coal and non-coal (i.e., non-carbonate minerals) particles in the near-face area samples analyzed by SEM versus percentages of coal and rock heights with respect to the total mining height (data presented in Johann-Essex et al., 2017a). The strata percentages are based on the seam thickness and total mining height data shown in Table 1; and in cases where a range of values was reported for one of these variables, the average value was used here.

Before exploring further trends in the SEM-derived dust data, spatial variability of results (i.e., between samples collected in a given sample set) was investigated by comparing duplicate and close-proximity sample pairs. There were a total of 73 duplicate pairs, which were defined as any two samples collected side-by-side (i.e., position 2 in Figure 2). There were a total of 132 close-proximity pairs, which were defined as any combination of two samples collected several meters apart during the same sampling event (i.e., positions 1 and 2, 1 and 3, or 2 and 3 in Figure 2). For these comparisons, the Freeman-Halton test of independence was used to determine statistical differences (at 95% confidence) between the particle chemistry class distributions of samples in each pair. Results showed that 78% of the duplicate pairs and 58% of the close-proximity pairs were in full agreement (Johann-Essex et al., 2017a). Samples collected in the I and F sampling locations were less likely to agree than those collected in the P and R locations. This may be related to a number of factors, including higher ventilation rates (i.e., better mixing) in the latter locations – although specific ventilation conditions were not collected as part of this study.

Because the above analysis indicated that dust characteristics can vary somewhat within a general sampling location, results for all individual SEM samples in a given sample set were averaged to come up with overall distributions for particle size, aspect ratio, and chemistry classifications for that set. This yielded 76 sets of average results (i.e., one for each sample set). These were then grouped by mine region (i.e., MCA, SCA or NA), mine (i.e., mines 1-8), or general sampling location category (i.e., I, P, F or R) in order to investigate trends in dust characteristics between groups. Statistical analysis was performed using analysis of variance

(ANOVA) testing using a 95% confidence limit; and when statistical differences between groups was detected, two-tailed t-tests were also performed to define the differences [36].

When analysis was focused on exploring differences between mine regions:

- Samples collected in NA had higher percentages of carbonate and heavy mineral particles, while those collected MCA and SCA had higher percentages of quartz and alumino-silicate particles. These findings are generally consistent with mining more roof and/or floor rock strata in the MCA and SCA mines, and anecdotal observation of relatively more rock dust application in NA mines.
- Samples collected in SCA had higher percentages of high-aspect ratio (i.e., elongated) particles relative to the other regions. It was expected that alumino-silicates might have higher aspect ratios than other particle types. The fact that ANOVA tests detected statistically more elongated particles in SCA, but not MCA, may indicate that, among other factors, the specific silicate minerals are different between these two regions or that the dust generating mechanisms are somewhat different.
- Samples collected in MCA had higher percentages of very small particles relative to the other regions. This finding may be related to differences in dust generating mechanisms also – and may help explain why MCA samples had relatively fewer elongated particles than SCA samples (i.e., aspect ratio should generally decrease with particle size).

When analysis was focused on differences between mines within a given region:

- Particle size and aspect ratio distributions were generally similar.
- Samples from mine 7 had higher percentages of carbonaceous particles than mine 8, while mine 8 had higher percentages of alumino-silicate particles than mine 7. This finding is consistent with mine 7 cutting more coal (with respect to the total mining height) than mine 8.
- Samples collected in mine 5 had higher percentages of alumino-silicate particles than mine 6, while mine 6 had higher percentages of carbonate particles than mine 5. Anecdotally, mine 6 had the most significant amount of rock dusting across all eight operations sampled. Thus, particles sourced from rock dust products may have biased the distributions in samples from this mine more so than samples from other mines.

When analysis was focused on differences between sampling locations:

- Samples collected in P and R location categories had higher percentages of small particles than those collected in I or F locations. Given that active cutting of geologic strata (i.e., coal and/or rock) is expected to be the primary source of dust particles in the P locations, this finding is not surprising. Regarding the R locations, it suggests that the production activities just upstream were also the primary source of particles in the return airways.
- Between the general sampling location categories (i.e., I, P, F or R), no statistical differences were found between chemistry classification distributions.

Personal Samples

As mentioned earlier, personal samples were only collected on filter media appropriate for TGA. All 59 of these samples were prepared and analyzed using the method described above, and the results are shown in Table A2 in the Appendix (which is taken from Phillips et al., 2018 [40]). Overall, the dust masses recovered for the analysis were relatively small, which may limit the accuracy of these results [39]. However, particularly when examined in concert with the area dust sample results, some worthwhile lessons can be learned. (It should be noted that the personal dust sampling by volunteers for this project was done several weeks to several months following area dust sample collection by the Virginia Tech research team.)

Figure 6 shows a direct comparison at the mine-level of the results from the personal samples and the results from the area samples analyzed by TGA and verified by SEM (which were presented Phillips et al., 2017). In all four of the mines where both personal and area dust samples were collected, the personal samples appear to have higher carbonate fractions than the area samples – and thus lower fractions of coal and/or non-carbonate minerals than the area samples. This may mean that average personal exposures are not strictly represented by average dust compositions obtained from area sampling. For example, even face workers like continuous miner operators can spend significant time in intake areas where carbonate from rock dusting activities may contribute substantially to respirable dust concentrations.

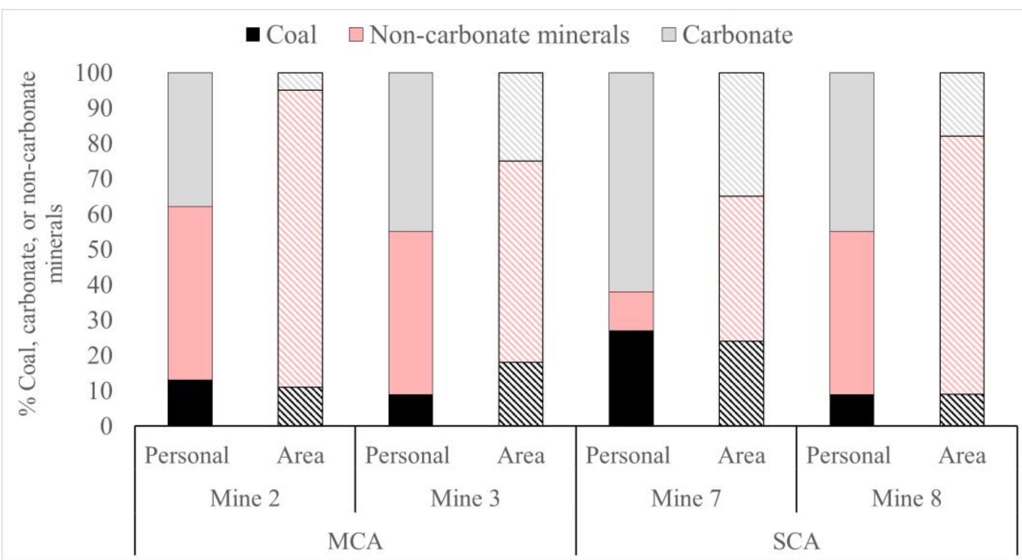

Figure 6. Comparison of average mass percentages of coal, carbonate, and non-carbonate minerals for personal dust samples versus area samples (hatched bars) collected in the same mines (taken from Phillips et al., 2018 [40]). Area sample results were previously published in Phillips et al. (2017)[38].

Like for the SEM results from area samples collected in near-face locations, the personal sample results were normalized to remove carbonates. Then, the ratio of coal to non-carbonate minerals in the respirable dust was compared to the ratio of coal height to rock height at the face. Based on average values at the mine-level, the personal dust samples again appear to have less coal than would be expected given the thickness of the coal seam being mined relative to the total mining height (**Figure 7**). When the same analysis was done just for the personal samples collected by continuous miner operators (i.e., analogous to Figure 5 for the area samples analyzed by SEM), the mass fractions of coal in the dust were still less than expected (**Figure 8**).

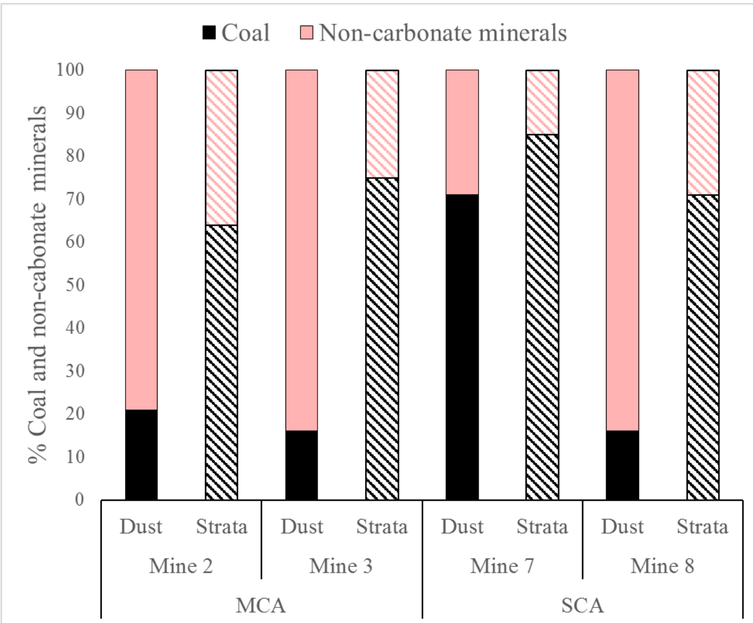

Figure 7. Normalized percentages of average coal and non-carbonate minerals mass fractions for personal dust samples versus percentages of coal and rock heights with respect to the total mining height (taken from Phillips et al., 2018 [40]). The strata percentages are based on the seam thickness and total mining height data shown in Table 1; and in cases where a range of values was reported for one of these variables, the average value was used here.

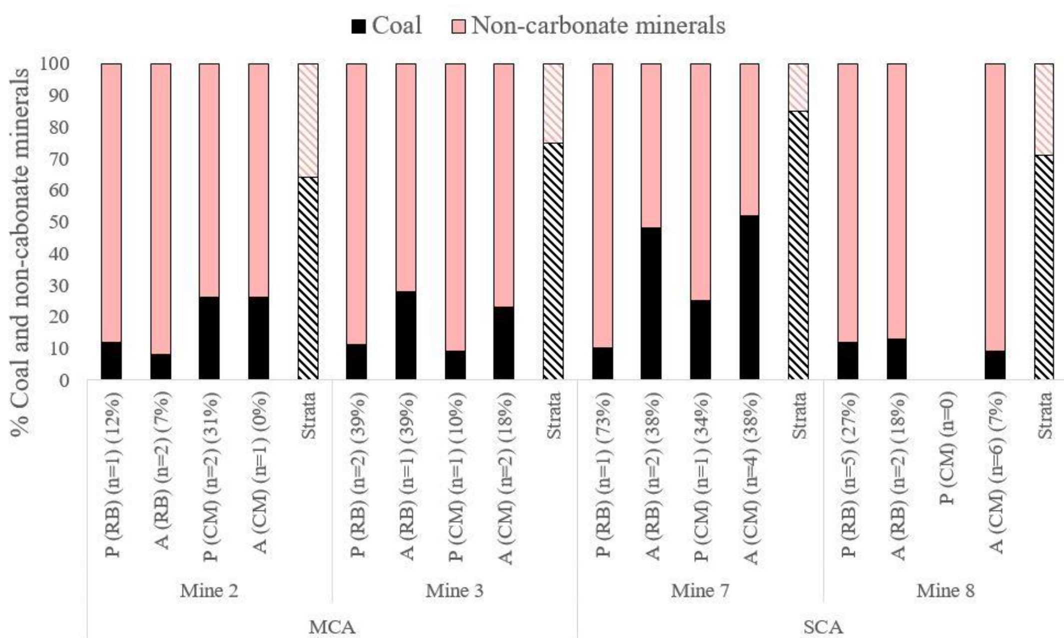

Figure 8. Normalized percentages of coal and non-carbonate minerals mass fractions for continuous miner and roof bolter personal (P) and area (A) dust samples versus percentages of coal and rock heights with respect to the total mining height (taken from Phillips et al., 2018[40]). The area samples shown here are those that were analyzed by TGA and verified by comparison to SEM area samples collected within the same sample set. The strata percentages are based on the seam thickness and total mining height data shown in Table 1; and in cases where a range of values was reported for one of these variables, the average value was used here.

