The Risk of Asbestos Exposure in South African Diamond Mine Workers

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Objectives: Asbestos is associated with South African diamond mines due to the nature of kimberlite and the location of the diamond mines in relation to asbestos deposits. Very little is known about the health risks in the diamond mining industry. The objective of this study was to explore the possibility of asbestos exposure during the process of diamond mining.

Methods: Scanning electron microscopy and energy-dispersive X-ray spectroscopy analysis were used to identify asbestos fibres in the lungs of diamond mine workers who had an autopsy for compensation purposes and in the tailings and soils from three South African diamond mines located close to asbestos deposits. The asbestos lung fibre burdens were calculated. We also documented asbestos-related pathological findings in diamond mine workers at autopsy.

Results: Tremolite–actinolite asbestos fibres were identified in the lungs of five men working on diamond mines. Tremolite–actinolite and/or chrysotile asbestos were present in the mine tailings of all three mines. Mesothelioma, asbestosis, and/or pleural plaques were diagnosed in six diamond mine workers at autopsy.

Conclusions: These findings indicate that diamond mine workers are at risk of asbestos exposure and, thus, of developing asbestos-related diseases. South Africa is a mineral-rich country and, when mining one commodity, it is likely that other minerals, including asbestos, will be accidentally mined. Even at low concentrations, asbestos has the potential to cause disease, and mining companies should be aware of the health risk of accidentally mining it. Recording of comprehensive work histories should be mandatory to enable the risk to be quantified in future studies.

Keywords: asbestiform; autopsy; lung fibre burden; naturally occurring asbestos; PATHAUT

INTRODUCTION

South Africa is a major producer of diamonds and gold and the leading producer of other commodities such as platinum, chrome, manganese, and vanadium. It was the third largest producer of asbestos, which was mined from the late 1800s to 2002. While much is known about the health effects of exposure to dust generated by the mining of gold, asbestos, and coal, little research has been done in other commodities, including diamonds. Unlike many other types of mining, diamond mining uses no toxic chemicals and produces no chemical pollutants; there are no documented ill-health effects of diamond mining.

Diamond miners work in mineral complex environments. Kimberlite, in which diamonds are found, also contains olivine, phlogopite, calcite, serpentine, diopside, monticellite, apatite, perovskite, and ilmenite (Wilson and Anhaeusser, 1998). Kimberlite also often contains fragments of ultramafic rocks, such as peridotite and eclogite, which are

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formed under very high pressure; and xenocrysts such as pyrope garnet, picro-ilmenite, chromium spinel, and chrome diopside (Wilson and Anhaeusser, 1998). Eclogites are susceptible to metamorphism, by which they form both calcic amphibole rock types, such as tremolite and actinolite; and glauco- phane, a sodic amphibole with a chemical makeup similar to crocidolite (Leake et al., 1997). Both chrysotile and amphibole asbestos fibres (primarily tremolite) have been described in association with kimberlite (Wagner and Reinecke, 1930; Wagner, 1971; Aoki, 1972). [P. A. Wagner was the father of J. C. (Chris) Wagner who wrote the seminal 1960 paper (Wagner et al., 1960) on the association of mesothelioma and exposure to crocidolite asbestos.]

Diamond mine workers in South Africa are thus at risk of asbestos exposure for two reasons. Firstly, diamonds are found in kimberlite, an ultramafic rock (Wilson et al., 2007) in which amphibole minerals also occur. Ultramafic rocks have a low silica and high magnesium and iron content and often contain asbestos (Anhaeusser, 1976; Pan et al., 2005; Perkins et al., 2008). Secondly, many of the diamond mines are in close proximity to asbestos deposits, both those that have been mined and those that were not commercially viable.

Health research has focused on the three main commercial types of asbestos (chrysotile, crocido-lite, and amosite), all of which were mined in South Africa. The health effects of other asbestiform amphiboles, including tremolite, actinolite, richterite, winchite, and anthophyllite, have been less researched, although there is strong evidence that they, too, cause disease (Price, 2008; Phillips and Murray, 2010).

