Airborne Mineral Fibers and Quartz Dust in Precambrian Metamorphic Limestone and Dolomite Mines in Finland

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The **airborne** concentrations of mineral fiber and quartz dust to which miners are exposed are reported here for four limestone and five dolomite mines. The *air* samples were collected at fixed monitoring points located in the **main** work areas. The material comprises 46 samples analyzed by phase contrast microscope (PCM), 90 samples analyzed by scanning electron microscope (SEM), and *50* samples of dust analyzed for quartz content. Fibers (length $>5\ \mu m$, diameter $<3\ \mu m$, and aspect ratio $\geq 3{:}1$) were counted and silicate minerals were identified with an energy-dispersive spectrometer. ***On*** the basis of morphology the fibers were classified as perfect fibers, fibrous cleavage fragments, or cleavage fragments. In various work stages the mean fiber Concentrations were 0.05 to **0.71** fibers/cc as measured with PCM and 0.06 **to** 0.34 fibers/cc as measured with SEM. The mean concentrations of the respirable quartz dust ($<5\ \mu m$) were 0.07 to 0.96 mg/m^3. The predominant fibrous silicates were tremolite and wollastonite. Of all the tremolite fibers meeting the counting criteria, **40** percent were cleavage fragments and **30** percent were perfect fibers. The figures for wollastonite were **55** and **35** percent, respectively. The highest fiber concentrations usually occurred at drilling, **crushing,** automatic sorting, and screening operations. The concentrations of respirable quartz were frequently high at limestone or dolomite **crushing.** We note that not only the workers but also the users of these mineral products may be exposed to airborne concentrations of fibrous silicates and quartz dust occurring as impurities.
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The air concentrations of mineral fibers and respirable quartz dust were examined at the workplaces in limestone and dolomite mines. The hygienic and geological **data** were collected by the Finnish Institute of Occupational Health and the Geological Survey of Finland at all major Finnish quarries from 1992 to 1993. The main objectives of the study were (1) to measure the concentrations of mineral fibers and quartz dust in the air at the main work sites during the various stages of Production, and (2) to identify the minerals classified as fibers and asbestos.

Limestone occurrences in Finland comprise typical Precambrian metamorphic varieties varying in composition from calcitic limestones to pure dolomites. The largest deposits, at Parainen, Tytyri, Sipoo, and Ihalainen, are mainly calcitic in composition. Dolomites are represented here by occurrences at Kalkkimaa, Paltamo, Ryytimaa, and Vampula, and to some extent at Louhi. Depending on the metamorphic grade, the limestones commonly contain tremolite, hornblende, serpentine, micas, diopside, quartz, and wollastonite as silicate impurities.(1,2) In 1993 limestone production in Finland amounted to 3 million tonnes, the bulk of which was used in cement production and as soil conditioner. In addition, Ihalainen produced about 27,000 tonnes of wollastonite in 1993.(3)

The main stages of the industrial production are mining, crushing, screening, concentrating, storing of intermediate and final products, packaging, and transport. These operations are often dusty, and the amounts of treated material are high. Workers using dusty equipment or participating in dusty work stages spent on average over half of their working time in air-conditioned control rooms. However, during normal surveillance tours and production failures they also worked in other places. At the time of the investigation the studied mines employed about 200 workers.

Small amounts of chrysotile and tremolite asbestos have been detected in the raw materials and products of limestone mines in the New Jersey area of the United States and in Finland and Norway.(4–7) In the 1980s a few cases of pneumoconiosis were diagnosed at Finnish limestone mines.(8) These were tentatively attributed *to* the quartz, wollastonite, or tremolite present in limestone as impurities. Mild parenchymal and pleural changes have been observed among wollastonite workers who have been exposed to dust levels ranging from 1 to 63 fibers/cc.(7)

Methods

Airborne Fibers

Respirable fibers were collected on a membrane filter with a suction pump. **An** open-face, three-piece holder was used. The **flow** rate (*2* to 10 L/min) and sampling time (*5* to 218 minutes) were adjusted at each site to be within the application range of the subsequent microscopic counting. The volume of air was determined with a rotameter calibrated daily. The fiber concentrations were determined from cellulose ester filters

