Evidence of element volatility at ambient conditions

Nataliya V. Yurkevich (✉ YurkevichNV@ipgg.sbras.ru)

Trofimuk Institute of Petroleum Geology and Geophysics SB RAS

Svetlana B. Bortnikova

Trofimuk Institute of Petroleum Geology and Geophysics SB RAS

Aleksander S. Kozlov

Institute of Chemical Kinetics and Combustion

Aleksander K. Petrov

Institute of Chemical Kinetics and Combustion

Alexey L. Makas

Trofimuk Institute of Petroleum Geology and Geophysics SB RAS

Sergey S. Volynkin

Nikolaev Institute of Inorganic Chemistry

Valentina A. Podolinnaya

Tohoku University

Research Article

Keywords: Zn, Cu, Fe, Al, Cd, Ni, aerosol diffusion spectrometer (ADS), metalloids

Posted Date: February 24th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-250773/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

Tailings represent a significant risk to the environment globally, but very little is known about the composition of the near-surface air. We conducted the laboratory experiments to determine the sizes of the particles and the chemical composition of the flow above the mine waste. A condensate of vapor–gas flow was collected in parallel with particle control by an aerosol diffusion spectrometer (ADS). We reveal that there were no aerosol particles bigger than 3 nm in the flow. The collected condensate contained chemical elements, ions of sulfates, chlorides, phosphates, and formates and a wide range of sulfur-, selenium-, and carbon-containing gases. The main findings of the study are the presence of the metals Zn, Cu, Fe, Al, Cd, Ni, and Ba and the metalloids As, Sb, Se, Ag, Co, Ti, and V in the true-gas phase or in the form of particles smaller than 3 nm in the air above the mine tailings. The surprising fact is that the migration of metals and metalloids in a true-gas form or in ultrafine particles (< 3 nm) is possible, which opens up a new research direction on the volatile forms of chemical elements in various climatic conditions and their bioavailability and toxicity.

Introduction

The problem of air pollution caused by mine tailings poses a great danger due to its impact on the composition of the environment and on the various communities that live nearby. The atmospheric transport of metal and metalloid contaminants plays a huge role in the global, regional, and local processes of migration and in the redistribution of elements, and has important health and environmental implications [1]. The atmosphere is much more mobile than the hydrosphere and lithosphere [2, 1, 3, 4]. The elements involved in the atmospheric-transport processes can be present in the form of gases, dispersed particles of various sizes (particulate matter [PM]), and ions sorbed by them.

The main method of assessing air pollution is collecting airborne samples using different devices: a high-volume air sampler [5–7], a proton-induced X-ray emission spectroscopy cascade impactor (PCI) sampler [8–9], the 10-stage micro-orifice uniform deposit impactor MOUDI [10–11], and hi-volume samplers [12]. These methods are used to collect PM with different dimensions ($> 16 \mu\text{m}$ ÷ $0.5\text{--}0.25 \mu\text{m}$). The determination of the mass, chemical, and mineral compositions of PM provides information on the concentrations of the elements in the air and the forms of their occurrence [13–18], which allows the assessment of the toxicity and bioavailability of aerosols [12, 19–20]. The migration of metals in the air as part of both fine and ultrafine aerosol particles is considered the main mechanism of air pollution in regions affected by abandoned mine tailings [21, 22]. The study by Yabe et al. (2018) [23] provided data on the metal contents (Pb, Zn, Cd) in the blood, feces, and urine of children from three townships near the abandoned lead–zinc mine in Kabwe. It was determined that the children living in townships that were close to and in the direction of the prevailing winds from the abandoned mine dumps recorded the highest concentrations of metals in their bodies. The authors concluded that polluted dust was the main exposure route for the affected townships.

It should be noted that in addition to these two main forms of transport in the atmosphere, there is a very interesting low-temperature vapor–gas transport of chemical elements that is practically not discussed in the literature but whose possibility has been shown earlier, both from solid matter and from solutions [24, 25].

