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Research Paper

Assessment of asbestos contamination in soils at rehabilitated and abandoned mine sites, Limpopo Province, South Africa

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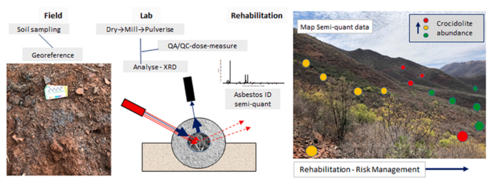
HIGHLIGHTS

- Asbestos contamination around derelict and ownerless mine sites.
- Time- and cost effective identification of asbestos presence and species in soils.
- Semi-quantitative asbestos content and distribution.
- Informs environmental rehabilitation and risk assessment strategies.

GRAPHICAL ABSTRACT



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ABSTRACT

Prior to its termination, asbestos mining in South Africa was centred on the large crocidolite fields of the present day Northern Cape, the amosite (grunerite)-crocidolite fields of Limpopo, and chrysotile fields of Mpumalanga provinces. The legacy of these activities continues to affect surrounding communities in contemporary South Africa. The asbestos fields of Limpopo host two important former mining areas at Penge and at the Bewaarkloof near Chuenespoort. A large abandoned site is located southeast of Penge at Weltevreden, where there is no evidence of any rehabilitation. Two former mines, Lagerdraai and Uitkyk, are rehabilitated sites in an extensive string of closed mines that operated in the southern Bewaarkloof. Samples from the abandoned and rehabilitated mine sites were studied using semi-quantitative X-ray powder diffraction (XRD) to determine asbestos contamination levels in soils, and to assess distribution patterns of asbestos mineral species in the surrounding soils. Only where below detection (typically 1–3 mass%) from XRD, samples were assessed optically. The Weltevreden site, with no observable rehabilitation efforts, contrasts with the rehabilitated sites at Lagerdraai and Uitkyk. The predominant asbestiform mineral species at each site were successfully identified, with underlying geological asbestos mineral distribution trends recognised in the soils at the Bewaarkloof. Trace amounts of asbestiform minerals were identified in soils downstream of the Weltevreden mine, as well as in surrounding hillsides. The results indicate that XRD is a potentially useful tool for benchmarking sites yet to be rehabilitated as well as monitoring the effectiveness of previous rehabilitation efforts. The method is also a suitable first-pass for target areas that may require more detailed, time-consuming, and costly analysis.

1. Introduction

Asbestos has been produced in South Africa since the 1930's, and up until 1981, the operations ranged from large-scale foreign-owned mine and plant establishments to pick and shovel adits and trenches on privately owned farms (Hart, 1988). The global ban on asbestos mining

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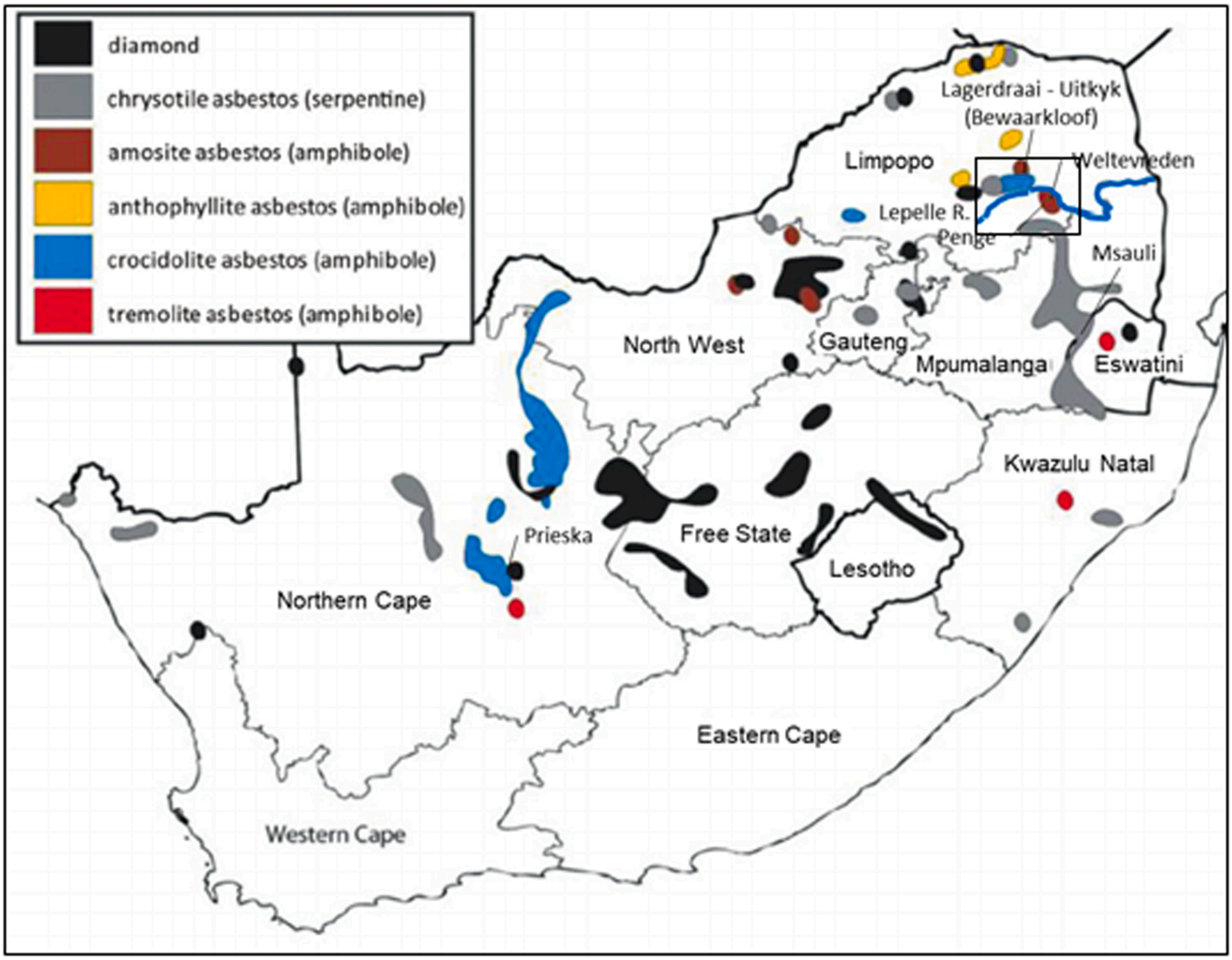

Fig. 1. Map showing major asbestos fields of South Africa, Lesotho, and Swaziland (Eswatini). The location of the Lagerdraai and Uitkyk asbestos mines straddles a crocidolite-amosite boundary in the Pietersburg asbestos field and Weltevreden occurs in the amosite-dominant field around Penge, as highlighted in the boxed area (Nelson, 2013, after Hart, 1988).

since the 1990's, however, has left a plethora of derelict mining and processing sites in the major asbestos fields of South Africa. Coupled with this is a legacy of health risks to communities, exacerbated by the large portion of sites having little- to no rehabilitation, or having a combination of degraded and/or insufficient rehabilitation efforts. Given the variability in scale and methods of mining, estimates of the exact number of derelict and ownerless (D&O) asbestos mines are understandably varied. Historically, South Africa was the only country to produce the three principal asbestos varieties; two were mined from two main belts, namely the Crocidolite Field centred on Prieska in the Northern Cape, and the Amosite Field centred on Penge in present-day Limpopo (Fig. 1). A third area, the Chrysotile Field, spans across eastern Mpumalanga and western Eswatini and was mined primarily at Msauli, South Africa, and at the Havelock Mine across the border in Bulembu.