Tremolite and/or actinolite asbestos fibres have been described in talc mines in various countries (Gamble and Gibs, 2008; Loyola et al., 2010) and limestone and dolomite mines in Finland (Juntilla et al., 1996). Amosite asbestos was reported in an iron ore mine in the USA (Nolan et al., 1999). The most well-known occurrence of asbestos-contaminated ore and subsequent health effects is the vermiculite mine in Libby, Montana in the USA, which contained tremolite–actinolite, richterite, and winchite asbestos fibres (Price, 2008; Whitehouse et al., 2008). Tremolite asbestos has also been reported in a South African vermiculite mine (Hessel and Sluis-Cremer, 1989).

There are diamond deposits in Limpopo province, close to chrysotile, anthophyllite, and crocidolite asbestos deposits (Fig. 1); in Gauteng near chrysotile deposits; in North West province near amosite deposits; and in the Northern Cape near crocidolite deposits. Of these, only the Northern Cape asbestos deposits were mined. The only operational kimberlite diamond mines are in Limpopo, Gauteng, and Northern Cape. There are no kimberlite diamond mines located near the amosite asbestos deposits in the North West province or near the tremolite deposits.

One of the larger South African diamond mines is located in the Asbestos Hills in the Northern Cape, and crocidolite asbestos was previously identified around the perimeter of the kimberlite pipe (P. J. Jordaan, unpublished data). Asbestos fibres (chrysotile, anthophyllite, and tremolite–actinolite) have also been previously identified in air samples from five unnamed South African diamond mines (Unsted and Jansen van Vuuren, 2001).

In this paper, we explore the possibility of asbestos exposure during the process of diamond mining by examining the lungs of deceased diamond mine workers for asbestos fibres, identifying asbestos fibres in the tailings and soils of diamond mines and documenting respiratory disease in diamond mine workers.

Analysis of asbestos fibres in lungs is a way to estimate lifelong exposure to asbestos, especially amphibole fibres which are retained in the lungs to a greater degree than chrysotile fibres. Although the correlation between lifetime cumulative exposure and fibre concentration in the lungs is not exact, the findings from lungs may give a better estimation of exposure than even a careful retrospective analysis of the patient’s history, at least in low-grade exposure (Hillerdal, 1999).

METHODS

Data sources

Anyone who has ever been employed in a South African mine has the right to have his/her cardiorespiratory organs examined for compensable disease, regardless of the cause of death and provided that the next-of-kin agrees (Republic of South Africa, 1973). The autopsies are performed at the National Institute for Occupational Health (NIOH) in Johannesburg. The findings of these examinations, as well as the commodities in which the person worked and the number of years for which he was employed in each, and demographic data, are recorded in the PATHAUT (Pathology Automation) database (Hessel et al., 1987a,b). All histological material is archived, and whole lungs from miners of specific commodities or with specific diseases have been stored since 2001. This database was used to identify, and collate information on, diamond mine workers.
The results of annual physical medical examinations of mine workers are housed at the Medical Bureau of Occupational Diseases (MBOD). These results, together with chest X-rays, spirometry test results, compensation information, work histories, and other relevant documents, are stored in files, identified by a number linked to the PATHAUT database. The files of the study subjects were reviewed for possible asbestos exposure.

Mining companies’ human resource departments keep paper-based and/or electronic records of all employees, including information on job descriptions, periods employed, etc. Where available, these records were reviewed for possible sources of asbestos exposure.

Asbestos exposure in diamond mine workers

Burden of asbestos-related disease at autopsy

Diamond mine workers with complete work histories, identified on the PATHAUT database as having never mined a different commodity, and for whom the calculated age at which they started working was no >25 years were selected for the period January 1975 to December 2008. Those with pathological findings indicative of asbestos exposure, viz. asbestosis, pleural plaques, and/or malignant mesothelioma, were identified and all available documents were reviewed for possible sources of asbestos exposure, including company human resources records.