Health data

Participation

Figure 9 shows the total study recruitment. 239 miners consented to participate in the study. However, we were unable to reach 89 after they had consented, either because they did not respond to repeated messages or no longer had a working telephone number. Another 19 withdrew from the study after consenting. 131 miners completed at least one part of the study.

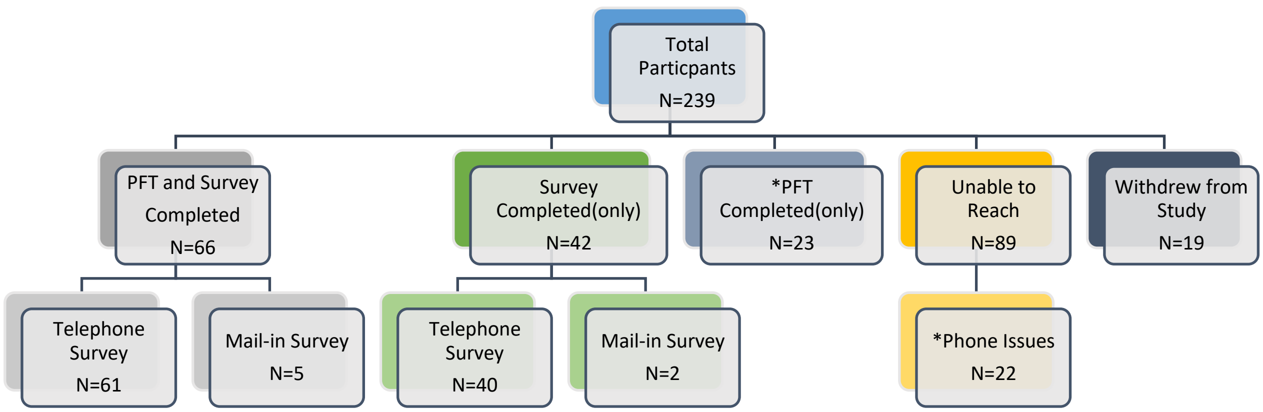

Figure 9. Total Study Recruitment

breakdown of study participation by region is shown in **Table 5**. The study includes 131 participants who have completed a PFT, survey, or both. By region, 38% were from MCA, 36% were from SCA and 26% were from NA. MCA had the highest percent of participants completing both the PFT and the survey (64%) and NA had the lowest percent completing both (35%). Approximately 1/3 of all participants completed the survey only.

Table 5. Participation by Region

Study Component	MCA		SCA		NA[1]		Total	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Both PFT and Survey	32	64.0	22	46.8	12	35.3	66	51.1
PFT only	4	8.0	19	40.4	0	0.0	23	16.8
Survey only	14	28.0	6	12.8	22	64.7	42	32.1
Total	50	100	47	100	34	100	131	100

[1] 3 miners from NA had retired at the time of participation

Survey response

Table 6 shows by region the standardized job names reported by survey participants. Bolter and electrician were the most common (14.5% each). Thirteen participants indicated that they spent all of their time outside of the mine and, thus, were not assigned any underground exposure estimates.

Table 6. Job Names by Region

Job Name	MCA (n=50)	SCA (n=47)	NA (n=34)	Total (n=131)	
	Number	Number	Number	Number	%
Beltman	2	2	1	5	3.8
Bolter	6	9	4	19	14.5
Continuous Miner Operator	3	4	0	7	5.3
Electrician	7	11	1	19	14.5
Fireboss	7	1	1	9	6.9
General Laborer	0	0	3	3	2.3
Lift Operator	1	0	1	2	1.5
Longwall Laborer	0	0	1	1	0.8
Longwall Mechanic	0	0	1	1	0.8
Maintenance Foreman	0	0	1	1	0.8
Mason	0	0	1	1	0.8
Mechanic Welder	1	0	0	1	0.8
Mine Foreman	3	3	0	6	4.6
Motor Man	2	1	5	8	6.1
Move crew	4	5	0	9	6.9
Outby Worker	1	2	2	5	3.8
Outside Mine Worker	4	2	7	13	9.9
Rock Dust Crew	2	0	0	2	1.5
Safety Representative	1	0	0	1	0.8
Scoop operator	1	2	1	4	3.0
Shear Operator	0	0	1	1	0.8
Shuttle Car Operator	4	4	1	9	6.9
Superintendent	0	1	0	1	0.8
Surveyor	1	0	0	1	0.8
Missing	0	0	2	2	1.5

Table 7 shows select results from the short survey (n=131). Overall, BMI was statistically significantly different among regions. Pairwise comparisons between MCA and NA, and SCA and NA were also statistically significant. Miners in NA had the highest BMI (35.3), which is classified as obese. MCA had the highest percent of smokers (58%), followed by SCA (43%), NA (29%).

Most of the responses to the specific conditions were ‘no’ or missing. Participants were most likely to report having had pneumonia or broken ribs. Percent reporting pneumonia was similar across all three regions; fewer participants in SCA reported having had broken ribs compared to MCA and NA. There were no self-reported cases of asbestosis, emphysema, silicosis, pneumoconiosis, or lung cancer.

Table 7. Select Short Survey Responses for Study Participants by Region

	MCA (n=50)		SCA (n=47)		NA (n=34)		Total (n=131)	
	Number	Percent (SD)	Number	Percent (SD)	Number	Percent (SD)	Number	Percent (SD)
BMI[1,3,4]	31.52	8.40	29.82	6.86	35.29	8.29	32.27	8.21
Smoking								
No	21	42.00	25	53.19	22	64.71	68	51.91
Yes	29	58.00	20	42.55	10	29.41	59	45.04
Missing	0		2	4.26	2	5.88	4	3.05
Asbestosis								
No	50	100.00	42	89.36	33	97.06	125	95.42
Yes	0	0.00	0	0	0	0.00	0	0.00
Missing	0	0.00	5	10.64	1	2.94	6	4.58
Asthma								
No	48	96.00	41	87.23	30	88.24	119	90.84
Yes	2	4.00	2	4.26	2	5.88	6	4.58
Missing	0	0.00	4	8.51	2	5.88	6	4.58
Chronic Bronchitis								
No	49	98.00	43	91.49	29	85.29	121	92.37
Yes	1	2.00	1	2.13	2	5.88	4	3.05
Missing	0	0.00	3	6.38	3	8.82	6	4.58
Emphysema								
No	50	100.00	44	93.62	32	94.12	126	96.18
Yes	0	0.00	0	0.00	0	0.00	0	0.00
Missing	0	0.00	3	6.38	2	5.88	5	3.82
Pneumonia								
No	43	86.00	35	74.47	29	85.29	107	81.68
Yes	6	12.00	8	17.02	4	11.76	18	13.74
Missing	1	2.00	4	8.51	1	2.94	6	4.58
Tuberculosis								

	MCA (n=50)		SCA (n=47)		NA (n=34)		Total (n=131)	
	Number	Percent (SD)	Number	Percent (SD)	Number	Percent (SD)	Number	Percent (SD)
No	49	98.00	44	93.62	32	94.12	125	95.42
Yes	1	2.00	0	0.00	0	0.00	1	0.76
Missing	0	0.00	3	6.38	2	5.88	5	3.82
Silicosis								
No	49	98.00	43	91.49	32	94.12	124	94.66
Yes	0	0.00	0	0.00	0	0.00	0	0.00
Missing	1	2.00	4	8.51	2	5.88	7	5.34
Pneumothorax								
No	50	100.00	44	93.62	31	91.18	125	95.42
Yes	0	0.00	0	0.00	1	2.94	1	0.76
Missing	0	0.00	3	6.38	2	5.88	5	3.82
Lung Cancer								
No	50	100.00	44	93.62	32	94.12	126	96.18
Yes	0	0.00	0	0.00	0	0.00	0	0.00
Missing	0	0.00	3	6.38	2	5.88	5	3.82
Broken Ribs[2]								
No	41	82.00	43	91.49	28	82.35	112	85.50
Yes	9	12.00	1	2.13	4	11.76	14	10.69
Missing	0	0.00	3	6.38	2	5.88	5	3.82
Pneumoconiosis								
No	49	98.00	44	93.62	33	97.06	126	96.18
Yes	0	0.00	0	0.00	0	0.00	0	0.00
Missing	1	2.00	3	6.38	1	2.94	5	3.82
Chest Injury								
No	48	96.00	43	91.49	32	94.12	123	93.89
Yes	2	4.00	1	2.13	1	2.94	4	3.05
Missing	0	0.00	3	6.38	1	2.94	4	3.05

	MCA (n=50)		SCA (n=47)		NA (n=34)		Total (n=131)	
	Number	Percent (SD)	Number	Percent (SD)	Number	Percent (SD)	Number	Percent (SD)
<u>Other Lung Problem</u>								
No	45	90.00	43	91.49	30	88.24	118	90.08
Yes	3	6.00	1	2.13	2	5.88	6	4.58
Missing	2	4.00	3	6.38	2	5.88	7	5.34

[1]Study factor overall $p<0.05$, [2]Pairwise MCA/SCA $p<0.05$, [3]Pairwise MCA/NA $p<0.05$, [4]Pairwise SCA/NA $p<0.05$

Table 8 shows select demographic and health characteristics collected from the long survey (n=108). All study participants are men. Overall, just over half of the participants were under 45 years old. The average BMI was in the overweight/obese range. Differences in smoking patterns among regions were statistically significant, primarily due to fewer smokers in the NA region compared to the MCA region. The majority of respondents reported not using respirators. Opinions on whether the job used the participants' skills was also statistically significantly different overall, due to more participants in the NA region feeling neutral about the question compared to those in MCA who felt strongly that their jobs used their skills. There were also statistically significant differences in reported sleep problems by region. More participants in MCA reported never having sleep problems than those in SCA or NA ($p<0.05$). Generally, they also reported approximately 2 days of poor physical and mental health per month (range: 0-30), low work stress (62% sometimes/hardly/never) and high job satisfaction (61% very/somewhat).

Table 8. Select Long Survey Responses for Study Participants by Region

Study Factor	MCA (n=46)		SCA (n=28)		NA[1] (n=34)		Total (n=108)	
	Number (Mean)	Percent (Range)	Number (Mean)	Percent (Range)	Number (Mean)	Percent (Range)	Number (Mean)	Percent (Range)
Sex								
Male	46	100	28	100	34	100	108	100
Female	0	0	0	0	0	0	0	0
Age Group								
20-24	4	8.70	1	3.57	1	2.94	6	5.56
25-34	11	23.91	9	32.14	3	8.82	23	21.30
35-44	7	15.22	10	35.71	10	29.41	27	25.00
45-54	10	21.74	6	21.43	9	26.47	25	23.15
55+	14	30.43	2	7.14	11	32.35	27	25.00
BMI	29.34	(19.12, 50.17)	29.20	(19.3, 42.00)	30.76	(20.3, 44.30)	29.75	(19.12, 50.17)
Smoke[2,4]								
No	17	36.96	16	57.14	22	64.71	55	50.93
Yes	29	63.04	12	42.86	10	29.41	51	47.22
Missing	0	0	0	0	2	5.88	2	1.85
Respirator Use								
No	33	71.74	25	89.29	24	70.59	82	75.93
Yes	13	28.26	3	10.71	8	23.53	24	22.22
Missing	0	0	0	0	2	5.88	2	1.85
Job Uses Skills[4]								
Strongly agree	13	28.26	8	28.57	7	20.59	28	25.93
Agree	26	56.52	13	46.43	15	44.12	54	50.00
Neutral	4	8.70	6	21.43	11	32.35	21	19.44
Disagree	3	6.52	1	3.57	1	2.94	4	3.70
Self-Reported Health								
Excellent/very good	19	41.30	13	46.43	11	32.35	43	39.81
Good	21	45.65	10	35.71	19	55.88	50	46.30
Fair/Poor	6	13.04	5	17.86	4	11.76	15	13.89
Sleep Problems[2,4]								
Often	8	17.39	11	39.29	7	20.59	26	24.07
Sometimes	10	21.74	5	17.86	13	38.24	28	25.93
Rarely	9	19.57	7	25.00	11	32.35	27	25.00
Never	19	41.30	5	17.86	3	8.82	27	25.00
Days Not Good Physical Health	2.00	(0, 30)	4.29	(0, 30)	2.30	(0, 29)	2.69	(0, 30)
Days Not Good	1.93	(0, 30)	6.57	(0, 30)	3.79	(0, 30)	3.74	(0, 30)