The South African Department of Minerals and Energy Resources (DMRE), in collaboration with the Council for Geosciences (CGS), maintains a database of derelict and ownerless- and working mines in South Africa and estimates that there are at least 5 976 derelict sites across all commodities across all nine provinces in the country. As of 2017 at least 230 are asbestos mine sites that require rehabilitation because of proximity to communities or settlements (Department of Mineral Resources and Energy, 2017); the inclusion of single shaft operations may push the total number of sites to 660 (Cornish, 2016). The DMRE funds Derelict and Ownerless Mines (D&O) rehabilitation projects, which aim to reduce the environmental impact of asbestos, especially on surrounding communities. The South African Council for Mineral Technology (Mintek) is supported by DMRE funding and conducts site inspections and assessments, rehabilitation oversight, and soil and rock sample analyses in support of a number of the major and minor rehabilitation efforts. A key aspect of Mintek's role in these projects is assessing the relative abundance of fibrous minerals in soil samples as an indicator of potential asbestos hazard. Given the number of sites and rural locations of many sites, a suitably quick and cost-effective method for initial assessment and continued monitoring of rehabilitated sites is preferred. Recent excursions have sampled and analysed contaminated soils around abandoned mines in the Bewaarkloof and Penge areas of the Limpopo Province. Powder X-ray diffraction (XRD) is a well-known tool for identifying and quantifying asbestos mineral concentrations in natural and man-made materials (e.g. Van Dijke, 1950; Crable, 1966; Marconi and Puledda, 1988, Deer et al., 1992). This study compares two areas of contrasting mine rehabilitation status through XRD analysis of soil samples, with the aim of determining contamination extent at the localities and immediate surrounds.

2. Study area background

The chosen sites for this study occur in two former asbestos mined areas, namely the Weltevreden Mine near Penge, and the Lagerdraai and Uitkyk sites in the Bewaarkloof Nature Reserve, near Chuenespoort

Table 1
Locations and status of some abandoned asbestos mine sites in the northern part of South Africa, with sites in bold sampled in this study.

Mine sites	Asbestos field	Latitude/Longitude (Decimal degrees)		UTM Coordinates (WGS84-Z36S, m)		Status
		Latitude	Longitude	Easting	Northing	
Weltevreden	Penge	- 24.41588°	30.33716°	0229977	7297087	Abandoned, Sampled and Analysed
Streatham		- 24.35635°	30.27576°	0223607	7303626	Under Rehabilitation
Penge		- 24.39804°	30.29173°	0225433	7298935	Historically Rehabilitated
Lagerdraai	Pietersburg	- 24.19158°	29.78672°	0783091	7321734	Historically Rehabilitated, Sampled and Analysed
Uitkyk		- 24.19595°	29.80926°	0785376	7321204	Historically Rehabilitated, Sampled and Analysed

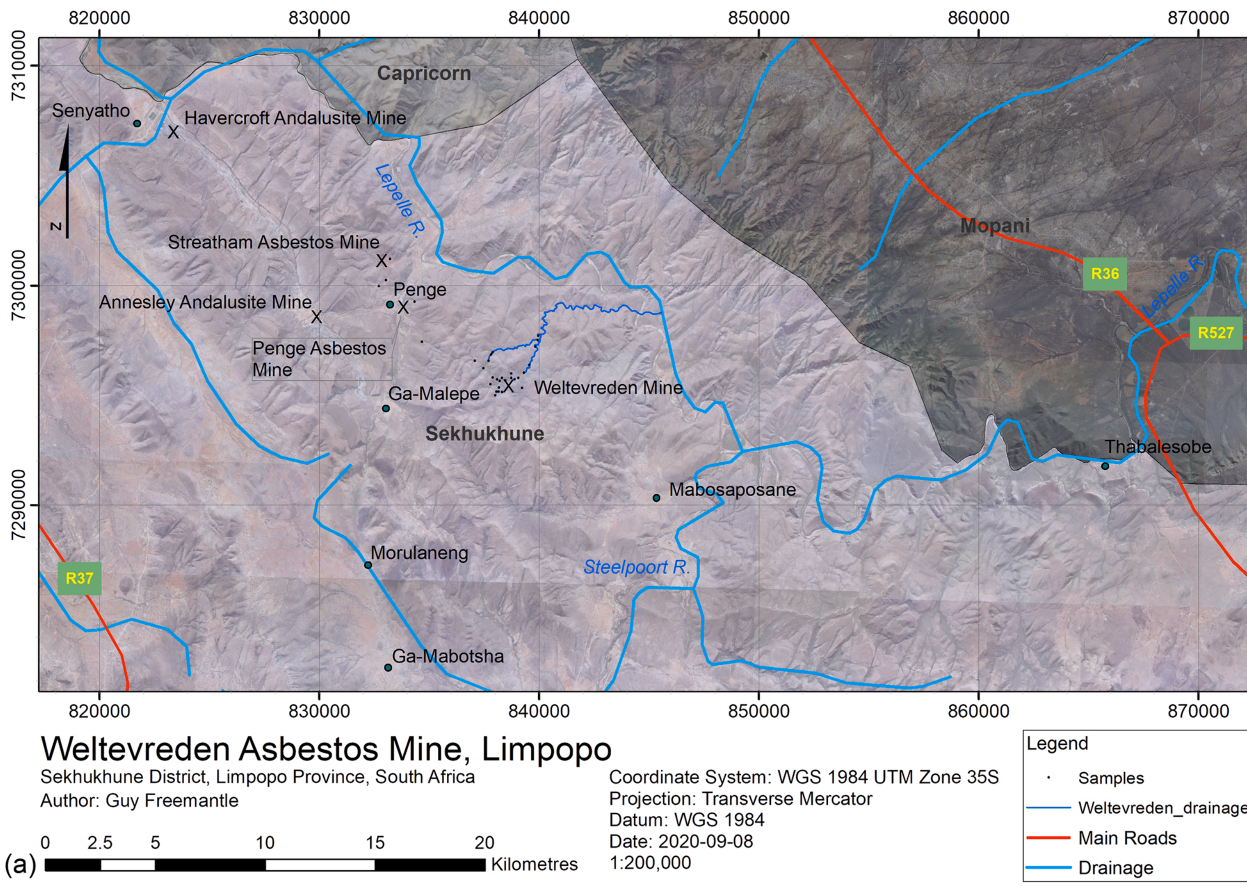

Fig. 2. (a) The Weltevreden mine site with sampling positions. The Weltevreden site is located 5.8 km SE of Penge town in a steep-sided valley that drains to the Lepelle River, ~ 7.5 km to the NE. The Weltevreden sites occupy steep gulleys that drain south into a prominent E-W valley and on into the Tlhabasane River valley. (b) The Lagerdraai-Uitkyk mine sites with sampling positions.,.