(Millipore AAWP; diameter, 37 mm; pore size, 0.8 μm) by phase contrast microscopy (PCM) using 500X magnification, and from polycarbonate filters (Nuclepore; pore size, 0.2 μm) with a JEOL 6400 scanning electron microscope (SEM) at 3000× magnification. All particles at least 5 μm long and no more than 3 μm in diameter, and with a length to diameter ratio of at least 3:1, were classified as fibers in accordance with the Finnish standard SFS 3868.(9) This definition corresponds to the criteria given by the National Institute for Occupational Safety and Health, the International Labour Organisation, the World Health Organization, and the European Union.(10–13) The U.S. Occupational Safety and Health Administration distinguishes asbestiform tremolite, anthophyllite, and actinolite from nonasbestiform varieties of these minerals.(14) The fibrous minerals were identified with SEM equipped with a Tracor Northern TN-5500 energy-dispersive X-ray spectrometer (EDS).(15,16)

On the basis of morphological inspection, the fibers were classified on SEM as perfect fibers, fibrous cleavage fragments, or cleavage fragments. Bundles of fibrils and individual particles with straight ends and parallel sides were classified as perfect fibers. Particles with oblique ends and straight prisms or irregularly cleaved sides but not parallel to each other were classified as cleavage fragments. Fibrous cleavage fragments included particles with features of both perfect fibers and cleavage fragments.

Respirable Quartz Dust

The samples for total dust were collected on membrane filters (Millipore AAWP; diameter, 37 mm; pore size, 0.8 μm) in an open-face, three-piece holder at a flow rate of 20 L/min and sampling time ranging from 78 to 400 minutes. The total dust concentrations were determined gravimetrically in accordance with the Finnish standard SFS 3860.(17) Respirable dust (<5 μm) was separated by liquid sedimentation, and the quartz concentration was determined with a Philips PW 1710 X-ray diffractometer using the intensity ratios of three major peaks in relation to those of the internal standards.(18) The quartz concentration is given in milligrams per cubic meter of air.

Results

Airborne Fiber Concentrations

A total of 136 samples (46 PCM and 90 SEM) of airborne fibers were collected at stationary measuring points at breathing height from the main workplaces in nine limestone or dolomite mines. In open pits and outdoor workplaces, the climatic factors such as wind speed and direction, rain, and humidity need to be considered. Rain and humidity also affect dust concentrations in indoor workplaces if the crushed rock to be treated comes from outside. All the air samples of this study were collected during dry weather.

The number of samples and the minimum, maximum, and mean fiber concentrations of samples analyzed by PCM and SEM, respectively, are shown in Figure 1. The mean fiber concentrations of the PCM samples were 0.05 to 0.71 fibers/cc, and those of the SEM samples were 0.06 to 0.33 fibers/cc. The fiber concentrations of parallel SEM and PCM samples usually showed only a weak correlation ($r = 0.46$).

Tables 1 and 2 list the PCM and SEM fiber concentrations at the different stages of production. High Concentrations exceeding 0.3 fibers/cc were most Gequent at drilling, preliminary and intermediate crushing, automatic sorting, and screening. The lowest fiber concentrations were measured in the control rooms, on the production lines, and at loading places.

Mineralogy of Fibers

The most common silicates occurring as fibers in the air samples of the limestone and dolomite mines were tremolite and wollastonite (Figure 2). In addition, there were various amounts of other silicates such as hornblende, diopside, plagioclase, potassium feldspar, talc, biotite, chlorite, and quartz, which occasionally may produce fiberlike particles. Chrysotile asbestos was not detected in the air samples despite its occurrence at low concentrations in some limestones and dolomites.

Fibrous tremolite was detected in the workplace air of seven mines and fibrous wollastonite in four mines. The mean concentrations of tremolite fibers were <0.1 to 0.3 fibers/cc, and those of wollastonite were <0.01 to 0.32 fibers/cc. The highest single tremolite concentration was 0.7 fibers/cc, and that of wollastonite was 1.4 fibers/cc. The mean concentrations of other fibrous silicates in the air samples from all mines were <0.01 to 0.34 fibers/cc.

Morphology of Fibers

The mineral particles in the air samples meeting the criteria for fibers and identified with SEM+EDS were classified into three groups: perfect fibers, fibrous cleavage fragments, and cleavage fragments. Of the tremolite particles studied, 40 percent were perfect fibers and 30 percent were fibrous cleavage fragments. In one dolomite mine the mean airborne concentration of tremolite particles classified as perfect fibers was over 0.1 fibers/cc. About 55 percent of the wollastonite particles studied were cleavage fragments, 30 percent were perfect fibers. and 15 percent were fibrous cleavage fragments. Most of the other fibrous silicates were cleavage fragments.