Asbestosis was diagnosed, microscopically, by the presence of diffuse interstitial fibrosis and two or more associated asbestos bodies. Historically, asbestosis on the PATHAUT database has been graded into three categories, conforming to those described by Roggli et al. (2010). Slight asbestosis comprises fibrosis involving the bronchiolar wall and adjacent alveoli. Moderate asbestosis is diagnosed when the fibrosis extends to more distant alveolar walls but excludes some alveoli between adjacent bronchioles (Fig. 2). Severe asbestosis comprises fibrosis involving all alveoli between adjacent bronchioles. Malignant mesothelioma is diagnosed according to the World Health Organization Classification of Tumours (Travis et al., 2004). Pleural plaques were defined as circumscribed areas of dense acellular...
collagenization with a basket weave appearance, involving the parietal, diaphragmatic, and/or visceral pleura, and with a minimum diameter of 5 cm.

Asbestos fibres in lungs

Stored lungs from all diamond mine workers (defined as above) were selected for the period January 2001 to February 2009 as lungs were not stored prior to this. The MBOD files were reviewed for work histories.

Tissue samples of ~2 cm$^3$ were cut from the upper, middle, and lower zones of one of the lungs of each mine worker. The tissue was weighed, digested using potassium hydroxide, rinsed to extract the residual minerals, and ashed at 400°C. The residue was mixed with 50 ml of distilled water, 1 ml of which was passed through a 0.2-μm polycarbonate filter. After drying, the filter was coated with gold and examined in a Jeol JSM 5600 scanning electron microscope (SEM) equipped with Thermo Noran energy-dispersive X-ray spectroscopy (EDS) capabilities. Two hundred fields were examined with an accelerating voltage of 15 kV and at a magnification of ×2000. Fibres defined as having an aspect ratio >3:1 were counted.

Fibres were categorized as asbestos or non-asbestos by identifying their chemical elements and the proportions in which these elements occurred, using EDS analysis. The asbestos fibres were classified as serpentine (chrysotile) or amphibole by comparing their spectral peaks against the Union Internationale Contre le Cancer standard asbestos samples and asbestos reference standards prepared and validated by the Institute of Occupational Medicine on behalf of the Health and Safety Executive (HSE), UK.

The naming of the specific amphiboles is problematic (Sokolova et al., 2001) as they often occur on a continuum, making the precise identification of a fibre difficult. For example, although actinolite is an intermediate member between magnesium-rich tremolite and iron-rich ferro-actinolite, in the magnesium–iron-rich amphibole series, all three amphiboles are often simply referred to as tremolite–actinolite and we followed this convention.

Asbestos fibres in mine tailings and soils

Three diamond mines were selected, based on their geographical locations. Mine A is in the vicinity of crocidolite asbestos deposits, Mine B is located near chrysotile asbestos deposits, and there are both anthophyllite and chrysotile asbestos deposits near Mine C (Fig. 1). Grab samples of tailings were collected from all three mines, and samples of surface soil were collected from Mines A and C.

Tailings samples were placed onto a pure carbon disc and gold coated in preparation for SEM examination. The method used for the soil samples was based on that used by the HSE in the UK (Davies et al., 1996). A 0.2 g sample of each soil was suspended in 50 ml of distilled water. The suspension was shaken and the particles were allowed to settle for 30 s. A 1 ml aliquot was then passed through a 25 mm diameter 0.8-μm Millipore polycarbonate filter. When the filter was dry, it was coated with gold and 420 fields were examined, as described above. For both tailings and soils, only qualitative analyses were performed.

Ethical considerations

Consent for autopsy examination was granted by the next-of-kin in terms of the Occupational Disease in Mines and Works Act of 1973 (Republic of South Africa, 1973). Approval for all studies utilizing retrospective data from PATHAUT was obtained from the University of the Witwatersrand Human Research Ethics Committee (clearance number 40421).