(Fig. 1). The Penge and Bewaarkloof areas are characterised by banded ironstones of the Penge Formation in the Transvaal Supergroup, where there is a general south to north transition from crocidolite- to amosite-dominant mineralisation in the Bewaarkloof area deposits as described in detail in Dreyer (1974). The Bewaarkloof mines occur in a crocidolite and amosite-bearing area that was known as the Pietersburg Asbestos Field, while the Weltevreden Mine is located in the amosite-dominated Penge field (Fig. 1). Amosite is a trade name for the asbestiform amphiboles belonging to the cummingtonite-grunerite solid solution series, $(Mg,Fe^{2+})_2(Mg,Fe^{2+})_5Si_8O_{22}(OH)_2$ - $Fe_7Si_8O_{22}(OH)_2$. The name is a partial acronym for "Asbestos Mines of South Africa" and was the mineral principally mined at Penge, essentially the iron-rich end members of the grunerite-cummingtonite series (Hart, 1988). The sampled sites' locations and the status' of the rehabilitation efforts are listed in Table 1, and include the locations of the Penge and Streatham mines for reference.

The Penge asbestos mining district was mined by Cape PLC and is a particularly significant location in terms of scale. It was reportedly the largest amosite asbestos mine complex in the world between 1920 and 1992, (Anso, 2001; Morris, 2007) and hosted approximately 23 mills as early as 1949 (McCulloch, 2002). Penge Town established itself around the Penge Mine. The owners, the Griqualand Exploration and Finance Company (GEFCO) commenced the first rehabilitation in 1986 (Matsabatsa, 2009; Agenbag, 2017) and continued until operations ceased in 1992. There is evidence of intermittent rehabilitation at Penge as recent as 2012 with renewed efforts underway since 2018 at the Streatham Mine, north of Penge Town. The Lagerdraai and Uitkyk mines, in contrast, were operated by Cape Asbestos South Africa from the 1920's until 1979, when minimal rehabilitation requirements existed for the closure. Rehabilitation efforts were made between 1991 and 1992, however, and this work covered most waste heaps and closed a number of adits but has left intact tip sites below numerous excavations, and some asbestos-bearing infrastructure remnants continue to expel fibres into the environment (Dreyer and Söhnge, 1992; Rajasakran, 2017). The

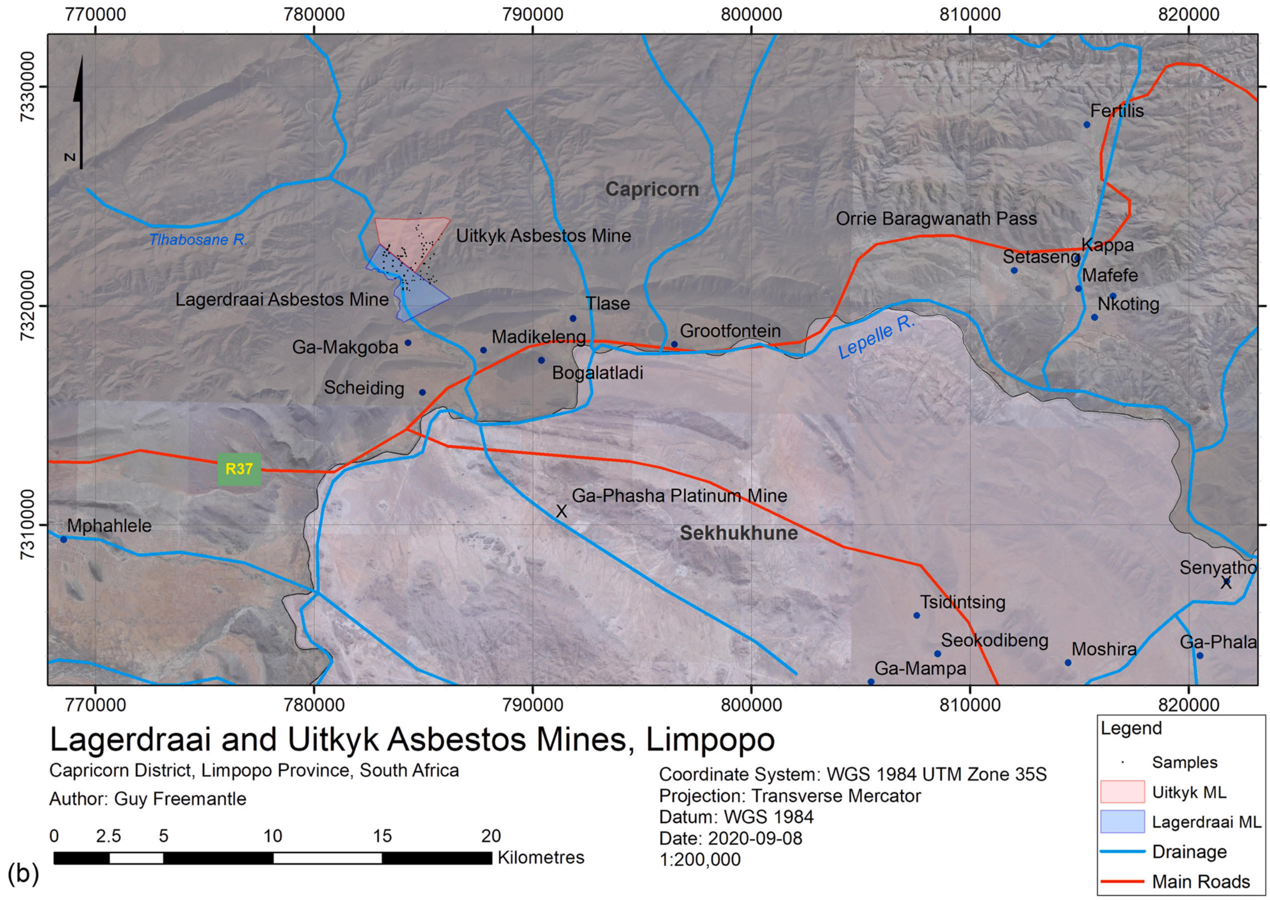

Fig. 2. (*continued*).

area has since been the focus of asbestos related disease (Felix et al., 1993; Braun and Kisting, 2006; Rajasakran, 2017). The Weltevreden Mine (Fig. 2) is ~ 9.5 km by road, 5.8 km directly SE from Penge town, and has undergone little to no rehabilitation. There is comparatively very little information pertaining to the role of this mine's contribution to local asbestos pollution, and to its contribution to water transportation of asbestos via the nearby Lapelle River. Locally the effects of asbestos pollution on the environment and inhabitants at the Penge site is the focus of research works as recent as Matsabatsa (2009), Phillips et al. (2012) and in numerous subscription periodical publications.

The Penge area sites essentially lie within the rain shadow of the escarpment that divides the western portion of the greater Mopani District, and the Lagerdraai and Uitkyk sites are situated in steep south-draining valleys on the southern edge of the Bewaarkloof Mountains (Fig. 2). The broader southeast Limpopo area receives less than half the rain that the wettest highlands do to the south (~ 560 mm vs 1 000 mm) and almost all of the rain is highly episodic and falls during convective thunderstorms within the wettest three months of December, January, and February (as summarised in Mpandeli et al., 2015). The deeply-incised creek beds that characterise the drainage patterns at the sites reflect the seasonal rainfall pattern and episodic high-runoff rates. Contemporary wind roses are available for chrome operations to the southwest of the Steelpoort site to the south of Penge (Sunderland, 2018) and to the south of the Lagerdraai and Uitkyk sites (Grobler and Smith, 2012; and Theron et al., 2013); these give east- and east-northeast prevailing wind directions for the general region. The prevailing winds in the north-eastern part of the Sekhukhune District (Penge) are driven from the east and northeast by subtropical high-pressure cells in the southern Indian Ocean. These winds were confirmed specifically at the Penge area. Importantly, 20.4% of measured wind is from the south west and 30.6% from the south-south west, suggesting local topography influences the wind direction and may drive fibres from Weltevreden into the town of Penge to the west-northwest (from Rajasakran, 2017).

