

Geochemical characteristics and genesis of urban surface-deposited sediments: a parallel investigation across a network of small Russian cities

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Abstract

Purpose

This study tests the hypothesis that the physicochemical characteristics and reproducible geochemical-mineralogical relationships of urban surface-deposited sediments are fundamentally controlled by the combined effects of the local lithogenic substrate, anthropogenic material inputs, and landscape conditions governing sediment production. To address this, a comparative study was conducted using a consistent sampling and analytical framework across cities with contrasting geological and anthropogenic characteristics.

Methods

A total of 300 sediment samples were collected from eight cities within the Sverdlovsk Oblast, Russia. A detailed landscape survey was conducted to document the general characteristics of each sampling site and the local catchment area from which the sediment was mobilized. Chemical, mineralogical, and particle-size analyses of the sediments were performed.

Results

The results indicate that while the sediments mineral composition is rooted in the local geological parent material, it has been significantly modified by minerals sourced from regional mining operations and utilized in construction. A unique mineralogical assemblage formed in each city governs the specific elemental baseline profile. The fine fraction ($< 100 \mu\text{m}$) proportion depends on the mineral characteristics, which can be attributed to the varying resistance of minerals to weathering in the urban environment. The main landscape factors influencing the fine fraction generation are terrain slope and disturbed surfaces.

Conclusion

Acting cumulatively, natural and anthropogenic drivers turn surface-deposited sediments into a comprehensive geochemical archive. A systemic understanding of the core physicochemical properties of the sediments serves as a fundamental prerequisite for effectively investigating the environmental implications of urban sedimentogenesis.

1. Introduction

In the 21st century, urbanization has definitively become the dominant vector of civilizational development, turning cities into the primary habitats for humanity. According to United Nations (2025) data, 58% of the global population resides in large and small cities and towns with a population density

exceeding 1,500 people per square kilometer. In Russia, this trend is exceptionally pronounced, with the urbanization rate reaching approximately 79%. In Sverdlovsk Oblast, historically a region with developed industrial manufacturing, up to 82% of the population lives in urban areas. Concurrently, a significant portion of the population (38%) is concentrated in small cities and towns (with populations under 200,000), which, due to their narrow industrial specialization, largely fall into the category of monocities (single-industry cities). Occupying a mere 2–3% of the Earth's land surface, cities generate the majority of global GDP while simultaneously serving as epicenters of anthropogenic pressure, primarily driven by the concentration of industrial production, transport networks, and energy consumption (Crippa et al. 2021; Liotta et al. 2023; Lwasa et al. 2023; United Nations, 2025; Hassani et al. 2026).

The process of urbanization drives a radical reshaping of the natural landscape, replacing it with a complex mosaic of anthropogenic surfaces (Yarmoshenko et al. 2020; Nazzal et al. 2025; Akatu et al. 2026; Dytłow et al. 2026). Soil compaction and the sealing of surfaces with impermeable materials, such as asphalt and concrete, cause a loss of soil filtration capacity and significantly alter the hydrological regime of the area (Chin 2006; Russell et al. 2017; Szabó et al. 2023). These urbanization-driven changes are cumulative, creating a unique physical and geographical setting where environmental parameters are determined by building density, traffic loads, and human activity intensity (Zgłobicki et al. 2018; Moskovchenko et al. 2022; Shin et al. 2024; Akatu et al. 2026; Kabir et al. 2026).

Urbanization fundamentally restructures natural geomorphological processes, including sedimentogenesis, making built-up areas into specific zones of generation, transformation, and accumulation of solid sedimentary material (Chin 2006; Russell et al. 2019). The essence of this process is described by the sediment cascade model, which comprises the stages of particle detachment, lateral migration, accumulation in geochemical traps, and subsequent removal by surface runoff into aquatic ecosystems or disposal at urban waste storage sites (Fryirs 2012; Russell et al. 2019; Yarmoshenko et al. 2020; Najafi et al. 2021). A critical characteristic of the urban sediment cascade is the step-like nature of lateral transport across permeable and impermeable surfaces along the landscape gradient, where material can undergo multiple cycles of re-deposition as dust and dirt under the influence of vehicular traffic and precipitation (Amato et al. 2011; Zafra-Mejía et al. 2025; Akatu et al. 2026). This continuous process forms a complex system of urban surface-deposited sediments. The structural complexity and systemic interconnection of urban sedimentogenesis manifest in the mixing of geogenic mineral particles within urban sediments with the wear products of road pavements, infrastructure elements, buildings, vehicle tires, brake pads, and microplastics (Amato et al. 2011; Le Pape et al. 2025; Dytłow et al. 2026).