RESULTS

Burden of asbestos-related disease at autopsy

Less than 2% (1887 of 100 124) of all deceased miners on the PATHAUT database had a record of having worked in the diamond mining industry from 1975 to 2008. Of these, 29.6% (559) had no record of having mined any other commodity. The numbers were fairly consistent over the study period, with an average of 16 cases year$^{-1}$. In the last 4 years, however, these numbers decreased to <10 year$^{-1}$. Twenty-four of the 559 mine workers (4.3%) started working at the age of ≤25 years and had one or more...
asbestos-related diseases at autopsy: 21 had asbestosis, six had pleural plaques, and four had malignant mesothelioma (six had more than one asbestos-related disease).

The PATHAUT data alone were insufficient to determine if work histories were complete for many of the mine workers. Information from additional sources showed that four of the 24 diamond mine workers had worked as boilermakers and five had worked in asbestos mines. For nine of the mine workers, there was insufficient information to determine if they had worked exclusively in the diamond mining industry. The remaining six had no evidence of having worked elsewhere. Four of the six had asbestosis, one had pleural plaques, and one had malignant mesothelioma (Table 1). Unfortunately, lungs for these mine workers were not stored as they all died prior to 2001.

**Asbestos fibres in lungs**

Twenty mine workers in the PATHAUT database fulfilled the selection criteria for lung fibre analysis. Nine mine workers were subsequently excluded: seven on the basis of asbestos exposure (one asbestos miner, three fitters and turners, and three boilermakers) and two who were diamond cutters who did not work on or near a diamond mine. None had an asbestos-related disease. Asbestos fibres were identified in five of the 11 lung samples (Table 2); all fibres were tremolite or fibres in the tremolite–actinolite series (Fig. 3). No chrysotile asbestos fibres were identified, although four of the five mine workers had worked in Mine B (close to a chrysotile asbestos deposit). The fifth mine worker worked in an area in which there are no asbestos deposits.

**Asbestos fibres in mine tailings and soils**

Tailings samples from Mine A (near crocidolite deposit) contained tremolite–actinolite series fibres (Table 3). No fibres were identified in the soil samples. The tailings samples from Mine B (near chrysotile deposit) contained both chrysotile fibres and tremolite–actinolite series. While the soil samples from Mine C (near anthophyllite and chrysotile deposits) contained no asbestos fibres, both the tailings samples and the dust collected from a crusher located above ground contained tremolite–actinolite series fibres. During the study, a sample of pure chrysotile asbestos was also collected from between the kimberlite pipe and the country rock in this mine.

**DISCUSSION**

Chrysotile and asbestiform amphiboles are associated with disease. This is the first report of asbestos fibres in the lungs of diamond mine workers. Tremolite–actinolite fibres were identified in the lungs of mine workers, as well the diamond mine tailings, supporting the hypothesis that diamond mine workers are at risk of exposure to non-commercial asbestos.

Two of the mine workers with asbestosis worked for very short periods. Both these men worked underground in the 1970s when dust control was known to be poor and may have been exposed to high asbestos levels. Although asbestosis is generally associated with relatively high exposure levels, it is possible that