The possibility of migration of chemical elements with a true vapor–gas phase in low-temperature conditions and the formation of volatile metal complexes are not considered in the literature. Our work has shown that the vapor–gas flow both above the surface of sulfide tailings and in the background areas carries a wide range of elements, including alkaline, alkaline earth, ore-forming metals, and metalloids [26]. These results were obtained by collecting and analyzing condensates of steam-gas flows from sulfide tailings in field and laboratory experiments.

The question of the forms of transfer of elements remains very relevant with ultrafine particles with sorbed metals, as is widely described in the literature [11], or in true-gas forms. To elucidate the forms of migration of elements in low-temperature conditions, an experiment was carried out on an original installation, including an aerosol diffusion spectrometer (ADS; developed and manufactured by the Institute of Chemical Kinetics and Combustion SB RAS (ICKC), Novosibirsk), a circuit for collecting condensates, and a gas chromatograph/mass spectrometer (GC/MS).

Materials And Methods

Experiment setup

The experiment was carried out in a sample of the material of the dump in which the cyanidation waste of the oxidation zone of the Beloklyuchevskoe deposit was stored.

The experiment setup included heating a sample of the waste material on an adjustable heating element; purging it with an airflow using a pump, a flow rate meter, and a BQ-class aerosol filter with a 1.5 L/min airflow and controlling the amount of aerosol particles in the air above the sample; collecting the condensate formed during the heating of the solid sample using a bubbler; and collecting the air into a sorbent for gas composition analysis (Fig. 1). The sample temperature was determined using a digital thermocouple thermometer (Fig. 1). The concentration of the aerosol particles in the tank was monitored using an ADS that consumes 1 L/min, and was controlled from a personal computer (developed and manufactured at ICKC SB RAS). An ADS was designed for the automatic determination of the concentration and size spectrum of the aerosol particles. The principle of operation of the device was based on the known dependence of the diffusion coefficient of microparticles on their size.

The main element of the ADS was a mesh-type diffusion battery. The filling of the battery was in the form of packs of meshes arranged perpendicular to the flow. The range of particle diameters measured by the ADS was approximately 3–200 nm. The diffusion battery consisted of eight sections connected in series. The technical side of the spectrometer operation was reduced to sequential counting of the number of aerosol particles as the flow passes through the sections.

The operation of the device was based on the dependence of the diffusion coefficient of microparticles on their size:

$$D(r) = \frac{kT}{6\pi\eta r} \left(1 + \frac{Al}{r} + \frac{Bl}{r} e^{-\frac{br}{l}} \right), \quad (1)$$

where k is the Boltzmann constant, T is the temperature, η is the air viscosity, r is the particle radius, l is the free path, $A = 1.246$, $B = 0.42$, $b = 0.87$.

This dependence leads to the fact that particles of different sizes have different deposition rates when the aerosol flow passes through porous media; that is, smaller particles move faster out of the flow, and thus, the coefficient of passage of particles through such medium contains information on the particle size. This circumstance is used in ADSs.

The positive difference between the air entering and leaving the container ensured reliable isolation of the sample from external aerosol. In the course of the experiment, after the cleanliness of the air path was checked, the heater was turned on, and every 5 s, a countable amount of aerosol particles with a diameter of more than 3 nanometers was recorded.

Thus, during the experiment, the condensate of the vapor–gas mixture separated from the sulfide waste substance was collected with constant control of the particle size in the flow.

Methods for analyzing the composition of the waste material

The history of formation, chemical and mineral composition of the dump was described by us earlier [26]. The sample for the experiment was a substance of quartz-pyrite bulk. To characterize the chemical composition of the sample, the content of oxides of the silicate group, the concentration of metals and metalloids were determined. The contents of major oxides in the bulk solid samples were determined via X-ray fluorescence analysis from a 3 g sample aliquot [26]. The elemental composition of solid material was determined using inductively coupled plasma atomic mass spectrometry ELAN-9000 DRC-e, Perkin Elmer, USA ("PLASMA" Company, Tomsk). The amount of mobile (water-soluble) forms of elements was determined from the composition of the aqueous extract. We used the standard procedure for obtaining aqueous extract from the waste material, according to the scheme: 10 g of the sample was left in 100 ml of bidistilled water for 24 h on a magnetic stirrer. Aliquots of the obtained solutions were separated from solids by filtering through 0.45 μm membrane filter [26].