Study Factor	MCA (n=46) Number (Mean)	MCA (n=46) Percent (Range)	SCA (n=28) Number (Mean)	SCA (n=28) Percent (Range)	NA[1] (n=34) Number (Mean)	NA[1] (n=34) Percent (Range)	Total (n=108) Number (Mean)	Total (n=108) Percent (Range)
Mental Health[3]								
Days No Usual Activities	1.63	(0, 30)	2.57	(0, 30)	1.06	(0, 20)	1.70	(0, 30)
Work Stressful								
Always	6	13.04	10	35.71	5	14.71	21	19.44
Often	9	19.57	7	25.00	4	11.76	20	18.52
Sometimes	22	47.83	10	35.71	19	55.88	51	47.22
Hardly ever	7	15.22	1	3.57	5	14.71	13	12.04
Never	2	4.35	0	0	1	2.94	3	2.78
Job Satisfaction								
Very	20	43.48	13	46.43	8	23.53	41	37.96
Somewhat	12	26.09	3	10.71	10	29.41	25	23.15
Neutral	9	19.57	8	28.57	11	32.35	28	25.93
Not too/Not at all	5	10.87	4	14.29	5	14.71	14	12.96

[1] 3 miners from NA had retired at the time of participation;
[2]Study factor overall $p<0.05$;
[3]Pairwise MCA/SCA $p<0.05$;
[4]Pairwise MCA/NA $p<0.05$

There were 22 participants in NA that completed the survey, but did not have PFT results. Of these 22, 16 are non-smokers. Although there is not a statistically significant difference in smoking habits between those who only took the survey compared to those with PFT results (p = 0.232), the proportion of non-smokers in those with survey data is 59.5%, while non-smokers make up only 48.3% of those with PFT results.

Pulmonary function test results

Those in NA were less likely to complete the PFT compared to those in SCA and MCA ($p < 0.001$). There was a not statistically significant difference in mine tenure between those with PFT results and those without (p = 0.10). Mean mine tenure for those without PFT results was 10.98 years, while for those without it was only 7.37 years. There were no statistically significant differences among those with and without PFTs for smoking, BMI, or age.

Figures 10a-b shows graphically the distribution of our primary outcome of interest, FEV1/FVC, by region. Overall, 89 participants had PFTs, with the fewest being from the NA region (n=12) and the most from the SCA region (n=41). Three participants from NA had recently retired, and were not technically eligible for the study, so results are shown once with their test results (**Figure 10a**) and without their results (**Figure 10b**).

Lower FEV1/FVC indicates poorer lung function with values below 80 considered abnormal. As shown, the ranges for values in MCA and SCA were similar, ranging from 70 to approximately 90. While participants in NA also had a lower range of 70, there were no NA values above 82. The mode for MCA and NA was approximately 80, while for SCA the mode was higher and the distribution was flatter.

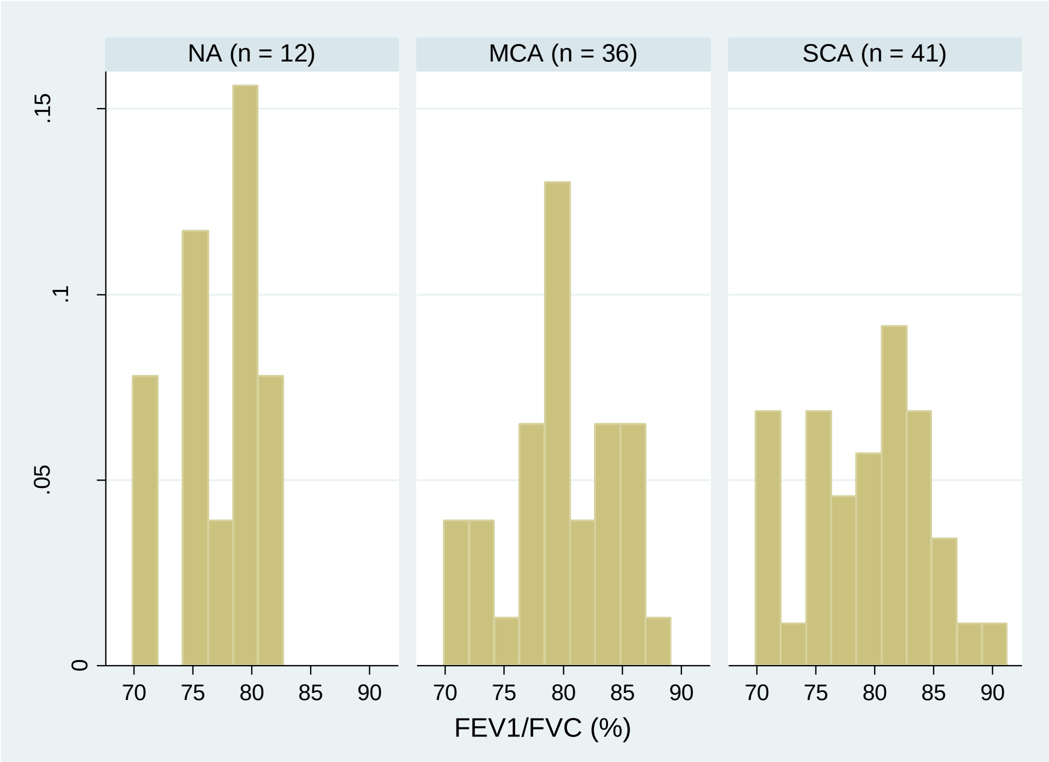

Figure 10a. FEV1/FVC Results by Region (Including All NA Participants)
ANOVA of difference in FEV1/FVC across regions gives p-value = 0.1794.

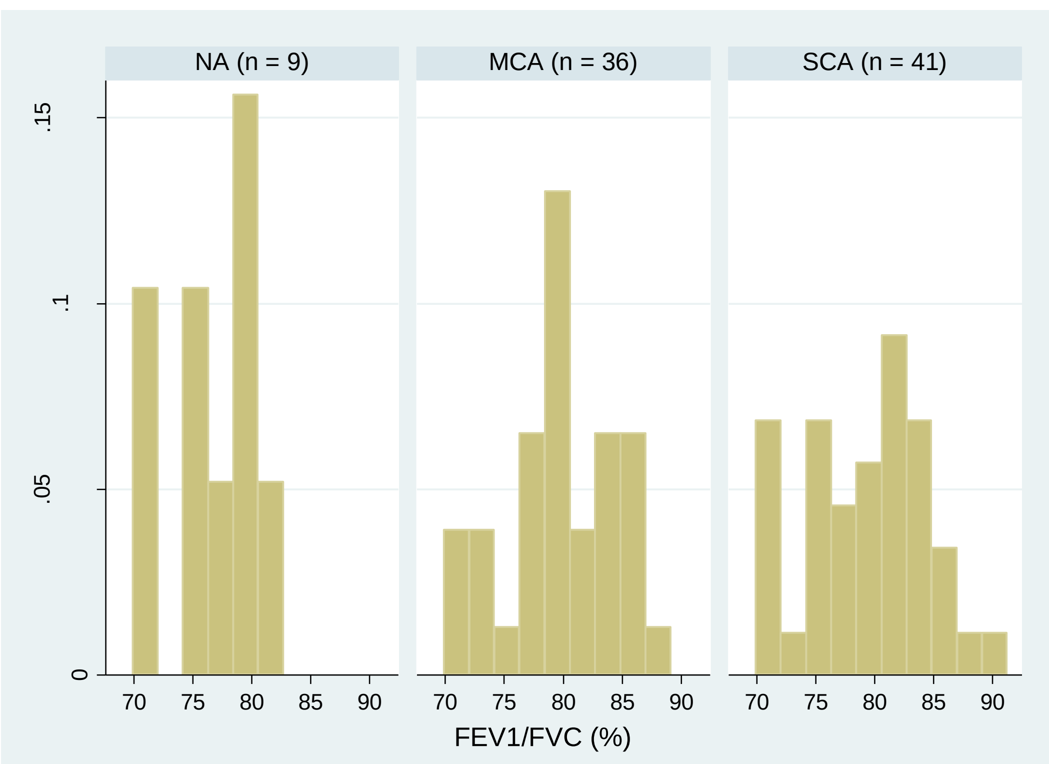

Figure 10b. FEV1/FVC Results by Region (Excluding 3 NA Retirees)
ANOVA of difference in FEV1/FVC across regions gives p-value = 0.1471

Table 9 shows the results of the PFTs by region for select study factors. Participants from SCA were statistically significantly younger than those from NA, and, overall, age was statistically significant predictor of PFT result. High blood pressure had a statistically significant association with the PFT results; only 6% of the participants had no evidence of high blood pressure (readings below 120/80).

Also shown are several measures from the PFT. None were statistically significantly different across regions. FEV1% was between 85-90% for all regions. FVC% and Ratio% were higher (92-97%). FEV1/FVC was very similar in MCA (79.9) and SCA (79.2), and slightly lower in NA (76.9 with retirees; 76.3 without retirees). Also shown is the number of participants with abnormal FEV1/FVC levels (<80). Overall, slightly more than half of the participants were abnormal. NA had the highest percent (58.3% with retirees; 66.7% without retirees).

Table 9. Select Personal Characteristics, Health Characteristics and PFT Results by Region

Study Factor	MCA (n=36) Number (Mean)	MCA (n=36) Percent (SD)	SCA (n=41) Number (Mean)	SCA (n=41) Percent (SD)	NA (n=12) Number (Mean)	NA (n=12) Percent (SD)	NA[3] (n=9) Number (Mean)	NA[3] (n=9) Percent (SD)	Total (n=89) Number (Mean)	Total (n=89) Percent (SD)
Age[1,2]	43.83	10.85	38.83	11.21	48.17	17.11	41.89	14.23	42.11	12.32
BMI	29.38	4.40	29.68	5.85	28.84	4.70	28.05	5.09	29.45	5.11
Smoke										
No	17	47.22	22	53.66	8	66.67	5	55.56	47	52.81
Yes	19	52.78	19	46.34	4	33.33	4	44.44	42	47.19
High blood pressure(HBP)[1]										
No	3	8.33	2	4.88	1	8.33	1	11.11	6	6.74
Pre-HBP	27	75.00	28	68.29	7	58.33	5	55.56	62	69.66
Stg1/Stg2	6	16.67	11	26.83	2	16.67	2	22.22	19	21.35
Missing	0	0	0	0	2	16.67	1	11.11	2	2.25
Asthma										
No	34	94.44	33	80.49	11	91.67	8	88.89	78	87.64
Yes	2	5.56	7	17.07	1	8.33	1	11.11	10	11.24
Missing	0	0	1	2.44	0	0	0	0	1	1.12
FEV1 %	89.97	10.65	90.49	11.81	85.33	11.61	89.33	8.41	89.58	11.33
FVC %	92.17	9.82	94.54	12.76	86.75	14.72	92.56	9.91	92.53	12.08
FEF_{25-75} %	86.50	24.70	82.80	21.10	82.75	17.70	81.44	17.03	84.29	22.08
FEV1/FVC	**79.94**	**4.68**	**79.24**	**5.06**	**76.97**	**3.92**	**76.39**	**4.13**	**79.22**	**4.81**
Abnormal (FEV1/FVC<80)										
Yes	19	52.78	20	48.78	7	58.33	6	66.67	46	51.69
No	17	47.22	21	51.22	5	41.67	3	33.33	43	48.31

[1]Study factor overall p<0.05 (ANOVA), [2]Pairwise SCA/NA p<0.05
[3]excluding 3 retirees

Table 10 shows the results of univariable regression for select personal characteristics and FEV1/FVC. As shown, only BMI was a statistically significant predictor ($p<0.05$) of FEV1/FVC univariably.