Quartz Dust Concentrations

A total of 50 samples for quartz dust measurements were collected from the nine limestone or dolomite mines. The mean, minimum, and maximum concentrations of respirable (<5 μm) quartz dust and the number of samples are shown in Figure 3. The mean concentrations of respirable quartz were 0.07 to 0.96 mg/m^3. The highest recorded concentration was 5.9 mg/m^3. On average, quartz accounted for 2.7 percent of the respirable dust, with a range of 0.7 to 13.4 percent. The calcitic and dolomitic occurrences did not differ from each other in this respect. However, the airborne concentrations of quartz in pure calcitic limestone mines were clearly higher than those in dolomite mines.

As shown in Table 3, the crushing operations ($n = 39$) had the highest mean total dust concentration, 37 mg/m^3 (range 0.4 to 379 mg/m^3). The mean total dust concentrations for screening ($n = 10$) and dnlling operations ($n = 2$) were 30 mg/m^3 (range 0.5 to 217 mg/m^3) and 14 mg/m^3 (range 1.3 to 26 mg/m^3), respectively. In other operations ($n = 24$) the mean concentration of total dust was 8.2 mg/m^3 (range 0.2 to 41 mg/m^3).

High quartz dust concentrations exceeding the Finnish exposure limit of respirable quartz (0.2 mg/m^3) were most fre-