3. Methodology

3.1. Field observations

Penge Town and its immediate surrounds appear well rehabilitated, though there are signs of exposed asbestos where livestock have grazed on vegetated waste heaps. The nearby Weltevreden Mine provides a stark contrast; field observations show the area is relatively untouched since abandonment, with the exception of plant and other salvageable metal scrap. The most obvious evidence of mining activities are the prominent, uncovered waste rock and processed material dumps of the Weltevreden mine. Processed material heaps have footprints in excess of 120,000 m^2 and lie completely exposed, to the east and southwest of the abandoned mine buildings and mine worker's quarters (Fig. 3a). The largest waste rock dump is situated 800 m northwest of the mine and dams a small valley that drains north-westward, linking with the main drainage from the main mine area (Fig. 3b). Mine buildings were inspected and plastering in particular contains asbestos fibres, which served as a filler in building materials. Significant remains of buildings appear on site, particularly plaster-clad mine worker housing (Fig. 3c). Asbestos minerals are visible in hillsides surrounding the Weltevreden mine and are visible in the creek bed for at least ~ 3 km downstream of the mine, and a fair assumption is that the fibres have made their way further down the steeply graded creek bed to the Lepelle River. The fine nature of the process dumps at the Weltevreden mine may be a source of windborne asbestos blown toward Penge by the prevailing easterly winds. Continued animal traffic probably exacerbates the potential risk

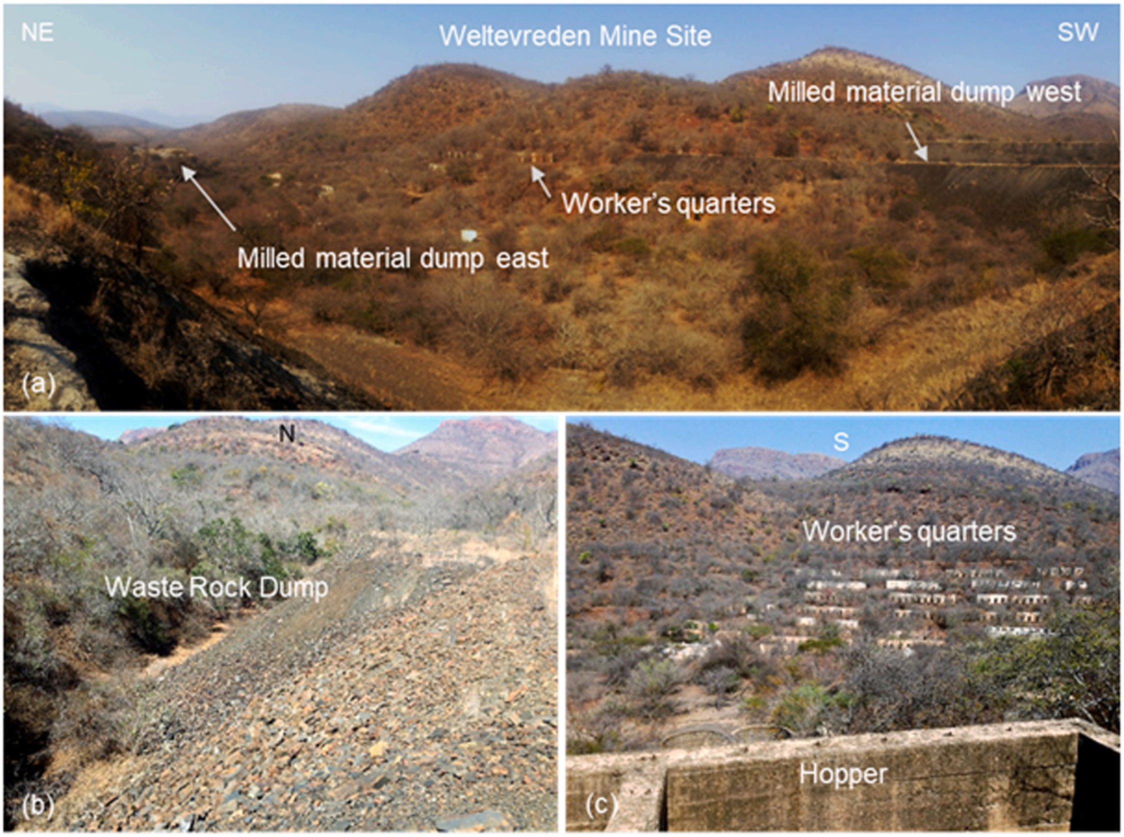

Fig. 3. Views of the Weltevreden mine site. (a) The Weltevreden Asbestos Mine site, seen from the north, covers an area of at least 100 ha. (b) Waste rock dump 1 km NW of the mine. (c) Hopper chute and reservoirs at the Weltevreden Mine looking S to worker's quarters across the valley.

Fig. 4. Observations at the Uitkyk mine site. (a) The Uitkyk mine is immediately adjacent to the Lagerdraai mine; view looks eastward toward Uitkyk. The alluvium in the valley is extensively polluted with processed asbestos waste; (inset) caked processed asbestos fibres at the site, sample U21. (b) Old mine housing foundation slabs, with asbestos fill, eastern part of Uitkyk, sample U17. (c) Waste rock with asbestos ore, near the head of the valley at Uitkyk, sample U02. (d) Old mine offices foundation slab; the area is near a site of processed asbestos, 200 m east of the river. (e) Process material remnants, cut by E to W erosion that drains to the Tlhabosane River.

by breaking and loosening the vegetated and hard crusts that cover the waste heaps, exposing loose fibres to the wind and rain, and moving dust along their tracks.

The south-facing slopes of the Bewaarkloof area are located, like Penge, within the Lepelle River catchment area, along with much of the region's rural populations. Field observations indicate that waste-rock piles contain abundant blue asbestos (riebeckite-crocidolite). There are abundant visible fibre bundles in the soils of the Tlhabosane River valley (Fig. 4a, and inset) along with processed asbestos fibres that formed foundation fill for mine buildings (Fig. 4b). These quantities would suggest water-transported asbestos has probably reached the nearby Lepelle River. There is ample evidence of cattle grazing along the river banks, but less so on the hill sides and up the steep, densely vegetated gullies, however, asbestos-bearing waste rock is abundant below the former adits (Fig. 4c) Mine closure was followed by rehabilitation efforts that included sealing of adits and trenches as well as extensive drainage engineering efforts to divert water erosion away from the old workings (Fig. 4d and e). The vegetation covering the rehabilitated dumps appears to be unpalatable to the local livestock, which helps preserve the cover and soil retention.