Table 10. Univariable Associations Between Select Personal Characteristics and FEV1/FVC

Factor	Coefficient	Standard Error	P-value
Age	-0.053	0.041	0.206
Smoking Status (yes)	-1.059	1.021	0.302
BMI	0.241	0.098	0.016*
High blood pressure			
Pre-HBP	0.515	2.092	0.806
Stg1/Stg2	0.510	2.291	0.825
Asthma (yes)	1.964	1.621	0.229
Mine tenure	-0.016	0.066	0.809

*p<0.05

CCSEM Particle Concentrations for Health Data Component

Figures 11-13 show TWA by region and standardized job name for the dust characteristics. The figures show the percent of total particle concentration for the three size bins of cross-sectional diameter, three aspect ratios, and 6 components included in the chemical composition, respectively, for the n=89 participants with PFT results.

These TWAs were based on the job categories reported by the participants, and assigned time spent in certain representative mine locations (**Table 5**). One participant in NA did not provide a job title and is not represented in the Figures or associations with dust characteristics. Bolter, motor man, and outby worker were represented in each of the three regions.

In MCA and SCA, bolter had the highest particle concentration in general. Bolter in NA had approximately one-quarter the total particle concentration compared to bolters in MCA or SCA. However, motor man and outby worker in NA had 2-3 times the TWA compared to those respective jobs in MCA or SCA, primarily due to higher particle concentrations of carbonate in NA. In NA, longwall laborer had the highest particle concentration, followed by mason. Beltman, motor man, move crew, and safety representative had the lowest TWA in MCA; motor man had the lowest TWA in NA; and motor man, move crew, and superintendent had the lowest TWA in SCA.

All jobs had the majority of particles in the [0.94-2.0) µm cross-sectional size group (**Figure 11**). Most jobs had the majority of particles in the [1.5-3.0) aspect ratio, with only a very small proportion of particles with the largest ratio (**Figure 12**). As discussed earlier, the primary differences in chemical composition were that NA had lower proportions of AS and Q, but a higher proportion of carbonate compared to MCA and SC. These are clearly illustrated by job classification in **Figure 13**. Heavy minerals and other materials comprised less than 1% each of the samples.

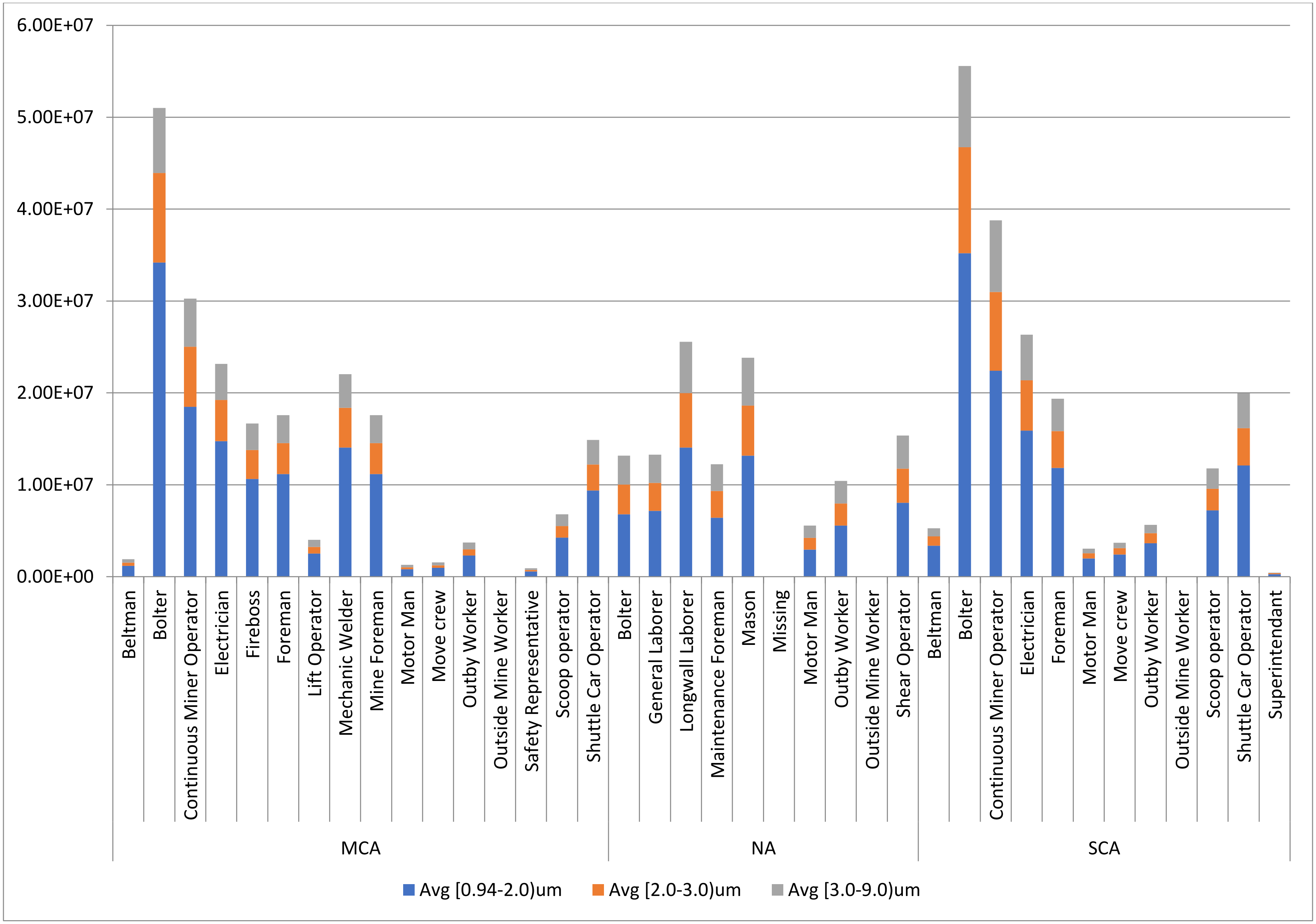

Figure 11. Cross-Sectional Diameter of Particles by Job Title and Mine Region Among Participants with PFT Results

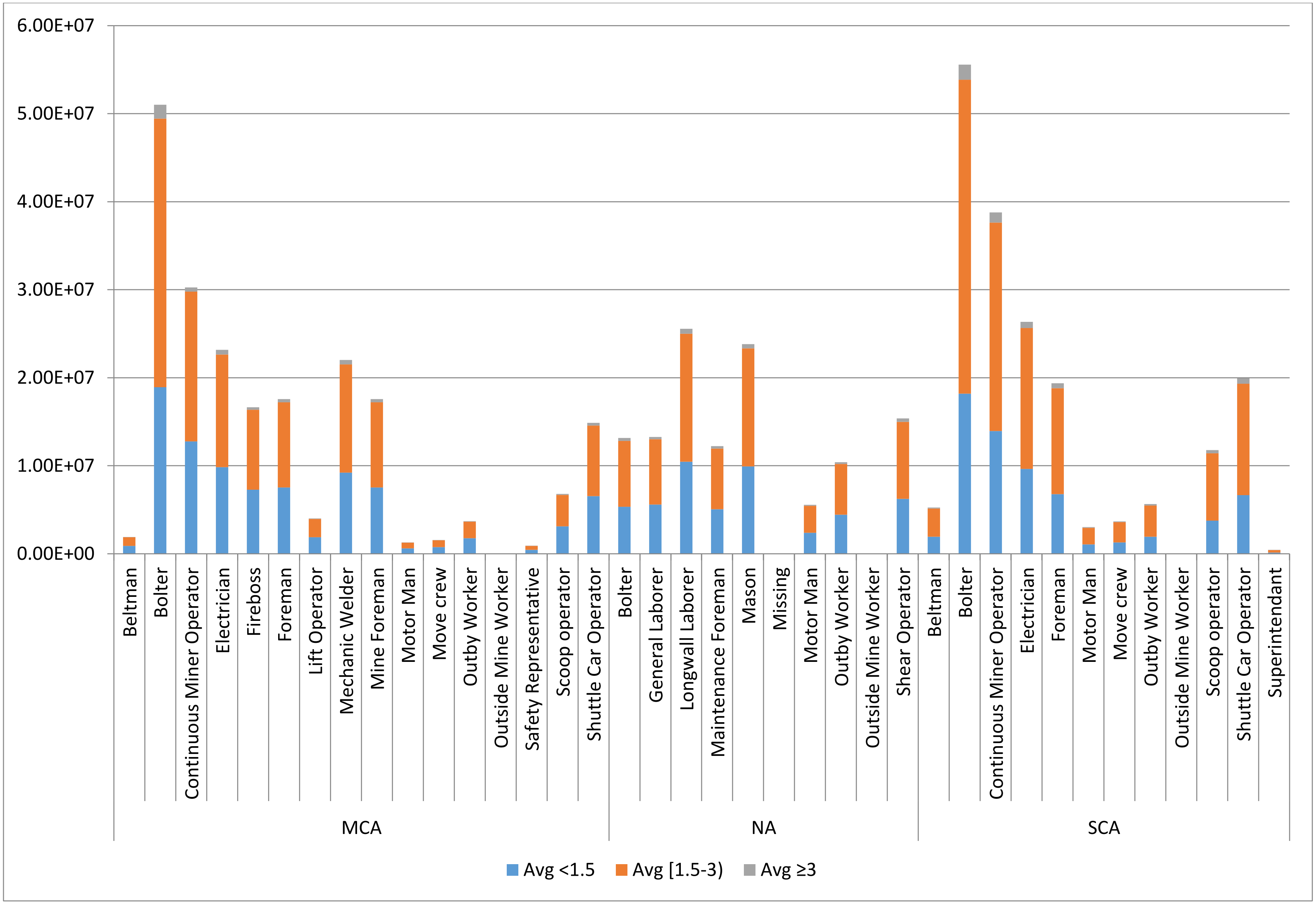

Figure 12. Aspect Ratio of Particles by Job Title and Mine Region Among Participants with PFT Results