Methods for the analysis of condensates and aqueous extracts from waste materials

The contents of the inorganic and organic anions (SO_4^{2-} , Cl^- , PO_4^{3-} , HCOO^-) in the aqueous extracts and condensates were measured with a Kapel 105-M capillary electrophoresis system (Lumex, Russia).

Quantitative analysis was carried out using an external calibration against the areas of ions peaks using the Elforun software. For replicate of multiple samples, the relative standard deviation was less than $\pm 15\%$ in the concentration range from 0.1 mg/l to 200 mg/l [27].

Agilent 8800 ICP-MS instrument (Japan) equipped with MicroMist nebulizer was applied for the elements determination in water samples. High-purity argon (99.95%) was used as plasma-forming, transporting and cooling gas. A solution of ^7Li , ^{59}Co , ^{89}Y and ^{205}Tl in 2% nitric acid with a concentration of $1\mu\text{g} \cdot \text{L}^{-1}$ for each determined element ("Tuning Solution", USA) was used for the adjustment. All measurements were conducted in three replicates ($n = 3$) for each element. The relative standard deviation did not exceed 13% for all measurements [27].

Method of analyzing the gas composition of the air above the sample surface

Analyses of the gases from the sample were carried out using a field GC/MS previously developed and manufactured at the Laboratory of Field Analytical and Measurement Technologies of IPGG SB RAS [28]. A parallel weighed portion of the sample (1 kg) with which the experiment was carried out was placed into a 1 L hermetically sealed glass pot. The sample was analyzed at a temperature of 50°C [24,26]. After the sample was kept at this temperature for 1 h, 500 ml of the sample's gas phase was pumped from the glass through concentrators comprising thin-walled stainless steel tubes with an outer diameter of 2 mm containing a layer of Tenax-TA sorbent (0.015 cm^3). The gas sample was introduced into the GC column through direct flash thermal desorption in a stream of helium at a temperature of 300°C . The parameters of the GC column were $0.32\text{ mm} \times 1\text{ }\mu\text{m} \times 15\text{ m}$ (HP-5MS, Agilent Technologies, USA). The GC separation mode involved holding the temperature at 90°C for 3 min then increasing it to 250°C at a rate of $10^\circ\text{C}/\text{min}$. The resulting GC/MS data were processed using the AMDIS (Automatic Mass Spectral Deconvolution and Identification System) program, and identification of the individual components was performed using the mass spectra of electron ionization using NIST/EPA/NIH Mass Spectral Library 2014.

In our previous studies, a number of sulfur- and selenium-containing compounds was identified in the steam–gas emissions of dumps with a similar composition [29], among which a significant proportion consisted of very volatile organic compounds with boiling points up to 50°C . The World Health Organization has identified these as an independent subgroup [30] because their quantitative determination in the air requires special analytical procedures due to the difficulty of capturing them using standard sorbents such as Tenax.

The main method of assessing the concentration is normalizing the area of the chromatographic peak of the analyte to the area of the peak of the reference substance, determined under the same analysis conditions. In this work, we used a source of the standard concentration of 2,4,6-trinitrotoluene vapors, prepared by applying a reference substance to the surface of a carrier with a developed surface [31] (Institute of Chemistry SB RAS, Novosibirsk). The support is based on fine stainless steel grids coated with a solution of the required concentration of the reference substance in polyphenyl ether. At room

temperature, the concentration of 2,4,6-trinitrotoluene was 0.8 ppb (7.4 µg/m³). With this method of assessing concentrations, the largest contribution to the measurement error of very volatile organic substances (e.g., carbon disulfide, dimethyl selenide, dimethyl disulfide) is made by the analyte capture coefficient K_i , which is defined as the fraction of the captured substance during sampling for the concentrator compared to the total capture. The reference substance is completely captured.

To consider incomplete capture, we experimentally measured the capture coefficients for acetone, dimethyl carbonate (DMC), dimethylethyl carbonate (DMEC), and dimethyl methyl phosphonate (DMMP), and based on these data, the aforementioned parameter was approximated for the analytes under study based on chromatographic retention indices. The experiment data for determining the collection coefficients are shown in Fig. 2.

