Mineral-Geochemical Indicators of Technogenic Sources of Aerosol Pollution

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Abstract

Granulometry, morphology data and data on mineral composition of aerosol particles are given. These have been obtained with the use of scanning electronic microscope LEO 1430 VP that was furnished with energy dispersive spectrometer OXFORD. Mineral-geochemical indicators of local sources of aerosol pollution under conditions of a megacity have been determined using ICP-MS, ICP-AES, XRD-SI, atomic absorption, and phase X-ray diffraction methods. Mobility of toxic elements that were accumulated in a snow covering has been found. A comprehensive approach has allowed us to estimate the contribution of particular commercial manufacturers to the general ecological condition of Novosibirsk.

INTRODUCTION

Studying selective ecological impact of commercial manufacturers that are located within the limits of large cities is one of urgent problems in geochemistry of technogenesis. Determination of the contribution of particular pollution sources constitutes a complex scientific problem; however, its solution may become the crucial factor for the measures to be effected on the ecological improvement of territories.

The investigation of a problem of regional aerosol pollution has begun since 1991 within the limits of the project "Aerosols of Siberia". It has been found that the composition of aerosols of the Novosibirsk Region and the Baikal region is produced for the most part due to the erosion of aluminosilicate soils [1, 2]. Cations of lithophilous elements make a significant contribution to ionic composition of the liquid phase of aerosols, as well as ions of sodium and chloride that are uncharacteristic for continental regions. It appears that the presence of the last-mentioned is related to their transport from saline soils and salted soils of Kazakhstan [3]. A process of adsorption of hydrocarbons, nitrogen-bearing compounds, and water on the surface of aerosol particles has been investigated [1, 2] together with time-space variation in the characteristics of aerosols, including concentrations of net atmospheric protein in the ground layer of the atmosphere [4, 5].

For the first time the authors have described spherical aerosol particles [6] in 1953. Later, it has been found that iron-bearing spherical particles are of technogenic origin and they are related to metallurgical production [7].

Study of mineral composition of aerosol particles in Siberia has begun only in recent years (2004–2005). The subject of investigation became aerosols of Tomsk agroindustrial area. Uranium oxides have been detected as the constituents of aerosol particles, the source of which, in opinion of the authors [8], is the Siberian Chemical Integrated Works.

Using Novosibirsk Integrated Tin Works JSC (NITW), Heat and Electric Power Plant (HEPP)-2, HEPP-3, HEPP-5 as an example, with the use of modern mineralogic-geochemical methods, this work examines the pollution of the city environment by aerosol particles arising in pyrometallurgy conversion of cassiterite concentrates, in coal combustion on thermal power stations, and in highway zone. The primal prob-

lem of the research is the determination of mineral-geochemical indicators of local technogenic sources of aerosol pollution.

Novosibirsk Integrated Tin Works manufactures tin, alloys, welding alloys, and babbits of various specifications on the basis of tin, lead, copper, and antimony, and it manufactures high-pure gallium, bismuth, and indium by processing compositionally complex ores and concentrates that are brought from mines of Primorye Territory, Yakutia, Magadan, and other regions of Russia, and from the near and far-abroad countries. When melting the ore concentrates, the use is also made of limestone flux and coke breeze. The enterprise has been founded during the Great Patriotic War in the suburbs of the city, but during the building development of the city, it has appeared practically at the centre of the left-bank part of the megacity. In the immediate proximity, 1–1.5 km northwest, northeast, and north of the pipe of the NITW, residential districts, country place, and Bugrinskaya grove, recreational zone are located. Furnaces of the HEPP-2, HEPP-3, and HEPP-5 of Novosibirsk burn power coals of Kuzbass with black oil added.

During wintertime, winds of southern and southwest directions dominate in the ground layer of the atmosphere at the Novosibirsk area, and the "wind rose" becomes more isometric in summer [9]. At the height of 0.5 km, in the boundary layer of the atmosphere, winds of southwest and western directions are predominant, which exactly determines the main directions of aerosol pollution from the pipes of the objects under investigation. The pipe of the NITW is 100 m high; the pipes of the HEPP-2 are 100 and 120 m high that of the HEPP-3 is 120 m high, and of the HEPP-5 is 260 m high.

Under Siberian conditions, snow serves an ideal model object to make an estimate for the dynamics of various forms of emissions that enter from commercial manufacturers, since solid aerosol particles and sorbed gaseous products are fixed in the steady snow covering from the beginning of November up to the end of March–the beginning of April.