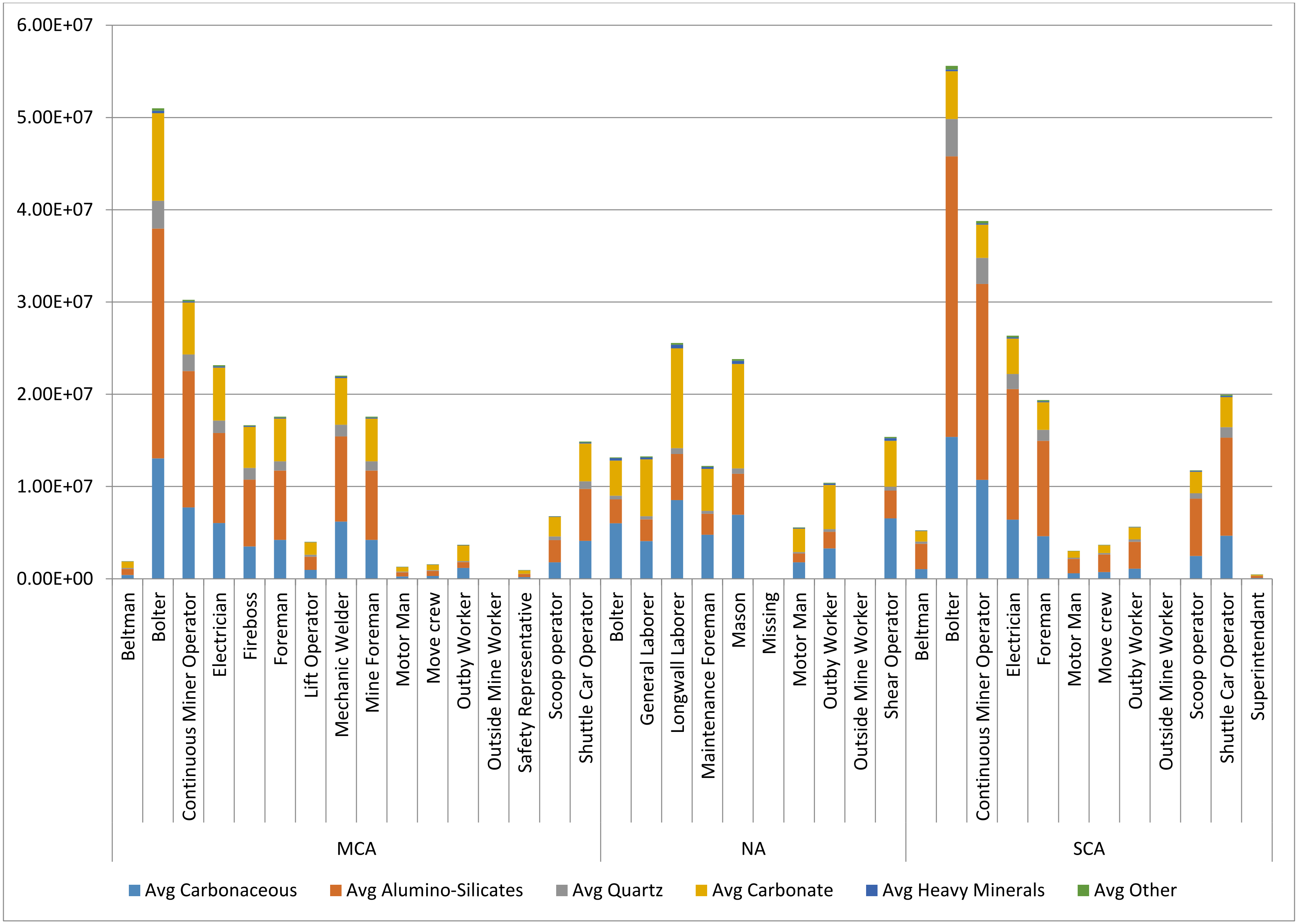

Figure 13. Chemical Composition of Particles by Job Title and Mine Region Among Participants with PFT Results

Figure 14 shows the cross correlations for the dust characteristics. Red indicates perfect positive correlation (the two characteristics always co-occur) and blue indicates perfect negative correlation (the two characteristics never co-occur). Particles with the aspect ratio ≥ 3 do not co-occur with either of the 2 smaller aspect ratio groups; they also do not co-occur with particles with cross-sectional diameter [0.94, 2.0) µm. Particles with cross-sectional diameter [0.94, 2.0) µm do not co-occur with those of the largest cross-sectional diameter [3.0, 9.0) µm, nor do they co-occur with Other or Heavy Mineral particles. Carbonate particles co-occur most strongly with particles with cross-sectional diameter [0.94, 2.0) µm. Carbonaceous particles do not have any strong correlations and Quartz particles have correlations near zero with every other characteristic.

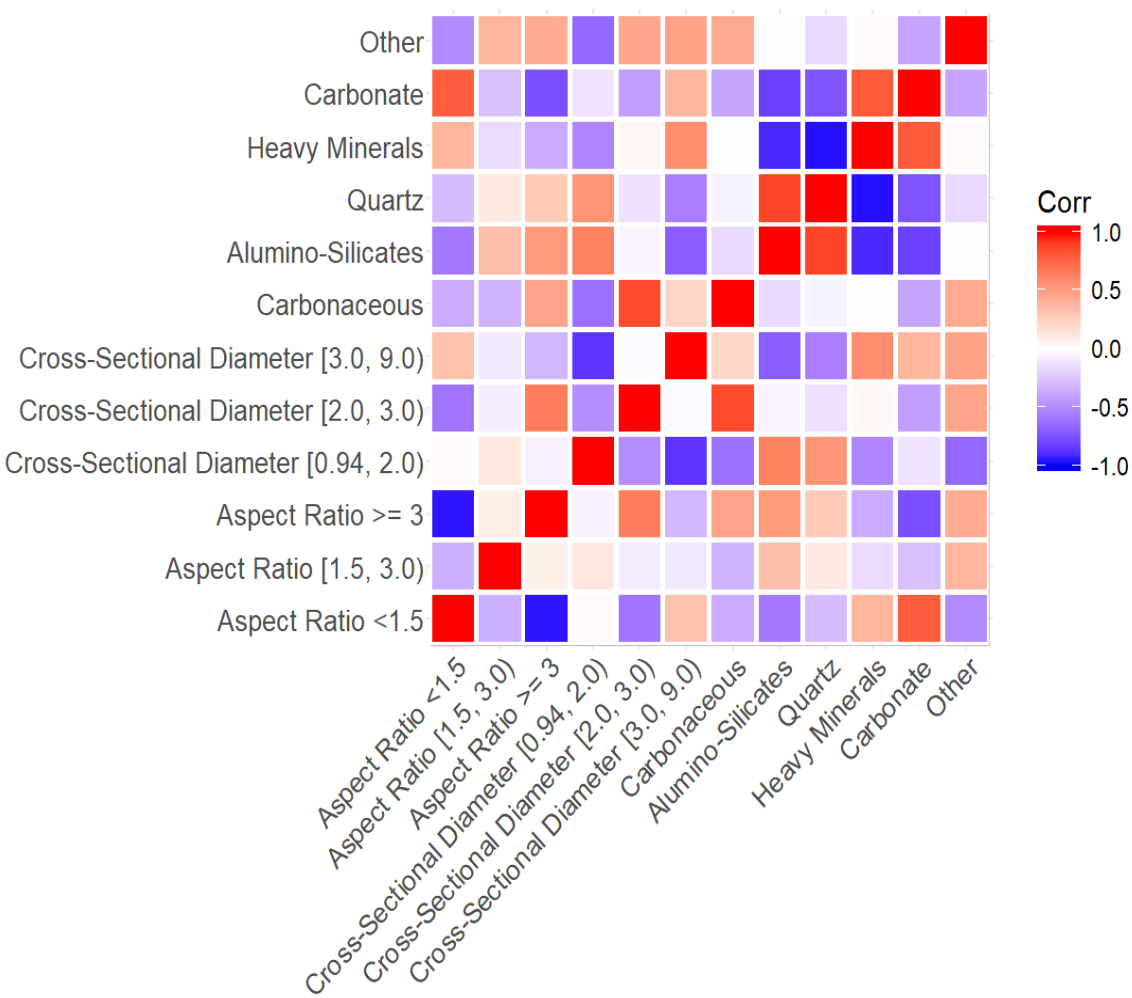

Figure 14. Cross Correlations Among Dust Characteristics

Correlation of dust characteristics and health data

Figure 15 shows the relationship between total particle concentration as calculated by the time-weighted average (TWA) and the FEV1/FVC results. The correlation coefficient for the association was 0.17 (weak).

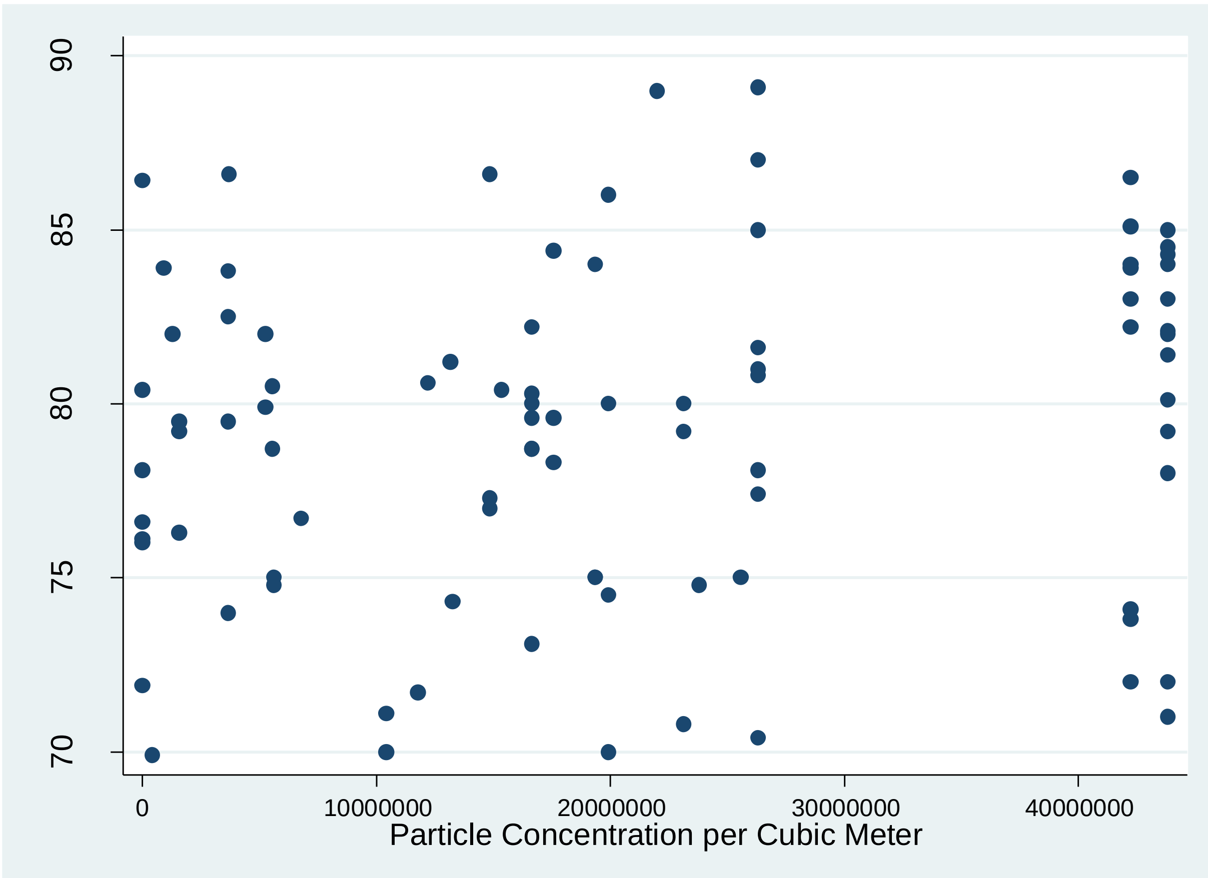

Figure 15. Total Particle Concentration by FEV1/FVC Result

Table 11 shows the univariable associations between FEV1/FVC and the centered logratio transformation of the total particle concentration proportions for each of the three cross-sectional diameters, three bins of aspect ratio, and six chemical components, based on the CCSEM-EDX methodology. We found no statistically significant associations with FEV1/FVC for aspect ratio or cross-sectional diameter. While we would expect to find a negative coefficient for the smallest cross-sectional diameter, we did not (coefficient = 5.43; p-value=0.319). Quartz and heavy minerals had statistically significant associations with FEV1/FVC, but no other chemical component did. The coefficient for quartz was positive, which is biologically implausible. The coefficient for heavy minerals was in the expected direction.

Table 11. Univariable Associations Between FEV1/FVC and Dust Characteristics (Area Samples Measured by CCSEM)

Dust Characteristic	Coefficient	Standard Error	P-value
Aspect Ratio			
<1.5	1.66	3.24	0.610
[1.5, 3.0)	-9.45	12.31	0.445
≥3	-1.13	3.44	0.743
Cross Sectional Diameter			
[0.94, 2.0) µm	5.43	5.42	0.319
[2.0, 3.0) µm	-2.86	10.77	0.791
[3.0, 9.0) µm	-6.21	6.23	0.322
Chemical Composition (%)			
Carbonaceous	1.68	2.91	0.566
Alumino-Silicates	2.20	1.33	0.101
Quartz	3.16	1.45	0.032*
Carbonate	-2.11	1.29	0.106
Heavy Mineral	-2.87	1.36	0.039*
Other	-2.38	4.06	0.559

*****p-value <0.05

Table 12 shows by region the correlation coefficients for the association between FEV1/FVC and the dust characteristics by region. For MCA and SCA, correlations were virtually null or weak for all characteristics. We found a different pattern of correlations for NA, which was more pronounced in the 7 active workers rather than when the retirees were included. For active workers in NA, we found moderate negative correlations for aspect ratios of <1.5 and [1.5,3.0) indicating that an increase in particles with these dimensions was associated with lower FEV1/FVC. We found a moderately positive correlation with higher aspect ratio, indicating that an increase in particles of this dimension was associated with higher FEV1/FVC. Similarly, we found a moderately negative correlation with the smallest particle size and moderately positive correlations with the larger particle sizes among active workers in NA when we considered cross-sectional diameter. For chemical composition, we found moderately positive correlations between FEV1/FVC and carbonaceous, alumino-silicates, quartz and heavy minerals. These findings are not consistent with our understanding of the literature. Exposure to silica and quartz in particular have been found to be associated with poorer lung function among underground miners [26, 33-35]. We found a moderately negative correlation between

FEV1/FVC and carbonate and other, indicating that a higher proportion of these particles was associated with lower FEV1/FVC. Normalizing the dust data by removing the proportion due to carbonate had no effect on the direction or strength of any association (data not shown).