As a result of this semi-quantitative approach, the concentration of analyte C_i was calculated using the following formula:

$$C_i = \frac{C_0 \times S_i \times V_i}{K_i \times S_0 \times V_0}, \quad (2)$$

where C_i , C_0 - concentrations of analyte and reference substances, respectively; S_i , S_0 – the area of the peak of the analyte and reference substance, respectively; V_i , V_0 – the volume of the analyte sample and the reference substance, respectively; K_i – analyte recovery factor.

Results

Mine tailings sample composition

As shown in Table 1, the main components of the mine tailings sample were quartz (25%), pyrite (22%), and barite (24%). Other sulfides (galena, sphalerite, and chalcopyrite), sulfosalts (tennantite and tetrahedrite), and remnants of rock-forming minerals (potassium feldspar, mica, and chlorite) were present in significantly smaller amounts.

Air composition

When the sample was blown with clean air, it was determined that there were no aerosol particles bigger than 3 nm in the airflow. While the air was being blown in the laboratory room, the presence of particles bigger than 3 nm with an average concentration of ~ 10,000 cm³ was recorded (Fig. 3). The figure shows only a fragment of the measurements that were obtained for 15 min. The experiment lasted 4 h, and during this time, no aerosol particles bigger than 3 nm were detected in the airflow. This means that the airflow was a true vapor–gas mixture.

Table 1
Composition of the tailings sample for the
experiment (SiO_2 – $\text{S}_{\text{sulfide}}$ in weight %, Cu–Li
in ppm)

Element	Content	Element	content
SiO_2	25	Cu	290
TiO_2	0.52	Zn	540
Al_2O_3	0.72	Pb	1800
Fe_2O_3	22	Cd	0.36
MnO	0.004	Co	4.2
MgO	0.012	As	650
CaO	0.24	Sb	220
Na_2O	0.18	Se	140
K_2O	0.44	Ag	22
P_2O_5	0.031	Rb	4.5
BaO	16	Sr	210
LOI	6.6	Ti	730
$\text{S}_{\text{sulfate}}$	3.2	V	6.5
$\text{S}_{\text{sulfide}}$	24	Li	4.5

The composition of the aqueous extract, which characterizes the concentration of water-soluble forms of elements (present in the sample in the form of secondary sulfates), is presented in Table 2. The aqueous extract is a sulfate solution in which the main cations are iron and calcium, which form a large number of secondary sulfates. Note the high contents of arsenic and selenium, which are apparently included in the composition of soluble sulfates as impurities.

Table 2
Composition of the aqueous extract from the sample (SO_4^{2-} –Pb in mg/L, Cd–Li in $\mu\text{g/L}$)

Element	Content	Element	Content
pH	2.7	Pb	0.43
Eh	670	Cd	2.3
SO_4^{2-}	2600	Ag	0.81
Cl^-	100	Co	6.2
PO_4^{3-}	0.92	Ni	18
Ca	84	As	1700
Mg	4.2	Sb	12
Na	1.5	Se	280
K	0.57	Ba	71
Fe	530	Sr	110
Mn	0.13	Ti	85
Al	12	V	22
Zn	0.20	Li	15
Cu	0.62		

Condensate composition

The main anion in the condensate was sulfate with a 12 mg/L concentration, which is equal to 73 mg-eq%. Chloride was in a smaller amount (2.4 mg/L, 20 mg-eq %), and the two other anions (phosphate and formate) made up a small fraction of the condensate.

Many chemical elements in the condensate were identified, and the main ones were Ca, Na, K, and Mg (Table 3). Of the trace elements, Zn had the highest concentration, followed by Cu and Pb. The total concentration of Fe, Al, Cd, Ni, Ba, and Sr was more than 10 $\mu\text{g/L}$. The metalloids As, Sb, and Se were found in $\mu\text{g/L}$ concentrations. Other elements (Ag, Co, Ti, and V) were found in small amounts (< 1 $\mu\text{g/L}$).