**Table 1. Asbestos-related pathological findings in six diamond mine workers**

<table>
<thead>
<tr>
<th>Case number</th>
<th>Age at death (years)</th>
<th>Total number of years employed</th>
<th>Years worked</th>
<th>Clinical cause of death</th>
<th>Pathological findings indicative of asbestos exposure</th>
<th>Severity of asbestosis</th>
<th>Asbestos bodies</th>
<th>Occupation</th>
<th>Mine</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>24</td>
<td>3</td>
<td>1972–1975</td>
<td>Gastric ulcer</td>
<td>Asbestosis</td>
<td>Slight</td>
<td>Yes</td>
<td>Underground labourer</td>
<td>B</td>
</tr>
<tr>
<td>B</td>
<td>69</td>
<td>35</td>
<td>1936–1971</td>
<td>Lung cancer</td>
<td>Asbestosis, Lung cancer</td>
<td>Slight</td>
<td>Yes</td>
<td>Mason, miner, carpenter, and timberman</td>
<td>Other a</td>
</tr>
<tr>
<td>C</td>
<td>30</td>
<td>5</td>
<td>1974–1979</td>
<td>Tuberculosis Pneumonia</td>
<td>Asbestosis</td>
<td>Moderate</td>
<td>Yes</td>
<td>Underground first aid attendant</td>
<td>B</td>
</tr>
<tr>
<td>D</td>
<td>40</td>
<td>20</td>
<td>1962–1982</td>
<td>Multiple injuries</td>
<td>Asbestosis</td>
<td>Slight</td>
<td>Yes</td>
<td>Labourer</td>
<td>Other a</td>
</tr>
<tr>
<td>E</td>
<td>43</td>
<td>25</td>
<td>1972–1997</td>
<td>Empyema</td>
<td>Mesothelioma, Pleural plaques</td>
<td>No</td>
<td>No</td>
<td>Labourer</td>
<td>B</td>
</tr>
<tr>
<td>F</td>
<td>50</td>
<td>27</td>
<td>1971–1998</td>
<td>Atrial fibrillation</td>
<td>Pleural plaques</td>
<td>No</td>
<td>No</td>
<td>Driver, Machine operator</td>
<td>B</td>
</tr>
</tbody>
</table>

*In vicinity of crocidolite asbestos deposits; mine no longer operational.
fibrosis may occur at lower exposure levels (Roggli et al., 2010). Alternatively, or in addition, they may have been exposed to asbestos in the environment, which would not have been recorded. We acknowledge that missing information on environmental exposure is a limitation of this study.

While the amphibole concentrations in the lung appear to be not particularly high, given the long duration of employment, they are all $\geq 125,000$ fibres $g^{-1}$ of dry lung tissue, the level considered in our laboratory to be indicative of significant exposure.

Chrysotile fibres break up into very fine fibrils which are not always visible using SEM. This may be the reason that we did not detect chrysotile fibres in the lungs, in addition to the rapid clearance of chrysotile fibres from the lungs.

The type of fibre found in the lung tissue appears to match that found in the tailings. None of the commercial types of asbestos mined in the adjacent asbestos mining areas were found in the lung tissue. The difference in risk from the two sources is not measurable, but the amphiboles identified in this

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### Table 2. Asbestos fibre content of lung tissue of diamond mine workers