3.2. Sample collection strategy

Sampling of the Bewaarkloof and Weltevreden areas focussed on the obvious sites of asbestos pollution: where mining activity and infrastructure remnants were most visible; in soil cover adjacent to previously rehabilitated areas (dumps, adits etc.); along drainage patterns within the mine areas and downstream, and in soils that may contain wind-borne, or animal-transported (cattle tracks) asbestos. Heaps of discarded waste rock (that contain in-situ asbestos minerals) are abundant at all three mine sites in the two areas. Remnant mine production infrastructure and buildings are most prevalent at Weltevreden whereas at Lagerdraai-Uitkyk infrastructure remnants are limited to partially intact foundation slabs on the flat ground below the mined areas. Sampling positions are given for all analysed samples in Appendix 1. All samples were collected using a hand trowel on surface, to a maximum depth of ~ 10 cm, with the aim of collecting ~ 0.5–1 kg per sample location. The samples were transported directly from the sites in sealed plastic bags to Mintek's Mineralogy Division in Randburg, South Africa.

The sampling positions at Lagerdraai and Uitkyk are influenced by the locations of waste heaps, the topography of four prominent N-S valleys that characterise mined areas, and the main E-W valley that extends east of the Tlhabosane River (Fig. 2b). Most samples were retrieved from the soil at the toe end of previously rehabilitated waste heaps and the abandoned mine building foundations. The creek beds that drain the sites were sampled, at both Weltevreden and Lagerdraai-Uitkyk. Drainage patterns at Lagerdraai and Uitkyk are topography-dominated and trellis-like joining the Lepelle River ~ 5 km to the south. Superficial drainage furrows in the flat ground were sampled to test dispersion of fibres away from the mines toward the Tlhabosane-, and consequently, the Lepelle Rivers. The river was effectively sampled along a 1.6 km section including the riverbed and the eastern floodplain. The drainage pattern at the Weltevreden site is of particular concern, as the entire mining operation remnants, including large heaps of processed asbestos ore, occupy a steep-sided valley that drains for approximately 8.5 km before joining the Lepelle River. Samples were collected for approximately 2.8 km downstream of the mine, and 1.5 km downstream of the waste rock heap to the northwest of the mine.

3.3. XRD sample preparation

The material was processed at Mintek's Mineralogy Division and treated as hazardous regardless of the presence of visible fibres, with all necessary safety precautions regarding ventilation and respiratory protection adhered to. Sampling rejects were stored in a restricted access area for safe discard at a later stage. The samples were reduced by rotary splitter and pulverised to 80% passing 45 μm for powder XRD analyses, without pre-sieving. The powders were side mounted to reduce preferred orientation effects in the diffractogram. A total of 85 samples were analysed with 31, 26, and 28 samples coming from Weltevreden, Lagerdraai, and Uitkyk, respectively.

3.4. XRD analysis and interpretation

Analyses were undertaken on a Bruker D8 diffractometer; the step size was 0.02° 2Θ, with a counting time of 3 s per step, applied over a range of 3° to 80° 2Θ. The method makes use of the net intensity of the main peaks of the mineral, and identification is based on the crystal structure of the mineral using Bruker's Diffrac Plus EVA software and proprietary library of structures from the ICDD Powder Diffraction File data base of the National Institute of Standards and Technology (NIST). Only crystalline minerals in amounts sufficient to diffract, usually not less than 1–3 mass percent, are detectable without time-consuming quantitative analysis of the diffractograms aided by Rietveld Refinement (e.g. Asahi et al., 2011). Semi-quantitative XRD was used in this study, as an indication of asbestiform mineral presence in soils. The relative abundance is derived using the Reference Intensity Ratio method (RIR), which is the peak intensity of the identified mineral relative to that of corundum (as outlined in Snyder, 1992). The RIR method was validated by dosing 3 samples, representing ~ 5%, ~ 10%, and > 15% ranges of asbestiform mineral abundance. The samples were mixed and micronised with a certified corundum standard in 5%, 10%, and 20% mass doses, respectively. Appendix 1 summarises the validation procedure and results. The peak intensities were matched in the same manner for all samples, where the automatically integrated quantification is represented as coloured towers matched to the diffractogram peaks (Appendix 1).

It is important to note that the Lagerdraai and Uitkyk sites are situated in Transvaal Group sediments within the metamorphic aureole of the Bushveld Complex (an area also notable for andalusite-bearing Al-saturated shales), and that riebeckite typically occurs in alkaline igneous rocks. Metamorphic riebeckite tends to be the fibrous variety, and potentially the hazardous crocidolite type. Additionally, the Bewaarkloof area was a significant crocidolite producer; as such riebeckite peaks are assigned to crocidolite where detected in the samples of this study. The use of the RIR method produced semi-quantitative proportions of minerals. Given the propensity for high intensity peaks caused by preferred orientation of crystallites, and associated uncertainties, these proportions are not reported as is, but grouped into trace, minor, and major proportions, with trace abundance being < 5%, minor being < 15%, and major being > 15% by mass.

3.5. Optical microscopy

Asbestiform minerals were not detected by XRD in 9 of the samples, 1 in each of the Lagerdraai and Uitkyk groups and the rest in the Weltevreden group. A portion of each of these samples was decanted into a 75 mm petri dish and observed with a variable magnification WILD M400 binocular microscope. Un-sieved samples were inspected, using a dissection needle to move detritus and large pebbles where present, and if fibres were readily identified, samples were photographed and noted

Table 2
Summary of the derelict and ownerless asbestos mine sites sampled in this study.

Mine/Site	Distance to settlements	Distance to waterways	Samples	Fibrous minerals
Weltevreden	Penge (6 km, NW); Ga-Malepe (5.1 km W)	Lepelle (> 9 km) via creek-bed	31 (28)[a]	Actinolite; Grunerite; Riebeckite/ Crocidolite
Uitkyk	Ga-Mathabane (4.6 km, SE) Madikelong-Makgoba (7 km, SE)	Lepelle (> 7.5 km) via creek bed	26 (25)	Actinolite; Grunerite; Riebeckite/ Crocidolite
Lagerdraai	Ga-Mathabane (4.6 km, SE)	Lepelle (> 7.5 km) via creek bed	28 (27)	Actinolite; Grunerite; Riebeckite/ Crocidolite
			85 (80)	

Sample numbers in brackets are those in which asbestos contamination was detected.
[a] Fibres were identified in 4 samples by optical observation.

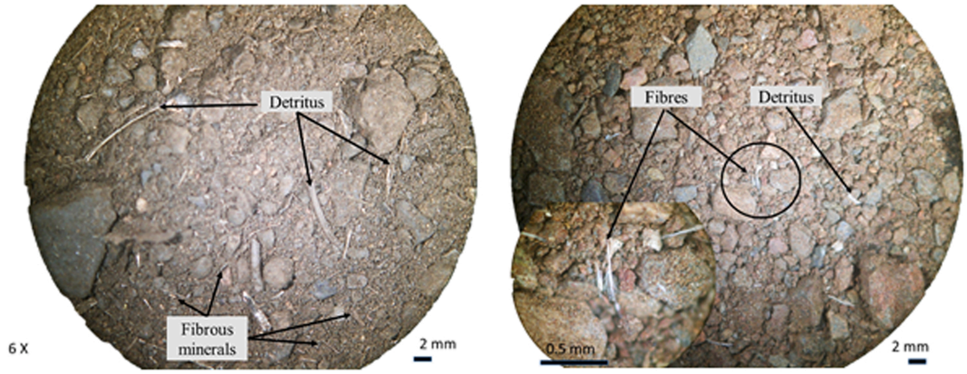

Fig. 5. Photographs of soils from the Weltevreden Mine area that did not report asbestiform phases in XRD analysis. (a) Overview of soil from site P17 showing a mixture of liberated fibrous minerals among typical Fe-rich soil with detritus, magnified 6X. (b) A bundle of liberated fibrous minerals in soil from site P38 magnified 6X and 20X in the inset.