Table 12. Correlation Coefficient for Association Between FEV1/FVC and Dust Characteristics By Region (Area Samples Measured by CCSEM)

Dust Characteristic	MCA (n=33)	SCA (n=39)	NA (n=10)	NA[1] (n=7)	Total (n=82)
Aspect Ratio					
<1.5	-0.0193	0.3358	-0.5551	-0.7596	0.0571
[1.5, 3.0)	-0.0714	-0.0683	-0.6881	-0.7652	-0.0856
≥3	0.0289	-0.2085	0.6080	0.7713	-0.0367
Cross Sectional Diameter					
[0.94, 2.0) µm	-0.0270	-0.2048	-0.6073	-0.6009	0.1113
[2.0, 3.0) µm	0.0114	0.2464	0.5847	0.7698	-0.0297
[3.0, 9.0) µm	0.0025	0.1372	0.2988	0.1488	-0.1107
Chemical Composition (%)					
Carbonaceous	0.0149	0.2429	0.6741	0.7693	0.0643
Alumino-Silicates	-0.0027	0.2242	0.1303	0.4951	0.1823
Quartz	-0.1190	0.2380	0.1303	0.5662	0.2374
Carbonate	-0.0037	-0.2398	-0.6628	-0.7681	-0.1798
Heavy Mineral	0.0375	-0.2362	0.6581	0.7216	-0.2288
Other	0.1592	0.2321	-0.6524	-0.7677	-0.0654

[1]excluding 3 retirees

Personal dust samples were available for some miners in MCA (n=19) and SCA (n=23). As discussed on page 25, these were analyzed using TGA and correlations were examined for percent coal, percent carbonate and percent non-carbonate in the samples [35]. The correlation coefficients were null to very weak, indicating that there were no associations between sample composition and FEV1/FVC in these data (data not shown). Again, normalizing the dust data by removing the proportion due to carbonate had no effect on the direction or strength of any association (data not shown).

Discussion & Conclusions

Despite extensive efforts to recruit miners to participate in this study, we had a limited sample size which precludes us from drawing strong conclusions regarding the associations of lung function and dust characteristics found in theses analyses. We are, however, able to make some observations.

The miners who had PFTs also had some differences demographically than those who have been involved in previous studies. Our mean age was 42.1 with no statistically significant difference by region. Wang et al [46] included miners with a mean age of 46.7 among those with no CWP, while Suarthana et al [17] had median ages of 50 and 52 for the regions that covered the same territory as those included in this study. They also found a median tenure of 22-25 years compared to our mean tenure of approximately 11 years. These differences indicate that our miners probably had less opportunity for exposure to the underground mine environment, but that personal risk factors are similar to those found in other cohorts.

There were some similarities in demographic characteristics and risk factors in our cohort to those previously shown in the literature [32, 46]. The mean BMI of our participants was in overweight to obese category, indicating that weight-related concomitant health problems may exist. This is supported by the finding that over 90% of participants with PFTs had pre- or existing high blood pressure, despite the average age of these participants being 42. Casey et al [47] found that among miners in the Enhanced Coal Workers' Health Surveillance Program, the prevalence of obesity was 52% higher and the presence of hypertensive blood pressure was 60% higher than the US population, respectively. We also found that half of the participants were smokers, although this increased to 63% among MCA participants. Blackley et al. reported 56% ever smoking among small and 49% ever smoking among large mine participants in their study [32]. The majority of participants in this study reported no respirator use. However, 40% of all participants reported their health as excellent or very good. Three quarters of the men agreed or strongly agreed that their job uses their skills. They also reported relatively high levels of job satisfaction.

More than half of the 89 participants with PFTs had FEV1/FVC below 80. The FEV1/FVC values found here are slightly higher than those reported in 2001 for living cases and referents by Beeckman [48]. In that study, cases and referents had mean FEV1/FVC of 71.1 and 77.2 ($p<0.001$), respectively; in this study mean FEV1/FVC was 79.9, 79.2, and 77.0 for MCA, SCA, and NA ($p=0.1794$), respectively. Wang et al. [41] found mean FEV1/FVC of 76.5 among underground miners (all regions) with no evidence of CWP, and mean FEV1/FVC of 72.5 and 69.9 among those with simple CWP and PMF, respectively. Blackley et al. [32] reported lower mean FEV1/FVC in miners from small mines (75.5) than in miners from large mines (76.5), however mean FEV1/FVC values were higher than those for all three regions in this study.

PFT cannot directly indicate CWP, which needs to be diagnosed via radiograph. However, we can compare patterns in our PFT measures of lung impairment to those of reported CWP in the literature. Suarthana found less CWP among District 3 miners (the equivalent of our NA) than predicted, but found significantly higher CWP in District 4 (equivalent to our SCA and MCA) than predicted. We found mean FEV1/FVC to be similar across all three regions. We did not find lower FEV1/FVC among miners in MCA and SCA in contrast to Suarthana's findings with CWP [17]. In fact, our participants in NA had slightly lower FEV1/FVC than those in MCA and SCA, although the results were not statistically significantly different. Our PFT results indicate that our participants in MCA, SCA, and NA are not representative of all miners in those regions.

Compared to the literature, we had better than expected FEV1/FVC results among SCA and MCA participants and worse than expected FEV1/FVC among NA participants. Because we relied on volunteer participation, this likely provides evidence of a self-selection bias.

This self-selection could operate in at least two possible ways:

1) Attending the study information sessions was voluntary as was consenting to participate. Miners had to have interest in the study to attend the information session and additional motivation to participate. This could mean that we recruited miners who were very motivated to participate because they had good mining experiences in MCA and SCA and recruited miners who were very motivated to participate because they had more negative mining experiences in NA. There is some evidence for this from the survey results (Table 8) where there was a statistically significant difference between MCA and NA respondents about their job using skills. 84% of MCA participants strongly agreed/agreed that their job uses skills compared to 64% from NA.
2) We did not recruit from all possible MCA, SCA, or NA mines. Our mining company partners are likely to be responsive to dust-related health problems by virtue of engaging in a partnership with this. This means that there are measures in place to reduce total exposure to their miners through better ventilation, engineering, and practices. Our dust samples may show high levels of alumino-silicates, for example, but that does not mean that the miners are being exposed to those levels because of mine-specific practices to attenuate exposure. Mines with which we did not partner may have different practices in place which expose miners to different particle concentrations.

An examination of the dust characteristics suggests that alumino-silicates were higher in MCA and SCA than in NA. Conversely, there was a higher proportion of carbonate in NA than in MCA and SCA. The carbonates found in the samples, particularly those in NA, may be due to rock dusting. Anecdotally, during sampling, the application of rock dust appeared to be much heavier in NA than in the SCA and MCA mines. Dusting mine surfaces with inert rock particles is a common practice in underground coal mines to reduce explosibility hazards related to coal dust. Rock dusting is required by federal regulation in the US (Title 30, Code of Federal Regulations, Section 75.403). Rock dust products are most often made from high purity limestone or dolomite (i.e., carbonate minerals) and may have considerable content in the respirable size range [49]. We found higher percentages of carbonate in the NA samples than in the MCA and SCA samples. Johann [50] notes higher use of rock dust products in NA mines and states, "While geologic materials cut in the mine may obviously contribute carbonate particles depending on their mineralogy, rock dust products appear to contribute substantial concentrations of carbonate particles to the total respirable dust in some cases."

While our cohort size was limited, we were able to evaluate associations between lung function and dust characteristics using compositional data analysis. This type of analysis controls for collinearity when analyzing parts that sum to a whole, like the proportions that make up each component of dust characteristic. Because the methodology is not appropriate for zeroes in the measurement, we only evaluated the 82 miners who had dust exposure and PFTs. This leads to stronger correlation coefficients would be found if all associations in the entire mine environment were included, because some miners validly have no dust exposure.

The number of NA participants was lower than targeted despite extensive recruitment efforts, and the PFT results among NA miners was lower than anticipated based on previous research. Our research leaves the question unanswered of why we did not find lower PFT results in miners from MCA and SCA than in miners from NA. There are several possibilities for this finding.

Job names were based on self-report and assigned to time spent in areas. While these allowed us to calculate TWA, we made broad assumptions about the time distribution and did not perform individual time studies to confirm these assumptions.

Our study design for sampling and recruitment was not a representative sample of all miners or dust conditions in the MCA, SCA or NA regions. The differences found in dust characteristics particularly between NA and SCA/MCA mines are likely indicative of the major trends in practices and conditions in these areas, at least during the period when we were sampling and within the specific regions we sampled. Greater differences might be found if we had sampled and recruited from the much smaller mines in CA.

The recent spikes in rapidly progressive lung disease that are now showing up in parts of CA may be associated with somewhat different dust conditions, and with miners not fully represented, than those in our study. We did not recruit or sample in the very small mines that have been previously implicated as hot spots for CWP [21, 32, 55]. Consistent with previously published literature, we found high total particle concentrations with a high proportion of alumino-silicates for roof bolters and continuous miner operators, especially in MCA and SCA. Blackley et al [26] found that, among miners with PMF, 43% reported working as roof bolters and 33% reported working as continuous miner operators. This was also consistent with an earlier study that found 68% of miners with advanced pneumoconiosis reported working as roof bolters. While our dust characteristics are consistent with the literature, our PFT results are not.

Many of the associations we found between FEV1/FVC and dust characteristics appear counter-factual. This seems most likely to be due to a non-representative sample of miners in our study. In particular, exposure to quartz and alumino-silicates in miners has been associated with poorer lung function [33, 51]. It is possible that we identified some true signals in these data, particularly in the relationship between carbonate exposure and FEV1/FVC among NA miners. Very fine carbonate particles are used in rock dusting [49], as evidenced by the high correlation coefficient we found between carbonate and the smallest cross-sectional diameter group. While these particles have not traditionally been thought to negatively influence lung function [52], there has been some evidence of increased wheezing, phlegm, and coughing associated with carbonate exposure [53].

Additionally, we needed volunteers to participate in this study, so all of the miners self-selected. It is possible that miners who were experiencing health problems were more likely to volunteer, which led to similar PFT results among the regions. It is also possible that miners who were healthier were more likely to volunteer, and that we would have found lower PFT results if we had used a different group of miners from these same mines. Our results showed lower than expected FEV1/FVC among NA miners compared to SCA and MCA miners. Whatever the reason(s), these results do not support those published recently of more advanced lung disease among SCA and MCA miners compared to those in NA.

It is also possible that while the PFT is a marker for abnormal lung function, it does not capture more advanced CWP and that chest radiographs may have noted more severe disease in participants from MCA and SCA. We required active employment from our participants, meaning that those who already had lung disease and not able to work were not eligible to participate. In that way, our findings are probably influenced in part by the ‘‘healthy worker effect,’’ the relative absence of deleterious employment-related health risks, the positive health effects of continuing employment, and better health care access [54].

Also, PFTs are a measure of cumulative effects from occupational and other exposures. The dust characteristics are a snapshot in time. There will be large changes in dust characteristics (e.g., due to changes in rock dusting practices or mining practices) both within a short time period and across long time period that are not captured here. We also used the job at time of participation for the dust associations. Changes in job duties, mine locations, or percent spent in different areas were not reflected here and could dramatically change the dust exposure assigned to an individual.