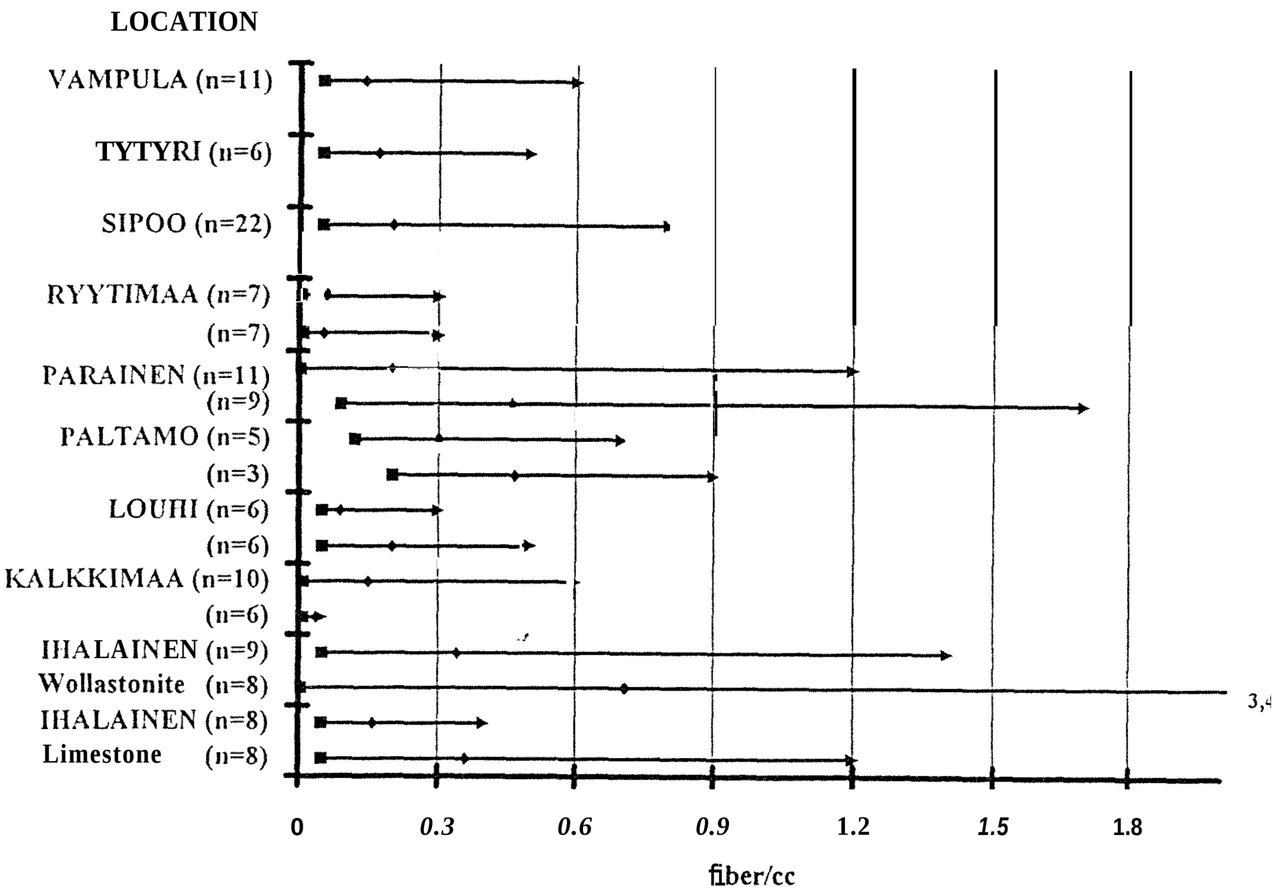

FIGURE 1. Individual mine minimum, maximum, and mean airborne concentrations of fibers in air samples analyzed by PCM and SEM. The lower arrows refer to PCM and the upper ones *to* SEM.

quent at intermediate and fine crushing. In particular, the production of fine-grained fractions caused abundant dusting. The dust concentrations were usually lower in stopes, quarries, and control rooms. and at sites where blasted **rock** was sorted.

Discussion

The results of our study show that silicate particles defined as fibers by the relevant criteria (i.e., tremolite, wollastonite, hornblende, diopside, plagioclase, potassium feldspar, talc, bi-

TABLE 1. Airborne Concentrations of Fibers in Various Production Stages Determined by PCM Analysis of Samples

Operation	No. of Samples	Fiber Concentration (f/cc) Mean	Median	Minimum	Maximum
Drilling	1	0.19	0.12	0.01	0.5
Loading	3	0.05	0.05	0.05	0.05
Dumping of blasted rock	1	0.09	0.09	0.09	0.09
Preliminary crushing	9	0.70	0.32	0.01	*3.3*
Manual sorting	3	0.22	0.20	0.16	0.3
Automatic sorting	2	0.58	0.58	0.26	0.9
Intermediate crushing	6	0.51	0.24	0.05	**1.7**
Screening	5	***0.32***	0.26	0.01	0.8
Fine crushing	1	0.01	0.01	0.01	0.01
		0.01	0.01	0.01	0.01
Production line Control rooms	6	0.08	0.04	0.005	0.33
Product stockpiles	1	0.16	0.16	0.16	0.16
Miscellaneous	4	0.25	0.11	0.01	0.9

TABLE 2. Airborne Concentrations of Silicate Fibers in Various Production Stages Determined by SEM Analysis of Samples

Operation	No. of Samples	Fiber Concentration (f/cc)			
		Mean	Median	Minimum	Maximum
Drilling	12	0.37	0.35	0.05	0.8
Loading	4	0.05	0.05	0.05	0.05
Dumping of blasted rock	3	0.10	0.05	0.05	0.2
Preliminary crushing	21	0.16	0.10	0.02	0.4
Manual somng	3	0.13	0.05	0.05	0.3
Automatic somng	3	0.61	0.40	0.05	1.4
Intermediate crushing	13	0.23	0.10	0.05	0.3
Screening	13	0.15	0.10	0.01	0.45
Fine crushing	3	0.09	0.05	0.01	0.2
Production line	1	0.05	0.05	0.05	0.05
Control rooms	8	0.03	0.02	0.005	0.1
Product stockpiles	1	0.21	0.21	0.21	0.21
Miscellaneous	5	0.22	0.05	0.005	0.7

otite, chlorite, and quartz) are emitted in the various stages of limestone and dolomite production. Of these, tremolite is the most common fibrous silicate. Most tremolite fibers originate from cleavage of coarsely crystalline tremolite, but some are probably derived from minor acicular or asbestiform tremolite components of the rock. In all mines, the work practices, equipment, and methods of dust control were very similar, but geological differences greatly determined the type and level of the accessory minerals in the deposits as well as in airborne dusts.

SEM analyses of air samples provide more information about the abundance, mineralogy, and morphology of mineral fibers than do PCM analyses. By identifying the dust particles by microanalysis, it is possible to distinguish between the asbestos and nonasbestos minerals. The PCM method is not suitable for assessing the concentration of airborne asbestos, as the bulk of