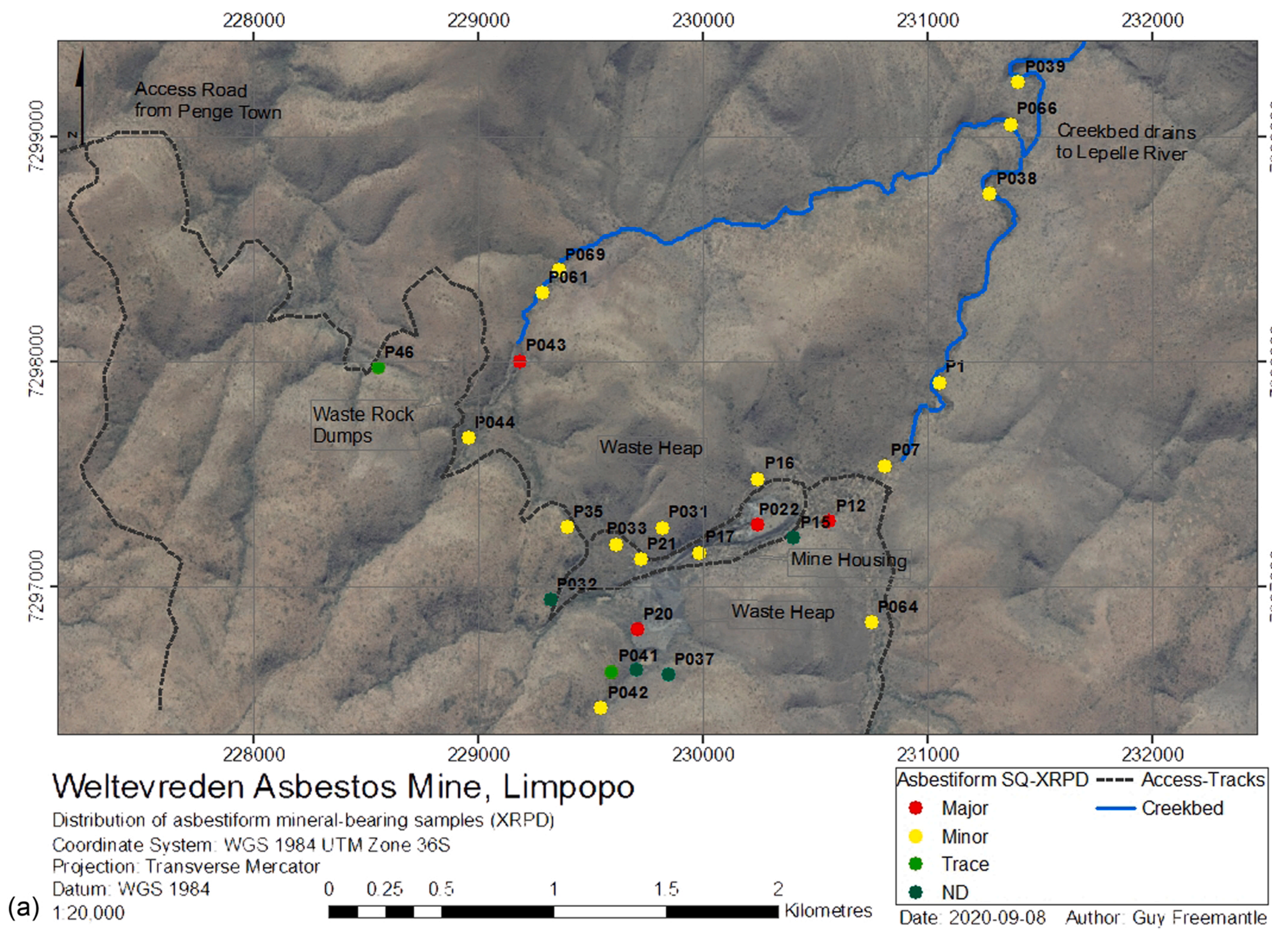

Fig. 6. Total fibre mineral abundance as estimated by XRD for the Weltevreden mine area (a) and the Lagerdraai and Uitkyk areas (b). Major (> 15% mass) Minor (> 5% mass) Trace (< 5% mass). Fibres were observed optically in the following samples: P017, P032, P037, and P038 for Weltevreden. Optical observations of samples U03 and L23 did not identify fibrous minerals for Uitkyk and Lagerdraai respectively.

as containing fibre.

4. Results

4.1. Asbestiform minerals and distribution

Table 2 summarises the results of the XRD analyses of the soil samples; asbestiform minerals were identified in diffractograms of 24, 25, and 27 of the samples from Weltevreden, Uitkyk, and Lagerdraai, respectively. Grunerite (amosite) is common to all three sites whereas crocidolite (identified in XRD as riebeckite) was identified in 27 of 28 samples at Lagerdraai-Uitkyk, but in just 3 of 31 samples at Weltevreden (Appendix 2a). Asbestiform minerals were not detected by XRD in a total of 9 samples across the sites. This implies that there is less than 3–4% asbestos minerals by mass in these specific samples.