We collected a limited, albeit large, number of dust samples. These represent only recent, discrete exposures and not lifetime exposure for any participant. These associations are cross-sectional and not causal.

We were not able to make robust associations between dust and health using the personal samples. We limited our analysis to a qualitative discussion of those data rather than an analytical approach. We had few samples from only two regions, and did not have the statistical power nor generalizability to analyze those data further.

In summary, while we were able to robustly analyze many underground dust samples and determine important compositional characteristics, our small, non-representative sample, and uncertainty about the relationship between cumulative lung function as measured in the PFT and point-in-time exposure as measured by the sampling led to uncertainties about these results. Overall, many of the associations found here are likely to be spurious and should be interpreted with considerable caution.

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Appendix

Table A1. Particle size, aspect ratio and chemistry classification distributions (%) determined by CCSEM-EDX for 203 area dust samples (taken from Johann-Essex et al., 2017a).

Set No.	Sample	Position (per Fig. 2)	Size			Aspect Ratio			Chemistry Classification					
			[0.94-2.0) µm	[2.0-3.0) µm	[3.0-9.0) µm	<1.5	[1.5-3)	>=3	C	AS	Q	CB	HM	O
1	B-1-F-PC2	2	72	17	11	50	49	1	53	20	3	22	1	0
1	B-1-F-PC3	2	75	18	8	52	47	1	51	19	2	26	0	1
1	B-1-F-PC4	3	76	19	5	49	50	2	57	20	4	19	0	0
2	B-1-M-PC6	2	72	19	10	31	67	2	26	72	1	0	0	0
2	B-1-M-PC7	2	73	17	10	38	60	2	50	44	4	1	1	0
3	B-1-I-PC8	1	79	14	7	57	42	0	19	9	0	71	0	0
3	B-1-I-PC9	2	85	12	3	53	46	1	15	8	1	75	0	1
3	B-1-I-PC11	2	85	11	4	58	41	1	12	2	1	85	0	0
3	B-1-I-PC12	3	86	10	4	57	42	1	13	3	0	83	0	1
4	B-1-R-PC13	1	67	25	8	38	60	2	37	54	4	4	1	0
4	B-1-R-PC14	2	75	18	7	42	57	1	37	54	5	3	0	0
4	B-1-R-PC16	2	72	20	8	41	57	2	33	59	5	3	0	0
4	B-1-R-PC17	3	71	20	10	36	62	2	35	61	2	1	0	0
5	B-1-B-PC19	2	68	20	12	33	65	2	19	76	3	2	0	0
6	B-1-M-PC23	2	55	28	16	56	43	0	11	24	2	62	0	0
6	B-1-M-PC24	2	63	31	6	60	40	0	7	6	0	86	0	1
6	B-1-M-PC26	3	65	31	4	57	43	1	9	7	0	83	0	0
6	B-1-M-PC27	1	64	29	7	61	38	1	20	7	2	71	0	0
7	B-1-B-PC37	2	68	20	12	37	60	3	27	69	2	2	0	0
7	B-1-B-PC38	2	72	18	10	37	60	3	33	61	4	1	1	0
8	B-2-I-PC28	3	33	22	45	46	53	2	6	84	4	3	1	1
8	B-2-I-PC29	2	54	21	25	47	52	2	34	51	9	4	1	1
8	B-2-I-PC31	2	51	20	29	37	61	2	38	44	9	7	1	1
8	B-2-I-PC32	1	39	26	35	40	58	2	8	85	2	4	1	0
9	B-2-R-PC33	1	65	22	12	27	71	2	1	71	28	0	0	0
9	B-2-R-PC34	2	70	20	10	32	66	3	5	56	39	0	0	0
9	B-2-R-PC36	2	71	16	13	33	66	1	3	65	32	0	0	0
9	B-2-R-PC39	3	65	20	15	28	70	3	4	68	27	0	0	1
10	B-2-B-PC41	1	62	24	13	31	66	3	34	51	9	4	1	1
10	B-2-B-PC42	2	64	22	14	30	66	3	0	95	3	0	0	1
10	B-2-B-PC51	2	63	21	17	31	66	3	1	87	11	0	0	1
11	B-2-M-PC43	1	44	22	34	36	61	2	11	73	12	1	2	0

11	B-2-M-PC46	2	43	22	35	37	62	1	23	60	13	3	1	1
11	B-2-M-PC52	2	52	20	28	46	52	3	32	50	13	3	1	1
11	B-2-M-PC53	3	49	25	26	29	68	3	11	74	11	1	1	2
12	B-2-F-PC61	2	69	19	13	41	58	1	72	24	3	1	0	0
12	B-2-F-PC63	2	70	17	13	40	58	1	54	29	13	2	1	0
12	B-2-F-PC64	1	58	23	20	40	59	1	40	38	11	7	3	1
12	B-2-F-PC66	3	63	24	14	40	58	2	51	32	8	8	1	0
13	B-2-B-PC62	1	63	24	13	33	65	2	3	94	2	0	0	0
13	B-2-B-PC68	3	65	19	16	28	68	3	3	94	3	0	0	0
13	B-2-B-PC69	2	61	20	19	28	67	5	0	100	0	0	0	0
13	B-2-B-PC71	2	63	26	12	33	65	2	2	97	1	0	0	0
14	B-3-I-PC72	2	69	16	15	51	47	1	15	30	8	46	1	0
14	B-3-I-PC73	3	77	14	9	55	44	1	21	8	7	64	0	0
14	B-3-I-PC74	1	64	14	21	47	53	0	16	21	8	54	1	1
14	B-3-I-PC76	2	60	20	19	47	51	2	33	27	13	25	1	0
15	B-3-R-PC77	1	66	21	13	37	60	3	18	78	4	1	0	0
15	B-3-R-PC78	2	72	16	12	36	62	1	42	50	7	0	1	0
15	B-3-R-PC79	2	68	17	15	39	58	3	36	58	4	1	0	0
15	B-3-R-PC81	3	59	19	22	37	60	2	16	79	5	0	0	0
16	B-3-B-PC87	3	44	22	33	32	66	2	3	92	2	3	0	0
16	B-3-B-PC89	2	67	20	12	47	52	1	31	30	8	27	3	0
16	B-3-B-PC91	1	68	20	12	47	51	2	23	36	9	32	1	0
16	B-3-B-PC94	2	67	20	13	43	55	3	44	34	7	16	0	0
17	B-3-M-PC83	2	65	21	14	35	64	1	37	59	3	0	0	0
17	B-3-M-PC86	2	68	17	15	36	62	2	37	56	6	1	1	0
17	B-3-M-PC88	1	68	19	13	33	65	2	28	66	5	1	0	0
17	B-3-M-PC92	3	70	17	12	35	63	2	29	67	4	0	0	0
18	B-3-F-PC82	2	53	19	28	42	54	4	63	25	4	7	0	1
18	B-3-F-PC84	2	66	21	13	51	48	2	46	27	5	20	1	0
18	B-3-F-PC93	3	64	20	16	40	57	3	58	29	5	8	1	0
18	B-3-F-PC96	1	69	18	13	44	53	3	46	25	5	24	0	0
19	B-4-I-PC97	2	46	29	25	44	55	2	19	64	9	6	2	0
19	B-4-I-PC99	2	49	19	31	42	56	2	26	63	6	4	2	0
19	B-4-I-PC104	1	41	22	37	38	60	2	13	67	7	12	0	1
20	B-4-R-PC98	2	73	19	9	56	43	1	15	10	2	73	0	0
20	B-4-R-PC101	3	66	20	14	52	46	2	15	8	2	74	0	1
20	B-4-R-PC102	2	69	18	13	47	51	2	22	22	8	46	1	1
20	B-4-R-PC103	1	38	23	39	43	55	2	21	65	4	10	0	0
21	B-4-B-PC107	2	73	17	11	35	63	2	46	36	17	1	0	0
21	B-4-B-PC108	1	80	15	5	35	64	1	45	29	25	0	0	0
21	B-4-B-PC109	2	79	13	8	38	60	1	43	33	22	0	1	0
21	B-4-B-PC111	3	73	18	8	40	58	1	49	28	21	0	2	0
22	B-4-F-PC113	1	52	25	23	35	62	3	65	26	5	3	0	1
22	B-4-F-PC114	2	52	24	25	36	59	4	69	25	2	3	1	0

22	B-4-F-PC116	3	56	24	20	39	58	3	65	24	3	5	1	0
23	A-5-R-PC1	1	60	22	18	42	56	2	47	47	2	3	1	0
23	A-5-R-PC2	2	57	22	21	41	57	2	37	54	1	5	2	1
23	A-5-R-PC3	2	61	20	19	41	57	2	50	45	2	4	0	0
23	A-5-R-PC4	3	67	19	14	35	63	2	48	44	2	4	1	0
24	A-5-I-PC6	1	34	29	37	45	54	1	15	66	4	12	2	1
24	A-5-I-PC8	2	38	25	38	46	53	1	21	40	5	32	1	2
24	A-5-I-PC9	3	38	24	38	35	63	2	10	70	8	9	0	3
24	A-5-I-PC11	2	49	23	28	45	53	2	40	31	3	23	1	2
25	A-5-H-PC12	1	48	26	26	40	57	3	36	28	3	31	1	1
25	A-5-H-PC13	2	49	29	23	45	53	2	35	24	2	37	1	2
25	A-5-H-PC14	3	34	29	37	44	54	2	23	50	2	24	0	1
26	A-5-C-PC16	1	40	25	35	40	58	2	6	31	2	62	0	0
26	A-5-C-PC17	2	46	27	26	48	51	1	15	15	2	66	1	1
26	A-5-C-PC18	2	50	25	25	50	49	1	28	13	2	55	2	1
26	A-5-C-PC19	3	45	24	31	43	55	2	9	14	1	76	0	0
27	A-5-MF-PC21	1	49	28	23	37	59	3	59	23	2	16	0	0
27	A-5-MF-PC22	2	51	25	24	35	63	2	56	30	2	11	1	0
27	A-5-MF-PC23	2	45	26	28	41	56	3	47	38	3	11	1	0
27	A-5-MF-PC24	3	41	28	31	36	61	4	50	33	2	14	1	1
28	A-5-T-PC26	1	55	22	23	38	59	3	27	52	4	16	1	0
28	A-5-T-PC27	2	60	25	15	38	58	4	38	41	2	18	0	1
28	A-5-T-PC28	2	59	21	20	36	62	2	41	43	2	12	1	1
28	A-5-T-PC29	3	63	20	17	35	64	1	51	33	5	10	1	1
29	A-5-B-PC31	1	46	25	29	43	55	2	25	29	9	34	3	0
29	A-5-B-PC32	2	50	26	24	41	57	2	35	28	1	34	0	2
29	A-5-B-PC33	2	57	25	18	46	53	1	40	22	3	32	2	1
29	A-5-B-PC34	3	46	27	28	45	53	2	26	38	4	29	1	1
30	A-5-F-PC36	1	62	26	12	46	53	2	38	6	1	54	0	1
30	A-5-F-PC37	2	66	20	15	49	50	1	42	9	1	47	0	1
30	A-5-F-PC38	2	66	19	15	45	54	1	48	12	1	37	0	2
30	A-5-F-PC39	3	56	24	20	47	51	2	33	22	2	41	0	1
31	A-5-F-PC41	1	41	28	30	35	61	4	59	20	1	19	0	0
31	A-5-F-PC42	2	45	26	29	36	60	4	22	20	1	57	0	0
31	A-5-F-PC43	2	41	27	32	32	62	6	81	7	1	11	0	0
31	A-5-F-PC44	3	48	28	24	35	61	4	19	24	0	57	0	0
32	A-5-R-PC46	1	69	19	11	34	62	4	1	59	0	39	0	0
32	A-5-R-PC47	2	62	23	15	33	63	4	0	40	0	59	0	0
32	A-5-R-PC48	2	62	24	14	34	64	2	0	46	0	53	1	0
32	A-5-R-PC49	3	62	23	14	33	65	3	1	22	0	76	0	0
33	A-6-I-PC1	2	65	20	16	35	63	2	40	32	5	19	4	0
33	A-6-I-PC2	2	60	21	19	36	63	1	40	16	2	41	1	0
34	A-6-R-PC3	2	68	19	13	29	68	3	0	15	0	85	0	0
34	A-6-R-PC4	2	66	21	13	34	64	3	0	9	0	91	0	0