One of the constituents within the diverse range of urban surface-deposited sediment types is road-dust sediment (RDS). RDS comprises material formed by the weathering and degradation of road pavements caused by moving vehicular traffic, which then deposits directly onto road surfaces (Amato et al. 2011; Gunawardana et al. 2012; Dytłow et al. 2026; Kasimov et al. 2024). The physicochemical properties and composition of RDS reflect the environmental impacts of motor vehicles, capturing both exhaust and non-exhaust emissions. The capacity to evaluate the contribution of road transport to the environmental

state of urban areas through RDS analysis is utilized by researchers worldwide (Dehghani et al. 2018; Nazzal et al. 2025; Zafra-Mejía et al. 2025; Kotov et al. 2026). In this context, a unified methodological framework is proposed for studying RDS as an indicator of transport-induced environmental impacts in order to facilitate comparative analysis and global-scale trend monitoring (Haynes et al. 2020).

In contrast to RDS, the loose solid material of urban surface-deposited sediments and the pollutants contained within it originate from the entire catchment area of a local microrelief depression where the particles accumulate. In addition to roads, this catchment area often includes significant sources of intensive dust and dirt generation, such as construction sites, earthworks, or unauthorized parking on lawns (Seleznev et al. 2023; Shevchenko et al. 2024; Yarmoshenko et al. 2024; Akatu et al. 2026;).

Urban surface-deposited sediments are typically characterized by a high content of the fine-grained fraction (Amato et al. 2011; Seleznev et al. 2019; Silva et al. 2026; Gronba-Chyła et al. 2026). Particles smaller than 100 μm can be resuspended into the air by wind and vehicular traffic, while particles under 10 μm can remain suspended in the atmosphere for extended periods (De Miguel et al. 1999; Charlesworth et al. 2010; Chen et al. 2026). Upon inhalation, this particulate matter poses a severe threat to human health (Candeias et al. 2020; Navarro-Ciurana et al. 2023; Hay et al. 2025). Numerous studies have established that the mineral component of urban PM is substantial, accounting for several tens of percent (Amato et al. 2011; Popovicheva et al. 2024; Brezov et al. 2025; Ma et al. 2025). Beyond health impacts, sediment deposition within the urban environment affects the aesthetic, economic, and other aspects of city life. Negative aesthetic consequences include the degradation of the visual appearance of public spaces (Yarmoshenko et al. 2020). Furthermore, the continuous influx of sediment necessitates increased municipal expenditures for street sweeping and storm sewer maintenance (Akatu et al. 2026; Teang et al. 2026).

Another dimension of the urban sedimentogenesis problem, and a major focus of environmental research, is the delivery of urban runoff into receiving waters. The pollution of rivers and other waterbodies with solid urban sediments fundamentally alters their hydrochemical and hydrophysical profiles. Walsh et al. (2005) termed this phenomenon “the urban stream syndrome”. As shown in a comprehensive review by Russell et al. (2017), which synthesized data on sediment yield from urbanized catchments worldwide, sediment export from urban areas does not decline to natural background levels even after the completion of land development. Due to the high capacity of urban runoff to erode sediment sources and the exceptional sediment transport efficiency of the urban drainage network, cities continue to deliver anomalous sediment loads to aquatic systems (Russell et al. 2017). Consequently, the assessment of sediment yield from urban catchments has become the focus of numerous global studies (Najafi et al. 2021; Popovicheva et al. 2024; Emamzadeh et al. 2025).

Understanding the genesis of surface-deposited urban sediments, the mechanisms governing their mineralogical composition, and their geochemical alteration is a vital task for advancing environmental assessments of cities, protecting public health, and evaluating impacts on adjacent ecosystems (Akatu et al. 2026). Such investigations require a comprehensive approach integrating particle-size, chemical, and mineralogical analyses of urban sediments, taking into account the specific landscape conditions of

sediment formation (Akatsu et al. 2026). To date, such integrated studies have been conducted in only a few cities worldwide (Gunawardana et al. 2012; LeGalley and Krekeler, 2013; Candeias et al. 2020; Dytłow et al. 2026). These studies have focused on individual cities, making it difficult to distinguish general mechanisms of urban sedimentogenesis from patterns arising from local geological, industrial, or infrastructural conditions. In particular, it remains unclear how consistently the mineralogical composition of urban sediments reflects the local lithogenic substrate when it is modified by construction materials and industrial inputs, and to what extent mineralogical composition and landscape conditions jointly control the generation of the fine sediment fraction. Addressing these questions requires a comparative study conducted using a consistent sampling and analytical framework across multiple cities with contrasting geological and anthropogenic settings.