Observations through a binocular microscope revealed that fibrous

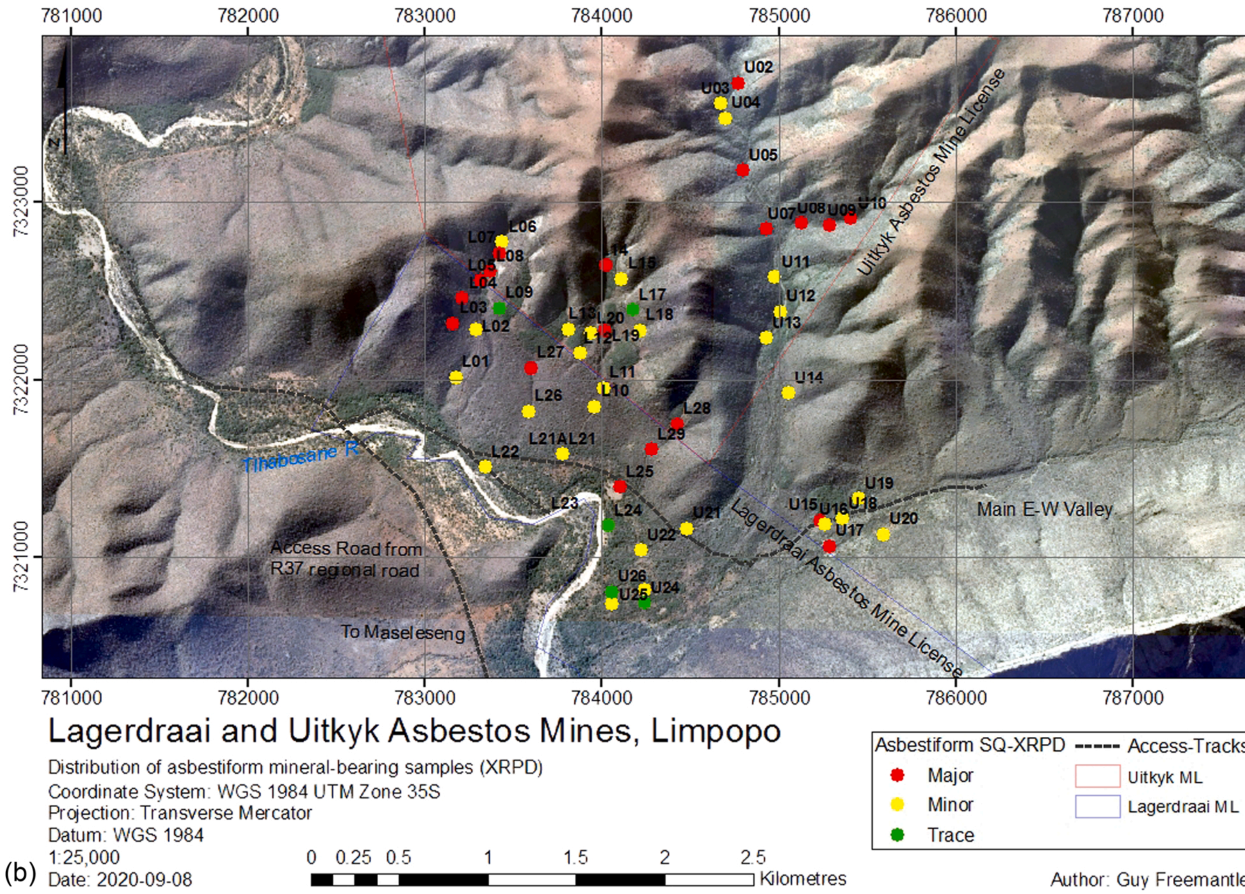

Fig. 6. (*continued*).

minerals with visibly high aspect ratios are easily observed in 4 of 7 samples from Weltevreden and none were observed in the remaining single samples from Lagerdraai and Uitkyk, respectively. Two contrasting samples are shown in Fig. 5, one at position P17 with abundant, liberated fibres (Fig. 5a) and the other (P38, Fig. 5b) with sparse, but conspicuous liberated fibre bundles. Despite the apparent abundance, the mass of fibres appears to be below detection with XRD, as no peaks were observed for potentially asbestiform minerals.

X-ray powder diffraction analyses are presented as relative abundance data points (major, minor, trace, or blank) on map segments, with a base map of the most recently available orthophotographs (Fig. 6). Symbols and coloration for all data points on the map segments are the same in this regard. Data are summarised in Table 2 for each site.

4.2. *Weltevreden*

There are three recognised asbestos mineral species identified in the samples of this area, namely: actinolite (with ferro-actinolite) grunerite (amosite) and riebeckite (as crocidolite). The results show that water-borne asbestos is detectable at least 2.8 km downstream from the Weltevreden Mine site; the abundance of visible fibres in the stream beds suggests drainage-transported asbestos has more than likely reached the Lepelle River, and in all likelihood has reached the waterway episodically during and after the mine's operation. The dominant asbestiform mineral is grunerite, which was found in 20 samples. Tremolite is noted as a potential fibrous trace mineral in 1 sample, and as a minor mineral in another. In total 24 of the 31 samples contain an asbestos species detectable by XRD. A further four samples were observed optically with confirmed fibres bringing the total to 28 of 30 samples being contaminated. Asbestiform minerals are detectable in samples from the hillsides surrounding the mine, sample P35 is of particular interest because it potentially indicates wind-borne contamination given its location ~ 1 km NW of the mine (Fig. 6a).

4.3. *Lagerdraai and Uitkyk*

Asbestiform minerals were identified in 52 samples from the combined sampling areas. There are three recognised asbestos mineral species identified in the samples, namely: actinolite (and ferro-actinolite) riebeckite (as crocidolite) and grunerite (amosite). One or more of these minerals occur in detectable abundance in 52 of the 54 analysed samples from Lagerdraai-Uitkyk. The most common asbestiform minerals are grunerite and ferro-actinolite, which were found in 15 and 16 samples at Lagerdraai and Uitkyk, respectively. Cummingtonite is identified as a trace mineral ($< 5\%$) in 3 samples, and as a minor phase ($> 5 < 15\%$) in 6 samples; the crystal habit of the mineral however, is not confirmed in this study. Fibres are detectable by XRD in soils around the rehabilitated waste heaps, although these look intact for the most part and fibres are not necessarily visible to the eye. Samples from near the mine workings are expected. The top soils along the E-W valley that provided access to the mines during operations appear to contain significant asbestos contamination (Fig. 6b).

5. Discussion

5.1. *Pollution detection and monitoring*

What this study has intended to show is that contaminated soils may be assessed with some consistency at a high level with relatively low effort and cost. At the same time the intention was to produce additional information such as mineral speciation and concentration levels that would not easily be done through conventional microscopy. X-ray