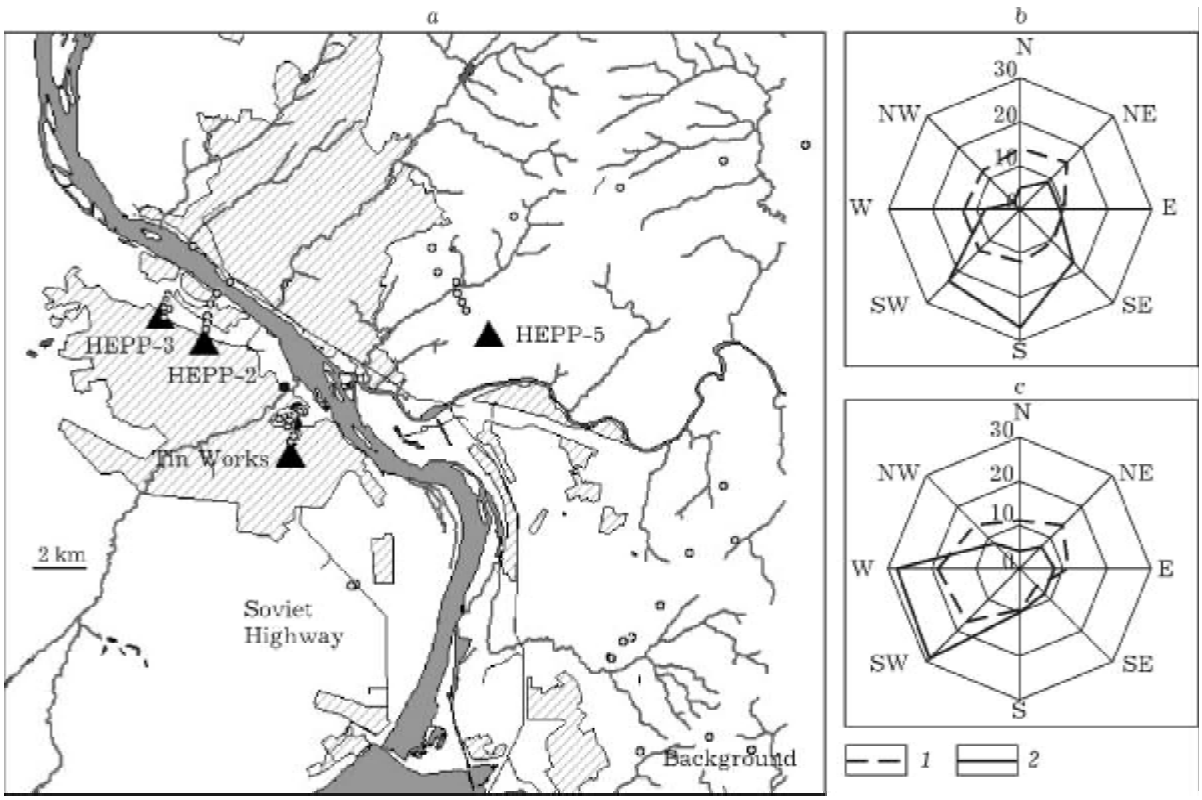

Fig. 1. Location of snow sampling points in the area of Novosibirsk (*a*) and "wind rose" in the ground (*b*) and the boundary (*c*) layer of atmosphere (at the height of 500 m): *1*, *2* – long-term data for summer (*1*) and winter (*2*) "wind rose" [9].

EXPERIMENTAL

Route sampling of snow has been performed in the vicinity of the NITW, HEPP-2, HEPP-3, HEPP-5 in the end of March 2005 and 2006, as well as on the roadside site along the Soviet Highway that is remote from commercial manufacturers (Fig. 1). The routes have been laid out in northern direction from the objects according to the winds that prevail in wintertime. To eliminate the effect of highways, all the sampling points were taken at the distance >150 m from them. A site in the region of the Klyuchi settlement that is located 4.5 km to the east from Akademgorodok (Novosibirsk) has been chosen as the background. By means of a hollow pipe (the inner diameter of 3.5 cm, a piston for stamping the snow), 16 portions of snow were selected in each point with unbroken snow covering. The total about 100 samples has been selected for the research.

With the use of the known procedures, an integrated elemental composition of solid aerosol particles, their mineral composition has been examined, the concentration of cations and anions of the liquid phase of the thawed snow has been quantitatively determined; the dynamics of entering solid ingredients has been evaluated at a variable distance from industrial facilities.

A solid fine-grained phase from each sample of thawed snow was concentrated on the "white belt" filter and examined by mineralogic-geochemical methods. Ionic composition of thawed snow was analysed by titration. Flame photometry was used to determine an ion concentration of sodium and potassium, and turbidimetric method, to determine the content of sulphates. The determination error was (%): HCO_3^- ≤ 12, SO_4^{2-} 23, Cl^- 16, Ca^{2+} 2, Mg^{2+} 10, ($Na^+ + K^+$) 25. Heavy metals (HM) that are dissolved in thawed snow and arsenic in various ranges of concentrations have been determined with the use of ICP mass spectrometer of high-resolution ELEMENT (Finnigan Mat, Germany) with ultrasonic sprayer of aqueous solutions U-5000AT+. Indium as an internal reference has been used to correct matrix effect and to control an instrument drift. Cd, Tl, Cu, Zn, Pb, and Hg elements were determined with a low resolution, Sb and Fe were determined with an average resolution, and As, with a high-resolution. The detection limit of the elements under investigation that was estimated based on 3σ variation of the background signal was equal to 0.002 and 0.1 ppm for micro- and macroingredients, respectively. The relative standard deviation during the determination of concentrations amounted up to 20 %.