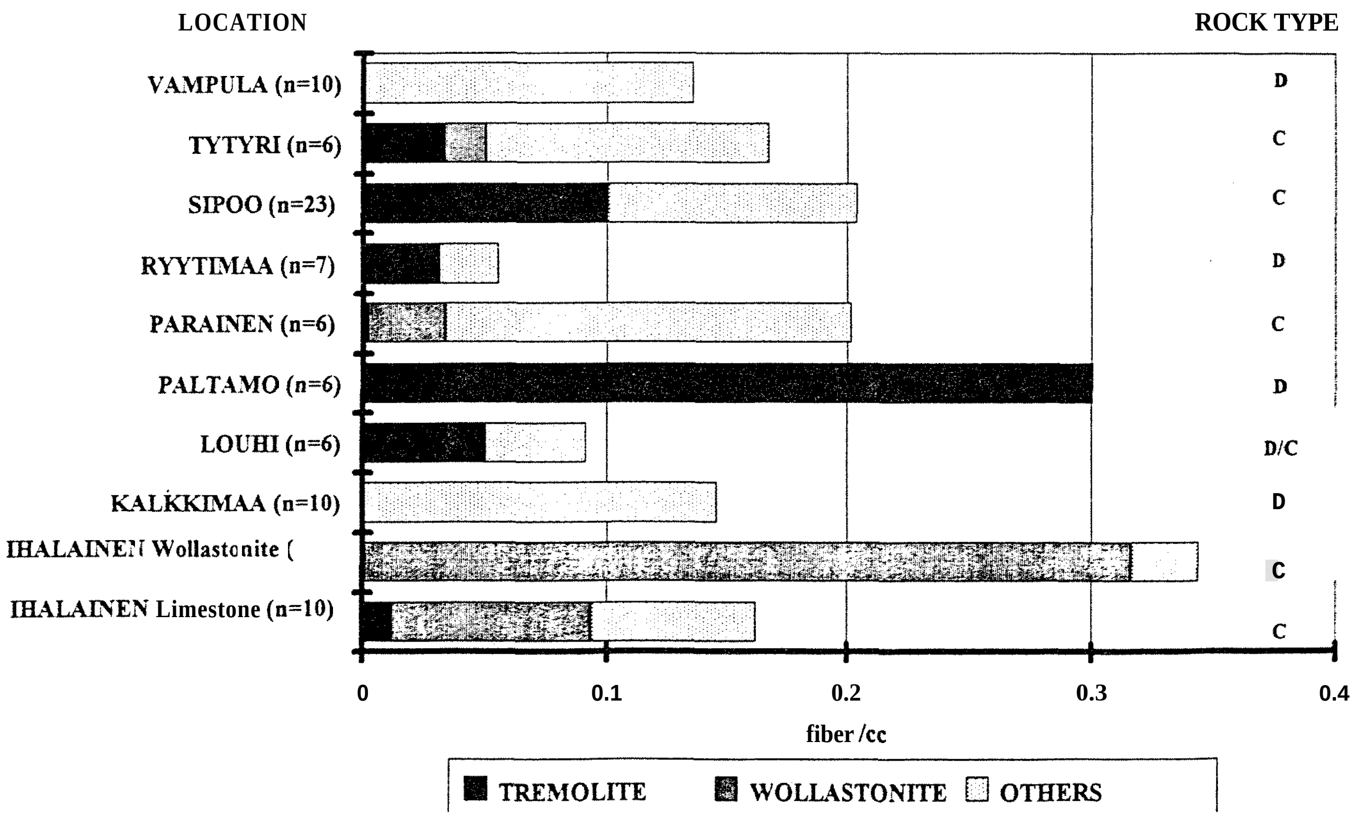

FIGURE 2. Mean concentration of silicate fibers in air samples by SEM, and the geological type of the limestone occurrences: calcitic limestone (C) and dolomitic (D).