35	A-6-F-PC5	2	56	19	25	38	60	2	29	17	2	51	1	0
35	A-6-F-PC6	2	65	23	12	42	56	2	43	18	2	36	1	0
36	A-6-H-PC7	2	63	22	16	46	53	1	27	5	3	62	2	0
36	A-6-H-PC8	2	34	20	46	45	54	1	4	5	0	89	0	0
37	A-6-T-PC9	2	69	18	13	38	60	2	2	2	0	95	0	1
37	A-6-T-PC10	2	68	20	12	41	58	1	4	5	0	90	0	1
38	A-6-MF-PC11	2	40	25	35	39	58	3	78	9	0	12	1	1
38	A-6-MF-PC12	2	50	23	28	39	57	4	83	8	0	7	1	1
39	A-6-I-PC13	2	35	26	39	45	53	1	26	4	1	68	0	1
39	A-6-I-PC14	2	35	23	42	43	55	2	18	4	0	75	0	3
40	A-6-R-PC15	2	54	28	19	46	53	1	31	8	1	57	1	1
40	A-6-R-PC16	2	57	29	14	44	55	1	35	8	1	56	0	1
41	A-6-F-PC17	2	76	15	9	41	57	2	51	17	9	21	3	0
41	A-6-F-PC18	2	34	25	41	38	58	4	39	13	1	43	1	3
42	A-6-B-PC19	2	63	27	10	41	57	2	29	14	5	44	7	1
42	A-6-B-PC20	2	65	20	16	39	58	3	28	11	4	53	4	0
43	A-6-TR-PC22	2	63	22	15	44	55	1	22	12	4	54	7	1
44	A-6-R-PC23	2	53	27	20	39	58	2	20	9	5	58	5	3
44	A-6-R-PC24	2	58	25	17	51	47	2	21	9	4	61	4	1
45	A-6-I-PC25	2	42	23	35	39	58	3	15	8	3	75	0	0
45	A-6-I-PC26	2	62	24	14	39	58	2	23	5	6	64	1	1
46	A-6-TR-PC27	2	62	24	14	44	51	5	72	7	2	18	0	0
46	A-6-TR-PC28	2	62	22	16	40	57	3	70	9	2	18	1	1
47	A-6-F-PC29	2	63	22	15	49	50	1	18	4	6	68	1	3
47	A-6-F-PC30	2	47	24	29	41	55	3	27	6	3	61	0	2
48	C-7-R-PC1	2	61	22	17	36	60	3	42	44	9	4	0	0
48	C-7-R-PC2	2	66	19	14	36	62	2	36	44	9	9	2	1
49	C-7-I-PC4	2	38	25	37	38	60	2	11	53	4	32	1	0
50	C-7-R-PC5	2	66	18	16	34	63	3	49	45	3	2	0	0
50	C-7-R-PC6	2	70	17	13	41	57	2	48	44	4	3	0	0
50	C-7-R-PC7	2	70	19	11	35	63	2	56	33	6	3	0	1
51	C-7-I-PC8	2	59	22	19	43	52	5	30	22	7	40	0	0
51	C-7-I-PC51	2	62	20	18	44	55	2	27	18	4	51	0	0
52	C-7-F-PC9	2	42	25	32	46	52	2	25	51	5	16	1	2
52	C-7-F-PC43	2	52	27	21	42	55	3	32	30	3	33	0	2
53	C-7-M-PC11	2	60	22	18	45	53	2	53	31	2	13	0	0
53	C-7-M-PC12	2	50	25	25	38	59	2	40	45	3	11	1	0
54	C-7-M-PC13	2	56	22	21	40	60	1	43	38	5	13	1	1
54	C-7-M-PC14	2	58	19	24	31	66	3	37	46	7	9	1	1
55	C-7-F-PC15	2	44	25	31	36	61	2	22	69	3	5	1	0
55	C-7-F-PC16	2	54	24	22	38	59	2	32	60	5	2	1	0
56	C-7-B-PC10	2	61	23	16	34	64	2	36	29	2	32	0	1
56	C-7-B-PC18	2	62	20	18	34	63	3	36	39	2	20	1	1
57	C-7-R-PC20	2	59	21	20	30	67	3	17	74	8	1	1	0

57	C-7-R-PC21	2	63	21	16	35	61	4	23	62	13	1	1	0
58	C-7-M-PC17	2	61	18	20	36	62	3	48	34	4	14	0	0
58	C-7-M-PC19	2	56	25	19	35	61	3	42	41	3	14	0	0
59	C-7-B-PC49	2	57	20	23	31	67	2	31	64	3	2	0	0
59	C-7-B-PC50	2	54	22	23	31	67	2	25	68	3	4	0	0
60	C-7-F-PC30	2	50	20	30	35	62	3	19	72	4	4	1	1
60	C-7-F-PC31	2	52	24	24	35	62	3	19	73	1	4	2	1
61	C-7-M-PC23	2	58	22	20	35	63	2	24	63	6	5	0	1
61	C-7-M-PC25	2	52	22	27	35	61	4	24	66	5	4	1	1
62	C-8-TD-PC24	2	63	23	15	28	69	3	0	40	0	60	0	0
62	C-8-TD-PC22	2	66	20	13	27	70	3	0	69	0	30	0	0
63	C-8-M-PC39	2	73	16	12	36	62	2	44	42	11	2	0	0
63	C-8-M-PC40	2	79	14	7	39	59	1	48	37	14	0	0	0
64	C-8-I-PC51	2	37	23	40	34	62	3	12	80	6	2	0	0
64	C-8-I-PC52	2	38	23	39	40	59	2	16	63	6	14	1	0
65	C-8-F-PC32	2	45	27	28	44	55	1	36	54	5	5	1	0
65	C-8-F-PC47	2	48	23	29	42	56	2	32	60	5	3	0	0
66	C-8-I-PC27	2	29	25	46	40	57	3	20	68	4	7	1	0
66	C-8-I-PC28	2	33	22	45	38	59	3	22	67	2	7	1	1
67	C-8-F-PC37	2	50	19	31	36	61	3	19	63	8	8	1	1
67	C-8-F-PC38	2	42	25	34	40	56	5	37	42	5	12	2	2
68	C-8-R-PC41	2	60	22	18	32	64	4	32	61	7	0	0	0
68	C-8-R-PC42	2	57	24	19	34	64	3	24	68	7	1	0	0
69	C-8-R-PC29	2	71	17	12	33	65	2	19	32	48	0	0	1
69	C-8-R-PC26	2	69	17	14	29	70	1	14	38	47	0	0	1
70	C-8-I-PC35	2	32	27	41	35	59	5	20	65	5	8	1	1
70	C-8-I-PC36	2	36	26	39	34	62	3	11	74	5	7	0	2
71	C-8-R-PC33	2	47	24	29	37	62	1	21	67	3	6	0	2
71	C-8-R-PC34	2	50	25	25	46	51	3	24	58	9	7	1	1
72	C-8-F-PC53	2	58	20	22	35	63	2	18	57	19	3	1	1
72	C-8-F-PC54	2	61	26	14	33	64	3	36	41	18	4	0	1
73	C-8-M-PC44	2	56	24	20	31	65	4	7	85	6	1	0	1
73	C-8-M-PC46	2	59	19	22	29	65	6	12	79	8	0	0	1
74	C-8-M-PC21	2	65	20	15	27	70	3	0	97	1	0	0	2
74	C-8-M-PC58	2	68	19	12	26	70	4	0	99	0	0	1	0
75	C-8-B-PC55	2	60	23	17	34	63	3	19	71	7	1	0	2
75	C-8-B-PC56	2	68	21	12	31	66	3	25	64	11	0	0	1
76	C-8-B-PC48	2	71	19	11	31	67	2	28	48	23	1	0	1
76	C-8-B-PC54	2	71	19	10	33	64	3	25	44	32	0	0	0

Table A2. Mass percentages of coal, carbonate, and non-carbonate minerals determined from TGA of personal respirable dust samples (taken from Phillips et al., 2018). Total dust is the dust mass recovered from the filter sample to the TGA instrument. MCA mines listed as "# NA" are those where two or less samples were collected.

		Job	Total Dust (µg)	Coal	Carb	Non-Carb
MCA	Mine # NA	Fireboss	13	1%	99%	0%
		Fireboss	18	35%	62%	2%
		Foreman	39	19%	34%	47%
		Move Crew	801	24%	68%	9%
		Outby Worker	19	34%	20%	45%
		Outside Mine Worker	19	34%	55%	12%
		Outside Mine Worker	23	0%	27%	73%
		Mine NA Avg (STDV) (n=7)	133 (295)	21 (15)	52 (27)	27 (28)
	Mine # 2	Continuous Miner Operator	35	18%	31%	52%
		Move Crew	48	20%	34%	45%
		Roof Bolter	307	10%	12%	78%
		Roof Bolter	226	10%	12%	78%
		Scoop Operator	12	0%	93%	7%
		Shuttle Car Operator	30	16%	42%	42%
		undisclosed	33	15%	40%	45%
		Mine 2 Avg (STDV) (n=7)	99 (117)	13 (7)	38 (27)	49 (24)
	Mine # 3	Continuous Miner Operator	508	8%	10%	81%
		Electrician	50	5%	95%	0%
		Outby Worker	108	16%	26%	58%
		Rock Dust Crew	653	2%	67%	31%
		Rock Dust Crew	558	1%	72%	27%
		Rock Dust Crew	127	6%	18%	76%
		Roof Bolter	12	6%	67%	27%
		Roof Bolter	625	7%	11%	82%
		Safety Represenative	29	25%	49%	25%
		Scoop Operator	34	16%	38%	46%
		Shuttle Car Operator	13	17%	53%	30%
		undisclosed	451	1%	63%	36%
		undisclosed	145	10%	16%	74%
		Avg (STDV) (n=13)	255 (258)	9 (7)	45 (27)	46 (26)
		MCA Avg (STDV) (n=27)	183 (243)	13 (11)	45 (27)	42 (24)
SCA	Mine # 7	Continuous Miner Operator	50	16%	34%	49%
		Electrician	22	24%	57%	19%
		Fireboss	9	24%	72%	4%
		Foreman	20	39%	61%	0%
		Outby Worker	27	5%	95%	0%
		Outside Mine Worker	33	17%	56%	27%
		Roof Bolter	11	24%	73%	3%
		Scoop Operator	20	23%	59%	18%
		Section Boss	17	27%	71%	3%
		Section Boss	14	48%	49%	3%
		Shuttle Car Operator	19	32%	50%	18%
		undisclosed	12	35%	63%	2%
		undisclosed	17	33%	67%	0%
		Avg (STDV) (n=13)	21 (11)	27 (11)	62 (15)	11 (15)
	Mine # 8	Electrician	209	0%	58%	42%
		Electrician	11	21%	77%	2%
		Electrician	11	29%	65%	6%
		Electrician	15	19%	64%	17%
		Maintenance Foreman	22	10%	87%	3%
		Move Crew	15	9%	39%	52%
		Outby Worker	5	0%	100%	0%
		Outside Mine Worker	41	5%	26%	69%
		Roof Bolter	26	1%	49%	50%
		Roof Bolter	39	12%	25%	63%
		Roof Bolter	173	6%	12%	82%
		Roof Bolter	290	8%	10%	82%
		Roof Bolter	32	15%	42%	42%
		Scoop Operator	32	4%	41%	55%
		undisclosed	48	17%	38%	45%
		undisclosed	8	10%	90%	0%
		undisclosed	8	0%	100%	0%
		undisclosed	15	27%	62%	10%
		undisclosed	18	0%	65%	35%
		Avg (STDV) (n=19)	54 (79)	10 (9)	55 (28)	35 (29)
		SCA Avg (STDV) (n=32)	40 (63)	17 (13)	58 (23)	25 (27)
		All Samples Avg (STDV) (n=59)	106 (184)	15 (12)	52 (25)	33 (28)