This study tests the hypothesis that the physicochemical characteristics of urban surface-deposited sediments are controlled by the combined effects of (i) the local lithogenic substrate, (ii) anthropogenic mineral inputs, particularly construction materials and industrial by-products, and (iii) landscape conditions governing sediment production and fine-particle accumulation. It is further hypothesized that these controls generate reproducible relationships between mineralogical composition, elemental geochemistry, and particle-size distribution that can be identified through cross-city comparison. To test these hypotheses, a total of 300 surface-deposited sediment samples from eight small cities in the Middle Urals were investigated using a consistent framework integrating mineralogical, chemical, particle-size, and landscape analyses. This approach allows for a broader assessment of the extent to which the composition and properties of surface-deposited sediments can be explained by complex mechanisms of sedimentogenesis in the urban environment rather than treated as a collection of city-specific geochemical characteristics.

2. Materials and Methods

2.1. Study area

This study was conducted across a network of eight small cities and towns within Sverdlovsk Oblast, Russia: Alapaevsk, Asbest, Kachkanar, Kamensk-Uralsky, Nevyansk, Pervouralsk, Serov, and Verkhnyaya Pyshma. The main demographic characteristics of these investigated urban areas are summarized in Table 1.

The study area is characterized by a continental to moderately continental climate. A stable snow cover typically forms in late October or early November and persists for 145–175 days. The mean air temperature ranges from – 19.5 to – 14.5°C in January and from 16.5 to 19.5°C in July. By the end of winter, the average snow depth reaches 40–70 cm. The maximum monthly precipitation occurs in July (75–95 mm), whereas the minimum is recorded during the winter season (9–23 mm). The mean annual precipitation is approximately 500 mm.

According to the classification of the United Nations Department of Economic and Social Affairs (UN DESA, 2025), Asbest, Verkhnyaya Pyshma, Kamensk-Uralsky, Pervouralsk, and Serov are classified as

small cities (population of 50,000–250,000), whereas Alapaevsk, Kachkanar, and Nev'yansk fall into the category of dense towns (population < 50,000 and population density > 1,500 inhabitants per km²) (United Nations, 2025).

Table 1
Main demographic characteristics of the investigated cities

City	Population	Population density (inhabitants per km ²)*	Founded
Alapaevsk	35 700	2 600	1639
Asbest	62 300	5 800	1889
Verkhnyaya Pyshma	77 500	6 700	1854
Kamensk-Uralsky	160 300	5 900	1682
Kachkanar	37 300	5 900	1957
Nev'yansk	22 000	3 400	1701
Pervouralsk	114 000	6 500	1732
Serov	92 000	5 100	1894
* within residential areas; authors' estimates based on the residential area and official population statistics			

All investigated cities are located within the Ural Orogen, which was formed through a complex sequence of geological and tectonic processes. Structurally, the Ural Mountains are conventionally subdivided into a series of north–south-trending Structural and Formation Zones, which succeed one another from west to east and differ in their geological evolution and lithological composition (Borozdina et al. 2024; Ivanov 2026). A characteristic feature of the Ural geological structure is its imbricate thrust architecture, in which tectonic sheets are successively emplaced over one another (Yuzhakov et al. 2015; Borozdina et al. 2024). Consequently, the present-day landscape is developed on a heterogeneous assemblage of Paleozoic sedimentary, igneous, and metamorphic rocks, overlain by Mesozoic weathering crusts and unconsolidated Neogene-Quaternary deposits (Kalugina et al. 2017).

Figure 1 schematically illustrates the locations of the investigated cities within the Ural Structural and Formation Zone.