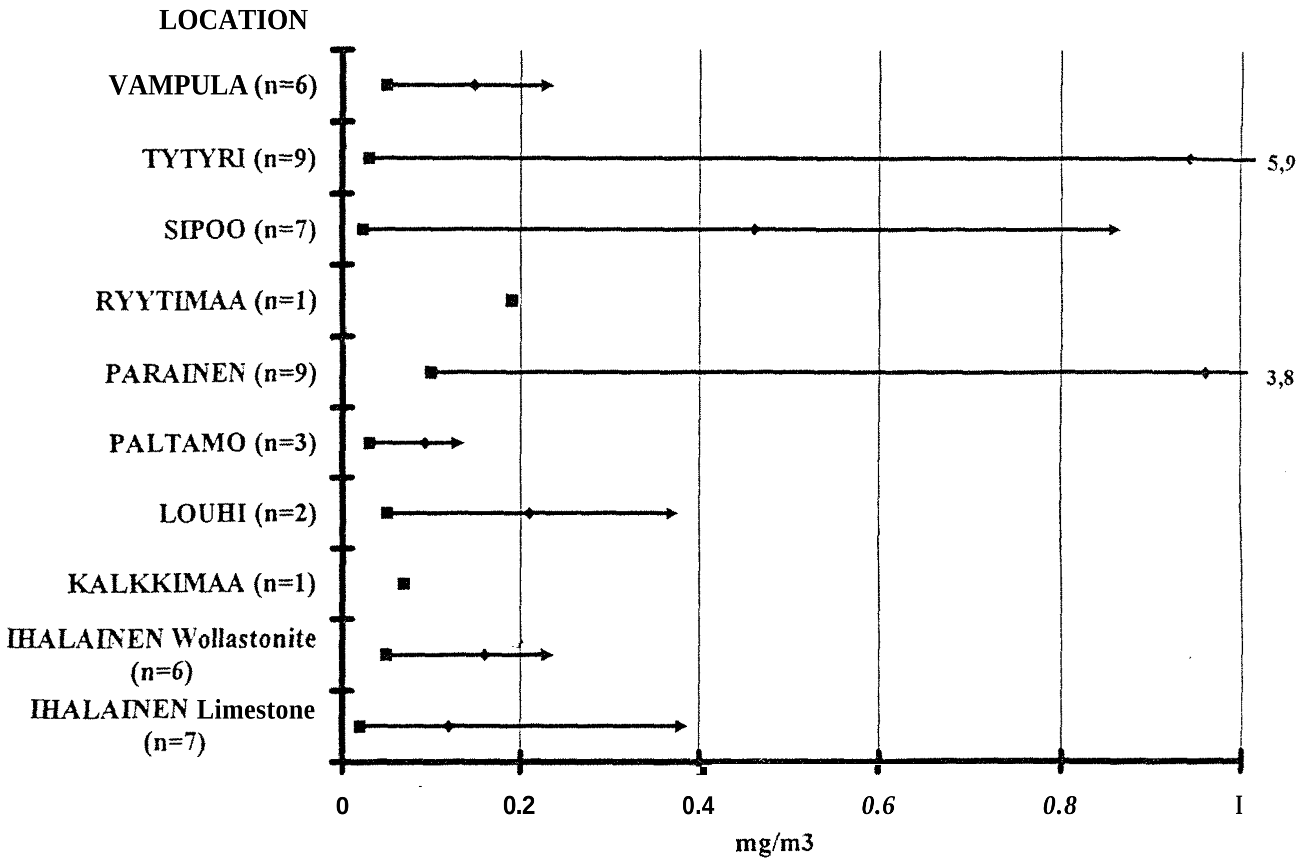

FIGURE 3. Minimum, maximum, and mean concentrations *of* respirable quartz dust *in* air samples.

the fibers with an aspect ratio of 3:1 may be nonasbestos minerals,

Respirable quartz dust may also pose a health hazard to the limestone miners. The airborne quartz concentration may be high in various production stages, although quartz may account for only a small percentage of total dust.

Limestone and dolomite are used extensively and have found numerous new applications in recent years. These results suggest that not only the workers in the mines, but also the users of powdered products, such as farmers and workers in the building industry, may be exposed to fibrous silicates and quartz dust. This should be investigated.

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TABLE 3. Airborne Concentrations of Respirable Quartz Dust in Various Production Stages

Operation	No. of Samples	Quartz Dust Concentrations (mg/m^3)			
		Mean	Median	Minimum	Maximum
Drilling	—	—	—	—	—
Loading	1	0.03	0.03	0.03	0.03
Dumping of blasted rock	3	0.48	0.35	0.22	0.86
Preliminary crushing	16	0.33	0.25	0.03	0.83
		0.04	0.05	0.02	0.05
Manual sorting	3	0.16	0.19	0.07	0.23
Automatic sorting Intermediate crushing	13	0.60	0.17	0.02	3.80
		0.22	0.07	0.05	0.93
Screening crushing	6	3.00	3.00	0.07	5.90
Production line	—	—	—	—	—
Control rooms	—	—	—	—	—
Product stockpiles	1	0.20	0.20	0.20	0.20
Miscellaneous	1	0.13	0.13	0.13	0.13

carry out this study. We express our cordial thanks to all people who contributed to the collection of the comprehensive research material, and especially to the Finnish Work Environment Fund for financial support.

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