<table>
<thead>
<tr>
<th>Case number</th>
<th>Age at death (years)</th>
<th>Total numbers of years employed</th>
<th>Years worked</th>
<th>Asbestos fibre type</th>
<th>No. asbestos fibres&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Asbestos fibre count&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Asbestos bodies</th>
<th>Clinical cause of death&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Occupation</th>
<th>Mine at which employed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Chrysotile</td>
<td>0</td>
<td>&lt;48 435</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>27</td>
<td>1974–2004</td>
<td>Tremolite–actinolite</td>
<td>16</td>
<td>794 448</td>
<td>No</td>
<td>Not stated</td>
<td>Underground labourer</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Chrysotile</td>
<td>0</td>
<td>&lt;49 635</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>28</td>
<td>8</td>
<td>1994–2002</td>
<td>Tremolite–actinolite</td>
<td>8</td>
<td>264 506</td>
<td>No</td>
<td>Not stated</td>
<td>Mechanic</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Chrysotile</td>
<td>0</td>
<td>&lt;33 063</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>31</td>
<td>1972–2003</td>
<td>Tremolite–actinolite</td>
<td>11</td>
<td>443 092</td>
<td>Yes</td>
<td>Cardiomyopathy</td>
<td>Sampling helper</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Chrysotile</td>
<td>0</td>
<td>&lt;40 281</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>39</td>
<td>21</td>
<td>1980–2001</td>
<td>Tremolite–actinolite</td>
<td>4</td>
<td>227 047</td>
<td>Yes</td>
<td>Tuberculosis</td>
<td>Underground labourer</td>
<td>Other&lt;sup&gt;d&lt;/sup&gt;</td>
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<tr>
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<td></td>
</tr>
<tr>
<td>6</td>
<td>26</td>
<td>5</td>
<td>1995–2001</td>
<td>Tremolite–actinolite</td>
<td>0</td>
<td>&lt;98 092</td>
<td>Yes</td>
<td>Pneumonia Tuberculosis</td>
<td>Driller</td>
<td>Other&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td>7</td>
<td>64</td>
<td>28</td>
<td>1961–1989</td>
<td>Tremolite–actinolite</td>
<td>0</td>
<td>&lt;75 172</td>
<td>No</td>
<td>Cerebrovascular accident</td>
<td>Labourer Driver</td>
<td>B</td>
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<td></td>
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<td></td>
<td></td>
<td>Chrysotile</td>
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<td>&lt;75 172</td>
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<td></td>
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<td></td>
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<tr>
<td>8</td>
<td>34</td>
<td>14</td>
<td>1988–2002</td>
<td>Tremolite–actinolite</td>
<td>0</td>
<td>&lt;53 553</td>
<td>No</td>
<td>Tuberculosis Pneumonia</td>
<td>Trammer Lasher Other&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
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<td></td>
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<td></td>
<td>Chrysotile</td>
<td>0</td>
<td>&lt;53 553</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>9</td>
<td>75</td>
<td>33</td>
<td>1952–1985</td>
<td>Tremolite–actinolite</td>
<td>0</td>
<td>&lt;58 867</td>
<td>No</td>
<td>Not stated</td>
<td>Miner</td>
<td>B</td>
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<tr>
<td></td>
<td></td>
<td></td>
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<td>Chrysotile</td>
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<td>&lt;58 867</td>
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<tr>
<td>10</td>
<td>54</td>
<td>27</td>
<td>1967–1994</td>
<td>Tremolite–actinolite</td>
<td>0</td>
<td>&lt;89 579</td>
<td>No</td>
<td>Myocardial infarction</td>
<td>Miner</td>
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<tr>
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<td>&lt;89 579</td>
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<td>Chrysotile</td>
<td>0</td>
<td>$&lt;34 931$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>Counting criteria: aspect ratio $>1:3$ and EDS analysis for chemistry.

<sup>b</sup>Calculated per gram dry weight; in our laboratory, $\geq 125,000$ fibres $g^{-1}$ dry weight is considered indicative of significant exposure; calculations based on number of fibres and dry weight of lung tissue; where no fibres were identified, calculated detectable limit was based on the count of one fibre.

<sup>c</sup>As stated on the death certificate accompanying the cardiorespiratory organs.

<sup>d</sup>Mine other than one of the study mines, A, B, or C.
study are probably associated with the kimberlite. However, tremolite asbestos fibres have previously been identified at low levels in South African chrysotile (Rees et al., 1992) and in the lungs of chrysotile asbestos miners (Rees et al., 1992, 2001) and it is possible that the chrysotile deposits in the area of the asbestos mines are contaminated with amphibole asbestos. It is unlikely that the contamination is as high as that in the mines in Quebec where high prevalences of mesothelioma have been reported (McDonald, 2010). No mesotheliomas associated with chrysotile exposure have been reported in South Africa (Rees et al., 1992).

We identified only one diamond mine worker (a labourer) with mesothelioma in this study. Mesothelioma is an indicator of exposure to asbestos and there is no known threshold below which the tumour does not occur. The high prevalence of HIV in the past two decades has reduced the longevity of South Africans, especially black men who comprise the majority of mine labourers. Black miners coming to autopsy are generally younger than white miners (Ndlovu et al., 2010) and have a much lower life expectancy.