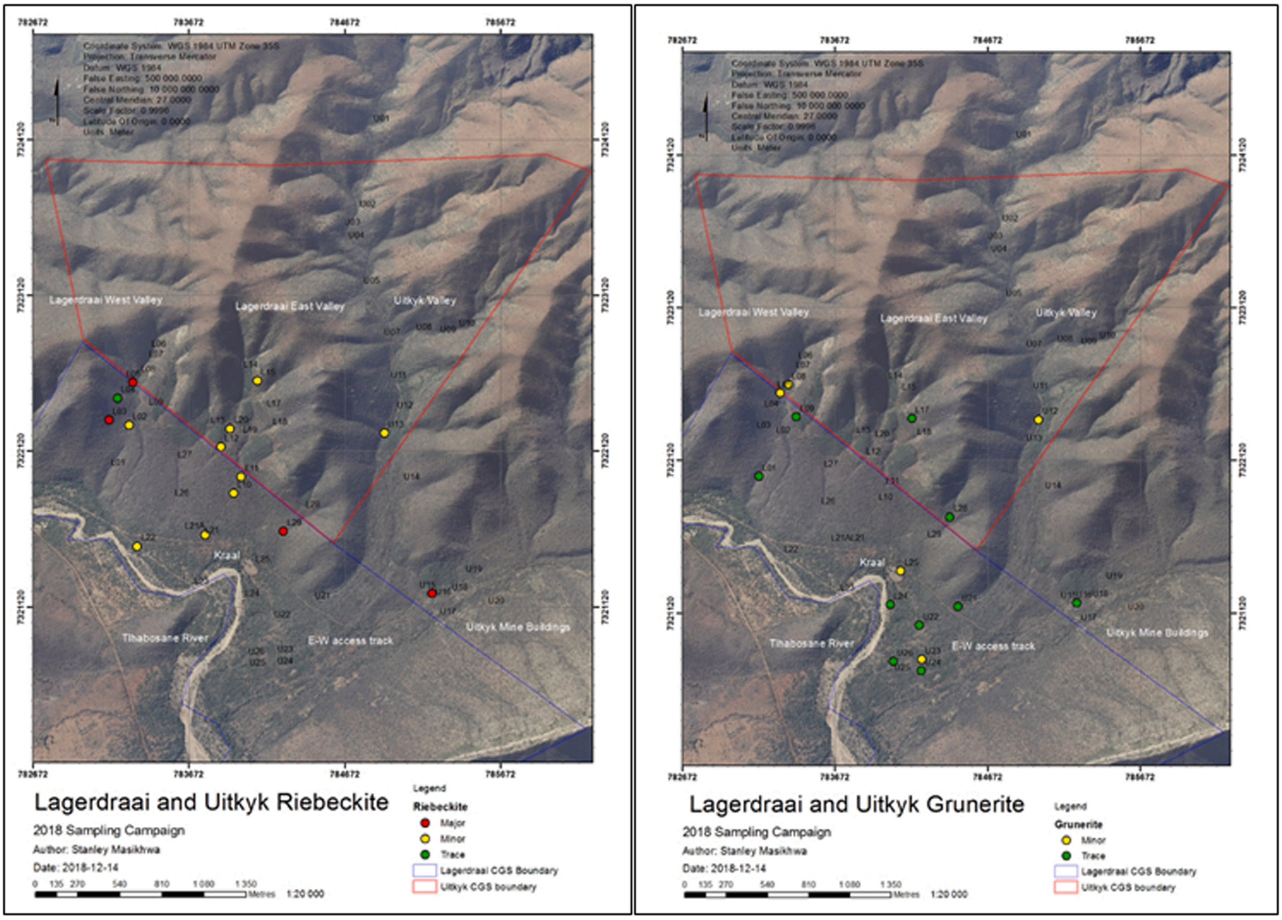

Fig. 7. Lagerdraai and Uitkyk riebeckite, crocidolite, and grunerite distribution. (a) Riebeckite distribution in the soil samples from the Lagerdraai and Uitkyk mine sites. (b) Grunerite distribution in the soil samples from the Lagerdraai and Uitkyk mine sites. The mine boundaries estimated from positions provided by the South African Council for Geoscience (CGS).

diffraction has effectively detected asbestos minerals in all but four of the samples; conventional binocular microscope observation confirmed fibre presence in these. The method also affords a degree of quantification that allows for trends and comparisons among samples, with confidence assisted through a set of three incrementally-dosed sample analyses (Appendix 1). For example concentrated riebeckite/crocidolite distribution in the Uitkyk Mine area contrasts with the minor concentration of the mineral in the Lagerdraai Mine area. XRD though, cannot discern between crocidolite and riebeckite alone; consideration for the underlying geological/soil conditions and the mine context would be required to assign a crocidolite classification with reasonable confidence.

5.2. Asbestos distribution and abundance

The sampling strategy of this study emphasised collection of material from obviously contaminated soils around abandoned mine workings, but also in the less-conspicuous soils in nearby hillsides, valleys and creek beds. X-ray diffraction studies of samples from the obviously polluted soils of the Weltevreden mine indicate high concentrations of predominantly grunerite asbestos pollution in the mine's immediate surrounds, along with less conspicuous but no less surprising pollution detected in the surrounding hillsides and creek beds. There does not appear to be any preferential distribution pattern among the three species (actinolite, grunerite, and riebeckite) at Weltevreden, as all three minerals were detected in varying concentration across the study area. The Lagerdraai-Uitkyk areas contain minor to trace amounts of grunerite in a small portion of the samples, but do show a distinct bias toward riebeckite and actinolite as the major fibrous phase in the Uitkyk and Lagerdraai sample sets, respectively (Appendix 2). The distribution of the major fibrous phases across the sampling area (Fig. 7) reflects the definitive description of asbestos mineralisation in the area given by Dreyer (1974). The prevalence of riebeckite (as crocidolite) toward the valley floor, and old mine workings, may simply be reflective of the preferential mining of one species over another, given crocidolite's more widespread industrial application.

5.3. Asbestiform mineral translocation

The Weltevreden site is a significantly large source of liberated asbestos fibres that will continue to enter the Lepelle River system and populations down the escarpment to the east. Lagerdraai and Uitkyk are also indirectly connected to the Lepelle system by the Mphogodima River. The mining areas have seasonal rainfall after dry winters, and are drained by steeply graded systems. The pollution transport hazard is compounded by the location of processed material dumps in low lying areas below the excavations.

Weltevreden is arguably the largest untouched asbestos mine site in the region. The processed material dumps in particular occupy entire sections of a headwater valley. It is proximal to the town of Penge and a potentially well-connected source of pollution for surrounding settlements in the southeast by its connection to the Lepelle River basin and through wind transport of fine asbestos-bearing dust through its predominantly upwind position relative to Penge Town.

Uitkyk and Lagerdraai are located in steep valleys with indirect drainage access to the Lepelle River and the relatively well-populated rural areas along its course. Mine workings have been well-rehabilitated with topsoil cover and livestock-resistant plants, but the foothills of the area host the remnants of the mine buildings and housing, all of which contain processed asbestos fibres in their foundations. The degradation with time of these structures is steadily releasing fine asbestos fibres into the immediate soil and into the wind and water pathways where the flat planes to the east are sparsely but extensively populated and in the path of the prevailing wind direction.

6. Conclusions and recommendations

The historical mining of asbestos in South Africa has left a legacy of ownerless and derelict mines. Systematic sampling, coupled with mineralogical analysis via powder XRD with supplementary optical microscopy, represents an effective way to assess asbestos contamination at these mines. Minerals such as crocidolite, which pose a high carcinogenic risk to afflicted persons, are not readily discriminated from riebeckite by XRD and will always require additional means of identification, however.

Of the two sites, Weltevreden shows higher potential for asbestos release, owing to non-rehabilitation of the site. Lagerdraai and Uitkyk, on the other hand, show lower potential for contamination of surrounding areas, owing to a degree of rehabilitation. The presence of untouched buildings containing asbestos in their structures, however, poses a risk for further contamination.

Rehabilitation and subsequent monitoring efforts should consider a campaign of strategic sampling and analysis by XRD, supplemented by optical observation to cross-check low samples with low fibre mass. The sampling strategy at a rehabilitation site should also take into account the transport mechanisms that may have moved liberated fibres away from the site. Continued monitoring of air and water pathways needs to be established before rehabilitation activities in order to establish a baseline against which post rehabilitation conditions are measured.

The most pertinent items to be addressed include permanent sealing of adits and trenches, removal of topsoil capping of waste rock heaps, diverting run-off away from capped heaps and dumps, clearing all remaining mine building remnants, and restricting grazing animal access to the contaminated parts of the main E-W valley floor.

Systematic sampling, taking into account the mine sites, building structures, topography, wind and drainage, coupled with mineralogical analysis as outlined in this study, provide valuable information to guide remediation efforts in stemming increases in asbestos contamination. Such endeavours are important to address the asbestos mining legacy in South Africa.

CRediT authorship contribution statement

Guy Freemantle: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Deshenthree Chetty:** Conceptualization, Funding acquisition, Writing – review & editing, Project oversight, Technical guidance. **Mapadi Olifant:** Sample collection, Sample preparation and Instrument analysis. **Stanley Masikhwa:** Sample collection, GIS assistance, Instrument analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2021.127588.

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