Mercury content of solid aerosol particles and of thawed snow was determined by the atomic absorption method with the detection limit of 0.008 ppm; the relative standard deviation did not exceed 10 %.

The integrated elemental composition of samples of solid aerosol particles was determined quantitatively by the X-ray fluorescent method with the use of a synchrotron radiation (XRD-SR) at the VEPP-3 station of elemental analysis of the Institute of nuclear physics, SB RAS. According to standard procedure, the samples were abraded up to 200 mesh and pressed in tablets of diameter 6 mm and mass 30 mg [10]. With the use of this method, concentrations of 35 elements (Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Ga, Ge, As, Br, Mo, Ag, Cd, Sn, Sb, Te, Hg, Tl, Bi, Th, Pb, *etc.*) have been determined with detection limits up to 0.1 ppm depending on excitation energy of the emission lines [11]. Relative standard deviation in the determination of concentrations of these elements comprised 10–15 %. The international standards of soil IAEA SOIL-7 were used as external standard samples.

The phase X-ray diffraction analysis of aerosol particles has been made with a DRON-3M powder diffractometer (CuK_α radiation, the voltage applied to the tube of 40 kV, the current intensity of 24 mA). The given method allows a qualitative estimation of mass fractions of minerals.

Morphology and material composition of particular aerosol particles were examined with the LEO 1430 VP scanning electronic microscope that was supplied with the OXFORD energy dispersive spectrometer (EDS). The diameter of the scanning beam of the spectrometer measured 3–5 μm, which made it possible to determine composition of aerosol particles >5 μm in size. In specific cases, the acquired spectra are representative of aggregates of smaller grains that are in close accretions. Electronic pictures have been made under secondary and

backscattered electron mode. The integrated and differentiated particle size analysis of particular aerosol particles has been performed by measuring their sizes and material composition. The measured particles totalled 1286 including 665 aluminosilicates, 509 spherical glassy particles, and 112 grains of ore minerals (cassiterite, hematite, and magnetite). Microprobe investigations were additionally made by means of a Comebax Micro unit.

The research has allowed a comparative analysis to be conducted for dissolved forms and suspended particles in thawed snow in the neighbourhood of the NITW and coefficients of mobility of elements to be calculated [12]:

$K_m = M_X 100/(aN_X)$

where M_X is a concentration of the dissolved form of an element X, mg/L; a is mineralization of thawed snow, mg/L; N_X is content of an element in aerosol particles, %.

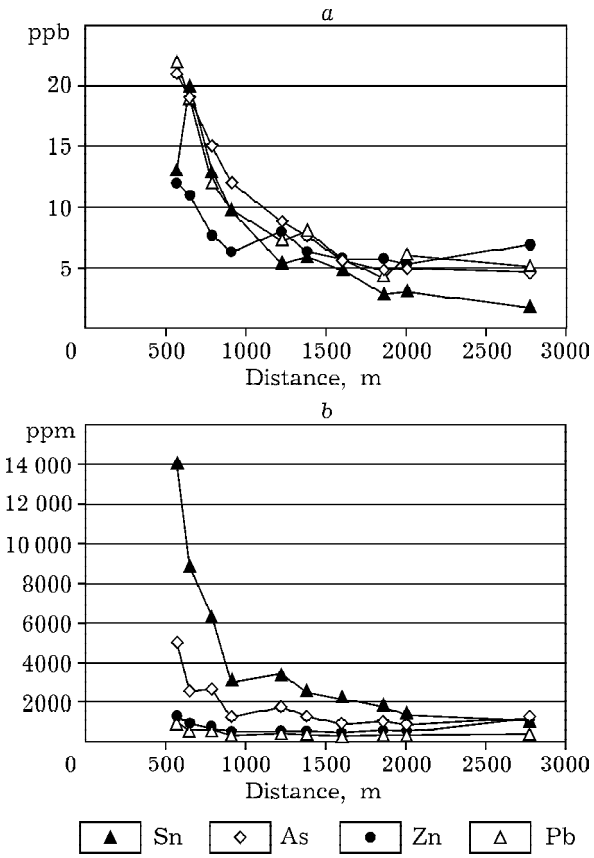

Fig. 2. Content of heavy metals and As in thawed snow (*a*) and in solid aerosol particles (*b*). Axis *Y* – concentrations of the dissolved elements in thawed snow (ppb), the total content of an element in solid snow deposits (ppm); axis *X* – the profile to the north from the pipe of the NITW.

RESULTS AND DISCUSSION

Ionic composition of thawed snow

General mineralization of samples of thawed snow from the reference sites that are located in vicinities of Akademgorodok and far from settlements and roads comprises 32–35 mg/L at the pH 6.0. Hydrocarbonate and calcium ions prevail as constituents of thawed snow; the content of chlorides and sodium is also significant.

The content of nitrates increases of thawed snow within the direct impact zone of the NITW (within the radius of 0.5–1.5 km); the mineralization comprises ~42 mg/L at the pH 6.2–6.4 (Table 1). As we go away from the NITW, mineralization, pH data, and data on ionic composition of thawed snow approach the background values.