Although the mining and use of asbestos are now banned in many countries, including South Africa (Department of Environmental Affairs and Tourism, 2007), the risk of exposure continues, both in the workplace and in the environment, and it is important to identify these sources. Fibres can be liberated from asbestos-containing products during demolition and renovation processes, as well as during weathering of asbestos-containing products (Phillips et al., 2009). Asbestos tailings dumps that have not been rehabilitated, and those where rehabilitation has not been successful in the long term, also generate fibres. A further source of asbestos exposure is deflation [the detachment of mineral dust from the ground surface, through weathering and erosion (Derbyshire, 2007)] of asbestos outcrops that were never mined (sometimes referred to as naturally occurring asbestos).

One of the limitations of this study is the quality of the work histories. Details of employment are recorded on the PATHAUT database from information received from the most recent mining company that employed the worker and, in most cases, is limited to that company. This was highlighted when we attempted to ascertain complete work histories from mine company records archived at the individual mines. South Africa is a uniquely mineral-rich country, and in many areas, such as the Bushveld Complex, there are concentrations of a variety of minerals. When mining one commodity, it is very likely that other minerals will be accidentally mined at the same time. Asbestos is a major concern as it causes severe health effects. Mining geologists and industrial hygienists should routinely look for asbestos. All mining companies need to conduct risk assessments and institute medical surveillance programmes for asbestos-related diseases.

Even at low concentrations in the ore, amphibole asbestos has the potential to cause disease in mine workers, as demonstrated in the Libby vermiculite workers where the concentration of tremolite in the ore was ~1% (Nolan et al., 1999). When reviewing cases with asbestos-related disease for compensation, exposure to asbestos, as a mineral associated with the commodity that was mined, should be considered.

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**Table 3. Asbestos fibres identified from different sources**

<table>
<thead>
<tr>
<th>Mine</th>
<th>Associated asbestos deposit</th>
<th>Source</th>
<th>Asbestos fibres identified(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Crocidolite</td>
<td>Soil</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tailings</td>
<td>Tremolite–actinolite</td>
</tr>
<tr>
<td>B</td>
<td>Chrysotile</td>
<td>Tailings</td>
<td>Tremolite–actinolite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chrysotile</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Anthophyllite</td>
<td>Soil</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tailings</td>
<td>Tremolite–actinolite</td>
</tr>
<tr>
<td></td>
<td>Chrysotile</td>
<td>Dust</td>
<td>Tremolite–actinolite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pipe perimeter</td>
<td>Chrysotile</td>
</tr>
</tbody>
</table>

\(^a\)Counting criteria: aspect ratio $>1:3$ and EDS analysis for chemistry.
It is important to identify specific areas of risk for exposure to asbestos. The PATHAUT database is the only medical surveillance tool in South Africa that might serve this purpose in the mining industry. The database currently comprises >100 000 records from 1975 and provides an ideal platform for the surveillance of asbestos risk groups and areas as asbestos-related diseases continue to be diagnosed at autopsy. Extrapolation from the findings might also identify a risk to the spouse and children of mine workers or a general environmental risk to the surrounding community.

The problem of incomplete work histories is not confined to the diamond mines. All mining companies have a social responsibility to record comprehensive work histories, from the time the worker was first employed, for the benefit of families seeking compensation for occupational disease. This should be done by the mine medical services at entry, annual, and exit examinations and should be recorded in the human resources and medical files. Details should be recorded with respect to dates, specific companies and occupations, tasks, and geographical location of each employer. Companies should also record where the mine worker was born and where he lived.

CONCLUSIONS

Our findings show that diamond mine workers are at risk of developing asbestos-related diseases. Asbestos is associated with the South African diamond mining industry, primarily due to the nature of kimberlite but also the location of the diamond mines in relation to asbestos deposits. South Africa is a uniquely mineral-rich country and, when mining one commodity, it is likely that other minerals, including asbestos, will be accidentally mined. Even at low concentrations, asbestos has the potential to cause disease. Although the use and mining of asbestos are banned, all mining companies should be aware of the continuing risk of asbestos exposure due to the accidental mining of asbestos, as well as task-related activities and environmental exposure. Recording of comprehensive lifelong work histories should be mandatory to enable the risk to be quantified in future studies.

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