Kachkanar and Pervouralsk are located within the Tagil Megazone. The geological basement of Kachkanar is composed of Silurian ultramafic and mafic intrusive rocks of the Kachkanar complex, represented predominantly by pyroxenites and gabbros. Pervouralsk is situated near the Main Ural Fault within the Tagil Megazone. The principal geological formation of the area is the Revda Gabbro Massif, whose central part is composed of ultramafic rocks, mainly hornblendites and pyroxenites.

Four of the investigated cities are located within the East Ural Megazone. Asbest is situated within the Bazhenovo ultramafic massif, a large complex of peridotites and dunites that underwent extensive hydrothermal alteration and serpentinization during early stages of the Ural Orogen. The Nevjansk area is underlain by Paleozoic metamorphic, volcano-sedimentary, and igneous rocks of Ordovician, Silurian, and Devonian ages. The geological basement of the Serov area consists predominantly of Devonian serpentinites, locally overlain by Paleogene sedimentary deposits. Verkhnyaya Pyshma lithologically is underlain mainly by Devonian mafic and ultramafic intrusive rocks (pyroxenites, gabbros, and gabbro-diorites), together with serpentinites, talc-carbonate rocks, and subordinate basalts, andesitic basalts, and their pyroclastic equivalents.

Alapaevsk and Kamensk-Uralsky are located within the Trans-Ural Megazone. The geological formation of the Alapaevsk area is composed predominantly of Cretaceous continental clayey-sandy deposits containing ferruginous horizons. To the west of the city lies the Alapaevsk Ophiolite Massif, composed of strongly serpentinized ultramafic rocks, including peridotites, dunites, and gabbros. The geological substrate of the Kamensk-Uralsky area consists of Devonian and Carboniferous volcano-sedimentary sequences represented by porphyrites, volcanic tuffs, and limestones. These rocks are overlain by Mesozoic continental sands and clays.

The Ural region is one of the largest and oldest mining and metallurgical provinces in Russia, with a long history of mineral resource exploitation. This context has led to the development of ferrous and non-ferrous metallurgy, mining, and heavy engineering industries. The investigated cities represent different types and stages of industrial development in the Urals, ranging from the early period of Russian settlement and the establishment of the first metallurgical works to the large-scale industrial expansion associated with planned economic development during the Soviet era.

Kachkanar was founded in 1957 to support the construction and operation of a large mining and processing plant. The city's economy is based on the extraction and beneficiation of iron ores from the vanadium-bearing titanomagnetite deposit. This principal industrial complex ranks among the largest of its kind in Russia. The deposit is exploited using open-pit mining, and waste rock dumps are located in close proximity to the urban area. In addition to iron ore concentrate, the Kachkanar plant produces crushed stone from pyroxenites and gabbros as a by-product for the construction industry.

Pervouralsk was founded in 1732 as a small factory settlement and underwent rapid industrial development during the 1920s and 1930s, becoming a major metallurgical center. At present, the city's principal industries include the production of steel pipes, refractory materials, and chromium compounds. A titanomagnetite deposit and a mining and processing plant are located on the southeastern outskirts of the city. In addition to iron ore production, the plant produces crushed amphibolite as a by-product for the construction industry. A granite quarry is also located in the vicinity of Pervouralsk.

Asbest was founded in 1889 following the onset of industrial mining at the Bazhenovo chrysotile-asbestos deposit, the largest of its kind globally. The deposit remains in active operation, and crushed

serpentinite is produced as a by-product for the construction industry.

Nevyansk, the oldest factory settlement in the Urals, is widely regarded as the birthplace of the Ural metallurgical industry. The first ironworks in Nevysk was established in 1701. By the beginning of the 20th century, the local iron ore deposits had become largely depleted, leading to the closure of the blast furnaces. Today, the site of this historical facility is occupied by a mechanical engineering enterprise, while tourism has become an increasingly important sector of the local economy.

Serov stands out as a leading center of ferrous metallurgy. Its principal industrial enterprises include an integrated steelworks established in 1894 and a ferroalloy plant commissioned in 1958.

The development of the copper deposit in Verkhnyaya Pyshma began in 1854 and continued until 1976. Following the commissioning of an electrolytic refinery in 1934, the city developed into a major center of non-ferrous metallurgy. Currently, copper manufacturing utilizes a full production cycle based on raw materials mined in other regions.

The first ironworks in Alapaevsk was established in 1704, followed by a second plant in 1824. Local limonite ores served as the principal feedstock for ironmaking. Metallurgical production ceased at the beginning of the 20th century, and the modern city's economy is dominated by the wood-processing and food industries. Additionally, a chrysotile asbestos deposit located approximately 25 km southwest of the city was also exploited until the 1990s.