Regularity in the decreasing concentrations of HM, arsenic, and antimony has been established as one moves away from the NITW (Fig. 2). Accordingly, high concentrations of HM are observed in the thawed snow near to the pipe of the NITW (μg/L): Sn, As, Pb ~20, Sb and Cd ~1.3, Tl ~0.1, Bi ~0.54, Te ~0.04. However, as one moves away from the pipe, their

TABLE 1

Ionic composition of thawed snow in the neighbourhood of the NITW (2005), mg/L

Zones	pH	Cl^-	HCO_3^-	SO_4^{2-}	NO_3^-	Na^+	Mg^{2+}	K^+	Ca^{2+}	M^*
1	6.4	2.8	18	2.3	4.0	3.7	0.66	1.5	6.4	40
2	6.2	3.6	12	2.0	9.5	3.8	0.66	1.9	6.0	40
3	6.1	3.2	12	2.0	2.0	3.7	0.62	1.0	5.4	30

Note. The zone 1 is located 680 m to the north from the pipe of the NITW, the zone 2 – 1400 m, the zone 3 – 2800 m.

*M – mineralization.

TABLE 2

Quantities of entry of aerosol particles to near zones of the investigated objects of Novosibirsk

Objects	Daily entry, mg/(m^2 · day)	Annual entry, t/year
HEPP-2	118	271
HEPP-3	143	329
HEPP-5	83	191
NITW	63	144
Highway*	131	48
Background	57	–

*Calculations have been performed in a 50-m strip along both sides of the highway, 1 km long.

sharp decrease is evidenced by several times under an exponential curve. The maximum (20 times) decrease of the content was observed for Te. Concentrations of dissolved Cu and Zn drop more smoothly. It should be remarked that mercury has been detected not only in thawed snow close to the pipe of the NITW, but also at the edge of Bugrinskaya grove (up to 0.08 μg/L).

General characteristic of aerosol particles

Dynamics of entry. By means of an estimation of mass entry of suspended particles, a daily average and annual dynamics of their entry has been determined per acre within the limits of an oval zone, extended in northern direction around the commercial manufacturer (the internal radius of 0.5 km, the external – 1.5 km). This so-called near zone is typified by maximum aerosol pollution (Table 2).

It is evident that aerosol emissions of the NITW and HEPP-5 are insignificant in their mass ratio by comparison to emissions from other sources. This is related to the fact that the pipe in the HEPP-5 is higher and an effective technology of emissions purification on electric separators is realized. Insignificant quantities of emissions of the NITW are caused by low rates of production at this manufacturer. Aerosol pollution along the 50-m zone of highway is comparable with the pollution from HEPP.

(For comparison, aerosol entry in Tomsk agroindustrial area is comparable to the data acquired for Novosibirsk (from 20 up to 124 mg/(m^2 · day) [8].)

Integrated elemental composition of aerosol particles. Elemental composition of aerosol particles appeared rather informative with regard to an assessment of local sources of technogenic pollution of Novosibirsk territory. Using comparative and correlation analysis, a group of indicator-elements of the aerosol pollution has been recognized that are associated with the activity of the NITW: Se, Mo, Ag, Cd, Sn, As, Bi, Hg, Tl, Cr. The content of these elements in the near zone of the NITW is 2–3 orders of magnitude higher when compared to that for near zones of the HEPP-2, HEPP-3, HEPP-5 and near to highway (Fig. 3). Concentrations of Zn, Sb in the neighbourhood of the NITW are comparable to concentrations of these elements near to HEPP-2 and HEPP-3 and they differ from those for the highway. Over background concentrations of Cu, Pb, Ga, Ge, Ni and Sr, Br in the near zones around the studied commercial manufacturers and highways are at approximately identical level and they cannot serve as indicators of local pollution sources.

The highway zone within the limits of 100 m band is typified by anomalously high content of K, Ca, Mo; then they drop down to background values, which is in agreement with the data received previously [13].

Evenly distributed in aerosol particles of all areas in question are Fe (2.5–3.5 %), Ti (0.3–0.4 %), U (3–4 ppm) and dispersed elements Rb (40–60 ppm), Y (20–35 ppm), Zr (150–250 ppm).

The following succession of mobility of elements has been revealed: Ca > Na > K > Zn > Sb> Cu > Pb > Ag > Bi > Cd > As > Fe > Th > Sn > Tl. The group of alkaline and alkali-earth metals appeared to be the most mobile (K_m > 1), as well as Zn (K_m ~ 1). Moderate mobility (K_m = 0.4–0.8) is typical for Sb, Cu, Pb, Ag, Bi, Cd; while As, Fe, Th fall into low