Table 3
Composition of the condensate collected in a laboratory
experiment (SO_4^{2-} –K in mg/L, Fe–Li in $\mu\text{g}/\text{л}$)

Component	Content	Elements	Content
SO_4^{2-}	12	Pb	45
Cl^-	2.4	Cd	11
PO_4^{3-}	0.35	Ag	0.10
HCOO^- (formate)	0.55	Co	0.4
Ca	4.3	Ni	17
Mg	1.2	As	4.5
Na	1.8	Sb	3.6
K	1.6	Se	9.9
Fe	25	Ba	15
Mn	6.0	Sr	31
Al	15	Ti	0.30
Zn	235	V	0.06
Cu	44	Li	3.1

Composition of the gas phase

During the experiment, the composition of the vapor phase above the sample of the waste material in a glass container was analyzed both under stationary conditions and under continuous purging with purified air at a 3 L/min flow. The results are presented in Table 4. The composition of the trace impurities of volatile compounds in the vapor–gas emanations of the rock material was represented by a wide range of volatile selenides and sulfides, and there were also molecular sulfur vapors. The highest concentrations were observed for carbon disulfide and dimethyl selenide. We previously found high concentrations of these substances at the Ursky dump, which has a similar composition [29].

Table 4
Concentrations of the gases over the substance of the test sample under stationary conditions and in the experiment

Compound	Formula	Concentration, mkg/m ³	
		Without purging	Purge
Carbon disulfide	CS ₂	100	12
Dimethyl sulfide	C ₂ H ₆ S	1.5	traces
Carbo selenide	CSSe	24	0.35
Dimethyl selenide	C ₂ H ₆ Se	140	0.62
Disulfide, dimethyl	C ₂ H ₆ S ₂	1.6	traces
Dimethyl thioselenide	C ₂ H ₆ SSe	traces	-
Thiocyanic acid, methyl ester	C ₂ H ₃ NS	3.8	-
Dimethyl diselenide	C ₂ H ₆ Se ₂	traces	-
Dimethyl trisulfide	C ₂ H ₆ S ₃	0.7	-
S ₆ , S ₇ , S ₈		0.5	0.4

However, in the experiment, the concentrations of the gases above the sample substance were insignificant because there was a constant blowing of clean air. Consequently, the main transport agent was water vapor, which was separated from the substance. The presence of chemical elements in a vapor–gas stream that does not contain aerosol particles indicates their transfer by true vapor–gas stream.

Simulation of this process is impossible because there are no thermodynamic constants of volatile compounds of elements for these PT conditions. Therefore, we can only assume that the elements found in condensates can form complex compounds with anions found in condensates, or can be carried by water vapor in the form of aqua ions or complex compounds.

The sources of the elements in vapor–gas streams are the secondary soluble sulfates formed in the waste material during the oxidation of sulfides. This is evidenced by the high correlation between the concentrations of the elements in the condensate and the water extract ($r = 0.85$), which reflects the amount of water-soluble forms of elements in secondary sulfates. Moreover, a high correlation coefficient was obtained when iron was excluded from the calculations. The anomalously inert behavior of iron in vapor–gas transport has been determined in field and laboratory experiments [25], and the results obtained in this study once again confirm this pattern, whose explanation has not yet been found. It was previously determined that when sulfates are heated, sorbed water is first separated, followed by

structural water, which dissolves the surface of the grains and rises in the form of steam with trapped elements [26].

Conclusions

The composition of the gas phase in the air above sulfide-containing mining wastes was studied. A clean, aerosol-free air stream was obtained in the laboratory experiment under the control of an ADS.

It was shown that inorganic and organic components were present in the true-gas phase. The collected condensate contained ions of sulfates, chlorides, phosphates, and formates, and its main cations were Ca, Mg, K, and Na. An amazing fact is the presence in the true-gas phase (or in the form of particles smaller than 3 nm) of elements whose compounds are traditionally considered low volatile. The metals Zn, Cu, Fe, Al, Cd, Ni, and Ba and the metalloids As, Sb, Se, Ag, Co, Ti, and V were found in slightly smaller amounts.

The gas phase contained a wide range of sulfur-, selenium-, and carbon-containing gases, including carbon disulfide, a second-hazard-class gas.

The main sources of metals in the air above sulfide dumps are pore solutions and secondary minerals.