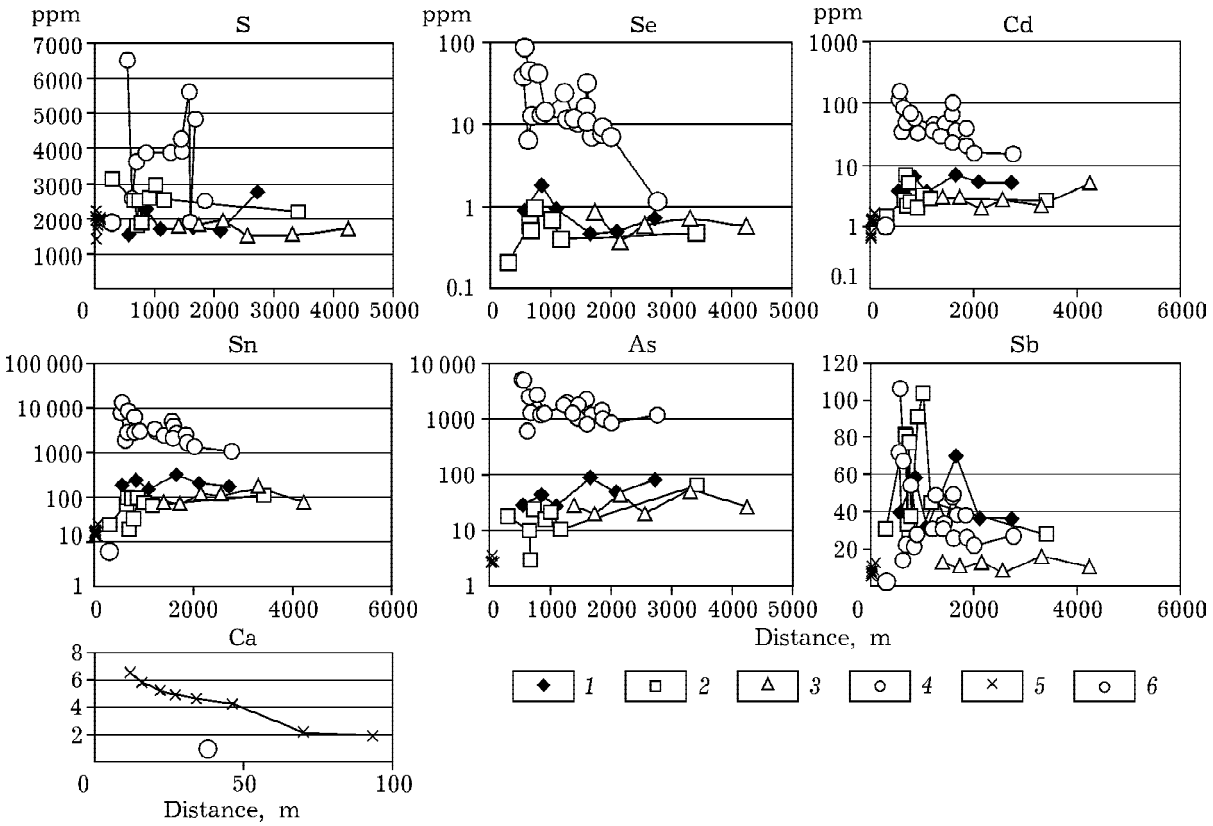

Fig. 3. Content of elements of aerosol particles near to the HEPP-2 (*1*), HEPP-3 (*2*), HEPP-5 (*3*), the NITW (*4*), the Soviet Highway (*5*) and at the reference site (*6*).

mobile group (K_m = −0.16... −0.1); Tl, Sn comprised the group of inert elements (K_m < 0.05). An anomalously low coefficient of mobility that has been observed for As calls for additional study. It appears that it is difficult to determine correctly its mobility because of large concentrations of this element in the solid phase (in aerosol particles).

Integrated phase mineral composition of aerosol particles. It is evident from data of Table 3 that aerosol particles that have arisen on the combustion of coal (thermal power station) and coke breeze (the NITW) are typified by the predominance of an amorphous phase, by presence of mullite, and by impurities of magnetite and hematite. Along with these substances, emissions of the NITW include grains of cassiterite and euchroite [$Cu_2 \cdot (AsO_4) \cdot (OH) \cdot 3H_2O$] that is an arsenic-containing secondary coppery mineral arising during pyrometallurgy processing of ore concentrates.

Amorphous phase of aerosols of the NITW and of the all studied thermal power stations is represented by fine-grained particles of glass and carbon that constitutes a product of poor combustion of coal. A typomorphic crystalline phase of high-temperature process that is typical for these objects is mullite [$(9Al_2O_3 \cdot 6SiO_2 \cdot (H_2O, F_2)$], which is being formed upon sintering of fine-grained silica-alumina particles. As opposed to aerosol emissions of the NITW and thermal power station, no mullite was observed on the sites that were remote from the commercial manufacturers, and the relative content of amorphous phase sharply decreases there. The composition of aerosols from reference sites is dominated by terrigenous association, wherein quartz, plagioclase, mica, and clay minerals prevail.

The circumstance that anhydrite appeared in aerosol particles in the area of Klyuchi settlement attracts interest for further study. It appears that this fact is associated to an activity of Chernorechenskiy Cement Works (Iskitim city). In addition, an anomalously high content of calcite has been observed within the limits of a narrow roadside strip (within 50 m) along the Soviet Highway.