The question of the mechanisms of atmospheric transfer and the forms of migration of a number of chemical elements in a true-gas phase at low temperatures remains open and will be studied in the future.

Declarations

Acknowledgments

We are grateful to the directorate of the Institute of Chemical Kinetics and Combustion SB RAS and Trofimuk Institute of Petroleum Geology and Geophysics SB RAS for providing the instrument base. We thank Professor Olga Shuvaeva (Institute of Inorganic Chemistry SB RAS, Novosibirsk) who gave valuable recommendations for the preparation of the concept of the experiment and the selection of adequate analytical methods.

Funding

Russian Science Foundation, grant # 19-17-00134.

Author contributions

N.Y., S.B., A.K., A.P. designed and implemented the experimental setup; A.M., S.V. and V.P., collected and analyzed condensates and air flow composition; N.Y., S.B., A.M., and A.K. conceptualised the paper and

the analysis; S.B., N.Y., A.K., A.M. wrote the original draft; N.Y., S.B., A.K., A.M. reviewed and edited the paper.

Competing interests

The authors declare no competing interests.

Data and materials availability

All data are available in the manuscript.

References

1. Csavina, J. *et al.* A review on the importance of metals and metalloids in atmospheric dust and aerosol from mining operations. *Sci. Total Environ.* **433**, 58–73 (2012).
2. Church, T. M. *et al.* In *The long-range atmospheric transport of natural and contaminant substances* 37–58 (Springer, Dordrecht, 1990). The long-range atmospheric transport of trace elements A critical evaluation
3. Rasmussen, P. E. Long-range atmospheric transport of trace metals: the need for geoscience perspectives. *Environ. Geol.* **33** (2–3), 96–108 (1998).
4. Seinfeld, J. H. & Pandis, S. N. *Atmospheric chemistry and physics: from air pollution to climate change* (John Wiley & Sons 2016).
5. USEPA. *Compendium of methods for the determination of inorganic compounds in ambient air, compendium method IO-3.1: selection, preparation and extraction of filter material* (CERI-Office of Research and Development, USEPA, Cincinnati, OH, 1999a).
6. USEPA. *Compendium of methods for the determination of inorganic compounds in ambient air, compendium method IO-3.5: determination of metals in ambient particulate matter using atomic absorption (AA) spectroscopy* (CERI-Office of Research and Development, USEPA, Cincinnati, OH, 1999b).
7. Beamer, P. I. *et al.* Use of dust fall filters as passive samplers for metal concentrations in air for communities near contaminated mine tailings. *Environ. Sci. Process Impacts.* **16**, 1275–1281 (2014).
8. PIXE International Corporation. PIXE Cascade Impactors. (retrieved February, 2010).
9. Corriveau, M. C., Jamieson, H. E., Parsons, M. B., Campbell, J. L. & Lanzirotti, A. Direct characterization of airborne particles associated with arsenic-rich mine tailings: particle size, mineralogy and texture. *Appl. Geochem.* **26**, 1639–1648 (2011).
10. Marple, V. A., Rubow, K. L. & Behm, S. M. A microorifice uniform deposit impactor (MOUDI) – Description, calibration, and use. *Aerosol Sci. and Techn.* **14**, 434–446 (1991).
11. Csavina, J. *et al.* Metal and metalloid contaminants in atmospheric aerosols from mining operations. *Water Air Soil Pollut.* **221**, 145–157 (2011).

12. Sánchez, J. E. C. *et al.* Metal (loid) bioaccessibility of atmospheric particulate matter from mine tailings at Zimapán, Mexico. *Environ. Sci. Pollut. Res.* <https://doi.org/10.1007/s11356-020-11887-6> (2021).
13. Tao, F., Gonzalez-Flecha, B. & Kobzik, L. Reactive oxygen species in pulmonary inflammation by ambient particulates. *Free Radical Biol. Med.* **35** (4), 327–340 (2003).
14. Kumari, S. *et al.* Determination of Quartz and its abundance in Respirable Airborne Dust in both coal and metal mines in India. *Proc. Eng.* **26**, 1810–1819(2011).
15. Csavina, J. *et al.* Size-resolved dust and aerosol contaminants associated with copper and lead smelting emissions: implications for emission management and human health. *Sci. Total Environ.* **493**, 750–756 (2014).
16. de la Sanchez, A. M., Sanchez-Rodas, D., Castanedo, G. & de la Rosa, Y. J.D. Geochemical anomalies of toxic elements and arsenic speciation in airborne particles from Cu mining and smelting activities: Influence on air quality. *J. Hazard. Mater.* **291**, 18–27 (2015).
17. González-Castanedo, Y. *et al.* Size distribution and chemical composition of particulate matter stack emissions in and around a copper smelter. *Atmos. Environ.* **98**, 271–282 (2014).
18. Mpanza, M., Adam, E. & Moolla, R. Dust Deposition Impacts at a Liquidated Gold Mine Village: Gauteng Province in South Africa. *Int. J. Environ. Res. Pub. Health.* **17** (14), 4929 (2020).
19. Guney, M., Bourges, C. M., Chapuis, R. P. & Zagury, G. J. Lung bioaccessibility of As, Cu, Fe, Mn, Ni, Pb, and Zn in fine fraction (< 20 µm) from contaminated soils and mine tailings. *Sci. Total. Environ.* **1** (579), 378–386 (2017).
20. Ettler, V. *et al.* Slag dusts from Kabwe (Zambia): contaminant mineralogy and oral bioaccessibility. *Chemosphere.* **260**, 127642 (2020).
21. Dudu, V. P., Mathuthu, M. & Manjoro, M. Assessment of heavy metals and radionuclides in dust fallout in the West Rand mining area of South Africa. *Clean Air J.* **28**, 42–52 (2018).
22. Mwaanga, P., Silondwa, M., Kasali, G. & Banda, P. M. Preliminary review of mine air pollution in Zambia. *Heliyon.* **5** (9), e02485 (2019).
23. Yabe, J. *et al.* Lead and cadmium excretion in feces and urine of children from polluted townships near a lead-zinc mine in Kabwe, Zambia Lead and cadmium excretion in feces and urine of children from polluted townships near a lead-zinc mine in Kabwe. *Zambia. Chemosphere.* **202**, 48–55 (2018).
24. Bortnikova, S. B. *et al.* Assessment of emissions of trace elements and sulfur gases from sulfide tailings. *J. Geochem. Exp.* **186**, 256–269 (2018).
25. Bortnikova, S. *et al.* Gas Transfer of Metals during the Destruction of Efflorescent Sulfates from the Belovo Plant Sulfide Slag, Russia. *Minerals.* **9** (344) (2019).
26. Bortnikova, S. *et al.* Mechanisms of low-temperature vapor-gas streams formation from sulfide mine waste. *Sci. Tot. Environ.* **647**, 411–419 (2019).
27. Bortnikova, S. B. *et al.* (2020). Element transfer by a vapor-gas stream from sulfide mine tailings: from field and laboratory evidence to thermodynamic modeling. *Environ. Sci. Pollut. Res.* (2020).

<https://doi.org/10.1007/s11356-020-11529-x>

28. Makas, A. L. & Troshkov, M. L. Field gas chromatography – mass spectrometry for fast analysis. *J. Chromatogr. B.* **800**, 55–61 (2004).
29. Yurkevich, N. Sulfur and Nitrogen Gases in the Vapor Streams from Ore Cyanidation Wastes at a Sharply Continental Climate, Western Siberia, Russia. *Water Air Soil Pollut.* **230**, 307 (2019).
30. Salthammer, T. Very volatile organic compounds: an understudied class of indoor air pollutants. *Indoor Air.* **26** (1), 25–38 (2016).
31. Nadolinni, V. A. *et al.* Method for preparing standard gas mixtures and a device for its implementation. RF Patent 2410678. Byull. No.3(2011).

Figures

Figure 1

Photograph and scheme of the experiment setup

Figure 2

Experiment data on the capture coefficient with a sample volume of 0.5 L, given as a function of the chromatographic retention index.

Figure 3

Fragment of the recorder chart of aerosol particles bigger than 3 nm in the air above the sample and in the lab.