TABLE 3

Phase composition of aerosol particles for various zones of the investigated objects according to X-ray diffraction analysis

Phase	NITW, m far from the pipe		HEPP-3, 300 m from the pipe	Soviet Highway, m far from the road axis		Reference site
	650	1860*		25	100	
X-ray amorphous	Very much of	Very much of	Very much of	–	A little	Not so much
Quartz	Not so much	Not so much	A little	Much	Much	Much
Calcite	–	–	Not so much	Much	A little	–
Plagioclase	A little	A little	Traces	Much	Much	Much
Amphibole	A little	–	–	Traces	Traces	–
Kalifeldspath	Traces	Traces	Traces	–	Not so much	A little
Mullite	Traces	A little	Traces	–	–	–
Mica	Traces	Traces	Traces	A little	Not so much	A little
Chlorite	Traces	Traces	Traces	–	–	A little
Clay minerals	–	–	–	Not so much	Not so much	Traces
Kaolinite	–	–	Traces	–	–	–
Talc	–	–	Traces	–	–	–
Magnetite	Traces	Traces	Traces	–	–	Traces
Hematite	Traces	Traces	Traces	–	–	Traces
Pyrite	–	Traces	–	–	–	–
Cassiterite	A little	–	–	–	–	–
Euchroite	Traces	Traces	–	–	–	–
Anhydrite	–	Traces	–	–	–	A little

*Bugrinskaya grove.

Integrated granulometric composition of aerosol particles. The studied aerosol particles vary in size from fractions of micron up to 150 μm; individual particles range up to 300 μm. Particles of fine sizes dominate in quantitative sense, but the great bulk of aerosols is concentrated in classes of greater coarseness. The size of 79 % aerosol particles in the near zone of HEPP-3 measures up to 10 μm; in so doing, half of them are presented by particles <3 μm microns in size. The main body of aerosols of the HEPP-3 is represented by particles of coarseness of 40–70 μm. As one moves away from the pipe of the NITW, the content of particles of oversized classes decreases and a fraction of particles of smaller sizes rises. The coarseness of ~46 % particles, 650 m from the NITW, is less than 10 μm, and 17 % from them are represented by particles 10–20 μm in size. The main body of aerosols is accounted for by particles >100 μm in size. The size of ~69 % of aerosol particles, 1860 m from the NITW (Bugrinskaya grove), does not exceed 10 μm, and 16 % from them range up to no more than 10–20 μm. The main body of aerosols is made up by particles with the sizes from 30 to 60 μm.

Three groups of aerosol particles can be distinguished in their material composition: I – silica-alumina particles of irregular-angular or pill-like form; II – fragments of crystals of cassiterite, hematite, and magnetite (high-reflecting particles under backscattered electron mode); III – silica-alumina hollow spheroids. Near zones of the HEPP-3 and the NITW are dominated in quantity and mass by particles of group I. In spite of a low content of particles of group II (4 and 16 % from the total number of particles for the respective zones of the HEPP-3 and the NITW), their content is significant due to their high density (7 and 20 mass %, respectively). As one goes away from the pipe of the NITW, the quantity of hollow

spherical particles increases, their content is insignificant though. The sizes of silica-alumina particles of the group I vary in the widest range, from fractions up to 300 μm; particle sizes of the II group near to the HEPP-3 are in a range 1–20 μm, and in the zone of the NITW are from 3 to 60 μm. The sizes of spherical particles range from fractions of micron up to 85 μm, which is comparable to data for aerosols of Tomsk agroindustrial area [8]. In opinion of the authors [8], spherical particles in aerosols of this area are represented by mullite, although they did not performed particle size analysis of aerosol particles in general.

Material composition and morphology of individual aerosol particles. Aerosol particles, the emergence of which is related to pyrometallurgy processing of cassiterite concentrates of the NITW, are characterized by the greatest mineral variety. As one goes away from the pipe, a separation of particles occurs according to their size, density, and aerodynamic properties. The largest and heaviest grains drop out in a near zone of the NITW, characteristic of which are fragments of fusion mixture components and droplets of alloys of colour and ferrous metals (Figs. 4, 5) that are absent from emissions of the thermal power stations. Found among them are large enough (from tens up to 300 μm) grains of spongy structured scoria, fragments of crystals of quartz, calcite, plagioclase, amphibole, and potassium feldspar, cassiterite, sulphide minerals as well as unburnt particles of coal, glassy phases, secondary minerals, arising in oxidation and sintering of sulphides, fusion of aluminosilicates, the smallest droplets of iron, tin, and alloys of non-ferrous metals. Large enough droplets of iron of spherical form, fine impregnations and clusters of metal tin and its alloys within coarser grains of scoria of a spongy form have been revealed in aerosol emissions of the NITW. These impregnations and clusters have been revealed not only in the neighbourhood of the NITW, but also on the territory of the Bugrinskaya grove that locates up to 2–3 km far from the NITW. Fragments of separate quartz grains have even retained in some sites their initial hexahedral form (see Fig. 5, *a*).

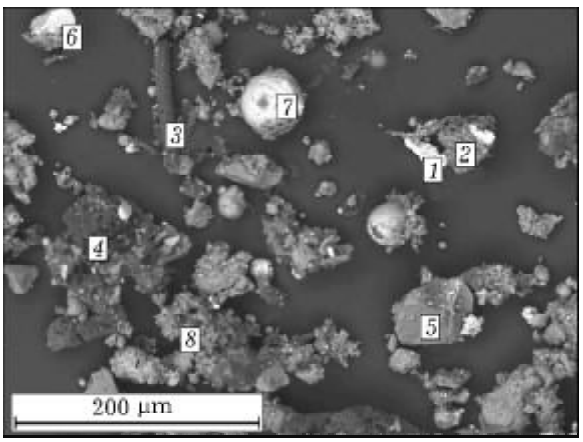

Fig. 4. Electronic images of aerosol particles from the near zone of the NITW (650 m to the north from the pipe, 2005): *1* – cassiterite grain of an irregular form (35 × 41 μm) in scoria; *2* – scoria of silica-alumina composition; *3* – a fragment of calcite grain (13 × 88 mm); *4* – a site of scoria of predominantly carbon composition (coal); *5* – a fragment of calcite grain (74 × 53 mm) in accretion with quartz and magnetite; *6* – fused grain of pyrite (24 × 35 mm); 7 – a spherical particle (53 mm) of predominantly iron composition with impurity of carbon; *8* – grain of scoria of an irregular form, silica-alumina in composition.

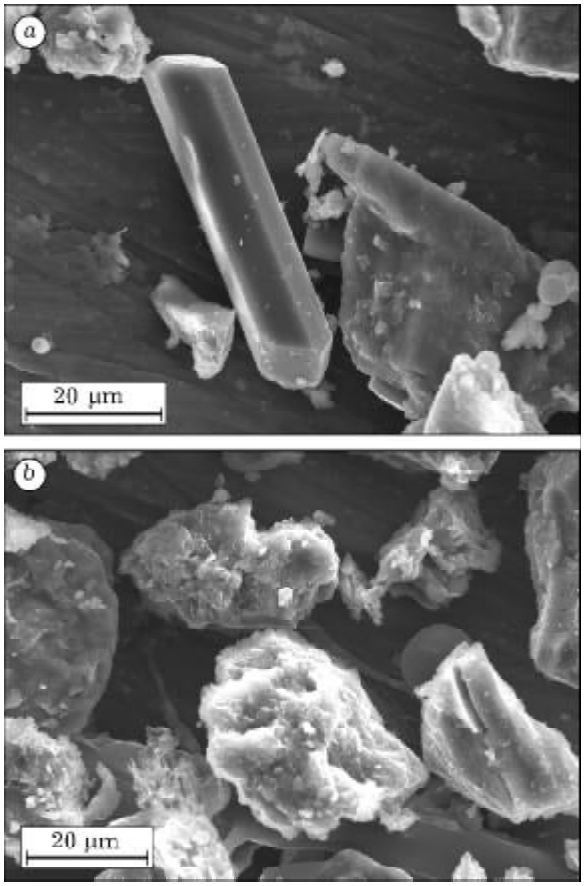

Fig. 5. Fragment of a quartz chip (12 × 53 μm) in the environment of fused grains of scoria, silica-alumina in composition (*a*) and microparticles of scoria of irregular cavernous form, up to 30 mm in size (*b*).

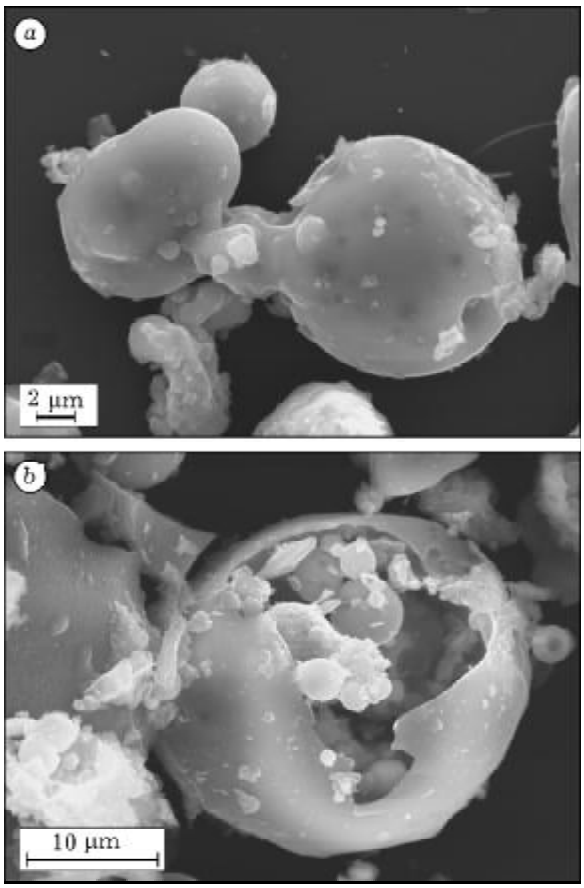

Fig. 6. Electronic images: *a* – isolated and caked microspheroids of scoria, sized from fractions up to 14 μm (the near zone of the NITW, 650 m to the north from the pipe); *b* – hollow microsphere (26 μm) that is filled with smaller spherical particles with the sizes of 0.08–5.5 μm (Bugrinskaya grove, 1860 m to the north from the pipe of the NITW).

The aerosol emissions of the NITW and thermal power stations are typified by the availability of particles of scoria, coal, and of spherically shaped particles that are both glassy isolated and connected among them (Fig. 6). The size of the last-mentioned can amount from fractions to the first tens microns. In most cases, hollow microspheres with a thin shell are formed, they being partially filled with smaller glass balls. The hollow spherical particles are of a low bulk density and they can be brought to significant distances with aerosol emissions of the NITW and thermal power stations. A higher density is typical for spongy particles of scoria of most intricate form (see Fig. 5, *b*). The largest ones of them settle down in near zones, but fine-grained scoria particles move on many tens kilometres and they can be observed even within the limits of reference sites.

CONCLUSIONS

1. An extended in northern direction, oval formed zone of intensive technogenic pollution with internal radius up to 0.5 km and external of diameter up to 1.5 km has been recognized in a near zone of the NITW. Within its limits, an increase in the content of As, Sn, Tl, Cd, Zn, Bi, Ag, Hg in thawed snow and in aerosol particles has been found that are related to processing of cassiterite concentrates. Typomorphic elements of emissions of thermal power stations are represented by Fe, V, Mn, I. Sites of the NITW and of the studied thermal power stations are typified by higher than usual content of Sb, Cu, Pb, Br. An increase in the content of nitrates is observed in thawed snow of the near zone of the NITW, which relates supposedly to high-temperature processes of pyrometallurgy production.

2. Specific mineral associations that have originated under the influence of high temperatures are characteristic of aerosol emissions of thermal power stations and the NITW. These mineral associations include a glass-containing X-ray amorphous phase, mullite, hematite, magnetite, and hollow spherical particles of predominantly silica-alumina composition. Euchroite, droplets of iron, alloys of non-ferrous metals and tin as well as residual cassiterite serve as indicator-minerals of pyrometallurgy conversion of cassiterite concentrates. Aerosols of reference sites and highways are represented for the most part by particles of aluminosilicates with a little content of X-ray amorphous phase. Calcite serves as a typomorphic indicator of aerosol pollution along highways.

3. As aerosol emissions move forward, fractionation of particles occurs according to their granulometric and mineral composition, density, and form of individual particles. Hollow silicate microspheres and fine-grained dust migrate for a long distance, while largest and densest particles (large fragments of crystals of ore minerals, droplets of metals) accumulate near to pollution sources.

4. Four groups of elements can be distinguished by their mobility extent in a liquid phase of thawed snow: a) most mobile elements (alkali and alkali-earth metals, zinc), b) moderately mobile (Sb, Cu, Pb, Ag, Bi, Cd), c) low mobile (As, Fe, Th), and d) inert (Tl, Sn).

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REFERENCES

1 V. P. Ivanov, S. N. Trukhan, D. I. Kochubey *et al.*, *Chem. Sustain. Develop.*, 13 (2005) 51.
URL: http://www.sibran.nsc.ru/English/csde.htm
2 V. P. Ivanov, S. N. Trukhan, D. I. Kochubey *et al.*, *Ibid.*, 14 (2006) 425.
URL: http://www.sibran.nsc.ru/English/csde.htm
3 B. S. Smolyakov, L. A. Pavlyuk and K. P. Koutsenogii *et al.*, *Ibid.*, 5 (1997) 193.
4 K. P. Koutsenogii and P. K. Koutsenogii, *Ibid.*, 5 (1997) 457.
5 A. I. Borodulin, S. A. Safatov, O. G. Khutorova, *Meteorol. Gidrol.*, 2 (2004) 72.
6 W. J. Thomsen, *Sky and Telescope*, 12 (1953) 147.
7 J. Hoppe, H. Zimmermann, *Kurze Originalmitteilungen*, 4 (1954) 93.
8 E. G. Yazikov, R. V. Goleva, L. P. Rikhvanov *et al.*, *Zap. VMO*, 5 (2004) 69.
9 Klimat Novosibirska, Gidrometeoizdat, Leningrad, 1979.
10 S. Yu. Artamonova, Yu. P. Kolmogorov, *Pov-nost'*, 9 (2005) 16.
11 V. Baryshev, G. Kulipanov, A. Skrinsky, X-Ray Fluorescent Elemental Analysis, in: Handbook on Synchrotron Radiation, in G. Brown and D. E. Moncton (Eds.), Elsevier Sci. Publ. B.V., vol. 3, 1991, pp. 641–688.
12 A. I. Perelman, Geokhimiya epigeneticheskikh protessov, Nedra, Moscow, 1965.
13 V. F. Raputa, V. V. Kokovkin, O. V. Shuvaeva *et al.*, *Chem. Sustain. Develop.*, 13 (2005) 641.
URL: http://www.sibran.nsc.ru/English/csde.htm