A historic iron foundry operated in Kamensk-Uralsky from 1701 to 1926. During the Soviet industrialization period, two major industrial enterprises were commissioned in the city: a pipe plant in 1934 and an aluminum smelter in 1939.

2.2. Urban surface-deposited sediment sampling

Depending on its size, a network of 30 to 40 sampling sites was established within the residential areas of each city. These sites were selected using Google Maps based on the following criteria: (i) uniform spatial distribution across the city, and (ii) balanced representation of different residential development types and construction periods.

In apartment building areas, each sampling site was located within a residential block and included buildings together with associated functional zones, such as roads, driveways, sidewalks, lawns, parking lots, and playgrounds. Areas outside the selected residential block were not included in the survey. In low-rise building areas dominated by detached housing, each sampling site comprised the roadside sectors, including the same adjacent functional zones. Approximately half of the sampling sites were established in apartment building zones, with the remainder positioned in low-rise detached housing sectors.

A composite sample of surface-deposited sediment was collected from three to five micro-depressions within each sampling site using a plastic scoop and a brush. Each sample was placed in a sealed polyethylene bag. The mass of each composite sample ranged from 1.0 to 1.5 kg.

A detailed landscape survey was conducted to document the general characteristics of each sampling site and its local catchment area, from which sediment was mobilized. The following parameters were recorded: date and time, address, coordinates, residential development type (apartment building area or low-rise detached housing), functional zone of the site, catchment characteristics, an expert assessment of infrastructure conditions and cleaning quality (three ranks: good, satisfactory, or poor), proportion of disturbed surfaces (0–10%, 10–50%, or > 50%), traffic intensity, and parking conditions. Sampling and landscape survey were accompanied by photographic documentation.

2.3. Initial sample preparation

The sediment samples were prepared for physicochemical analyses in accordance with Russian national standard (GOST 17.4.4.02–2017). Large fragments, foreign materials, plant debris, roots, and other coarse inclusions were removed manually. The samples were then oven-dried. A particle-size fraction > 3 mm, consisting predominantly of rock fragments, was separated by dry sieving through a 3-mm mesh sieve and excluded from subsequent analyses. The remaining < 3 mm fraction was gently disaggregated using a rubber-tipped pestle and thoroughly homogenized.

Representative subsamples (250–300 g) were obtained via quartering for particle-size analysis. Grain-size distribution was determined by dry sieving. The < 3 mm fraction was sieved through 1.0 and 0.1 mm mesh sieves to obtain three particle-size fractions: <0.1 mm, 0.1–1 mm, and 1–3 mm. The mass of each fraction was measured using an analytical balance. The proportion of each particle-size fraction was calculated as the ratio of its mass to the combined mass of the three fractions for each sample. Representative subsamples of the < 0.1 mm and 0.1–1 mm fractions were subsequently collected for mineralogical and chemical analyses. While considering the overall particle-size distribution of the urban sediments, this study specifically focused on the fraction < 0.1 mm. To quantitatively characterize this component, the D_{100} coefficient was introduced.

Other representative subsamples (150 g) were obtained to isolate the fraction < 1 mm directly from the original sample for bulk chemical and mineralogical analyses. Subsamples were milled to a particle size < 0.074 mm.

2.4. Analytical Procedures

Element concentrations were determined by inductively coupled plasma mass spectrometry (ICP-MS) using an ELAN 9000 mass spectrometer (PerkinElmer, USA) at the Chemical Analytical Center of the Institute of Industrial Ecology UB RAS, in accordance with the certified national standard method (PND F 16.1:2.3:3.11–98).

The mineralogical composition of the < 0.1 mm, 0.1–1 mm, and < 1 mm fractions was determined for 10 randomly selected urban sediment samples in each city. Mineralogical characterization was carried out using X-ray diffraction (XRD) and simultaneous thermal analysis at the Geoanalitik Shared Research Center, Zavaritsky Institute of Geology and Geochemistry, UB RAS. Thermogravimetric and differential thermal measurements were performed using a Diamond TG/DTA simultaneous thermal analyzer

(PerkinElmer, USA). XRD data were acquired on an XRD-7000 diffractometer (Shimadzu Corp., Kyoto, Japan), and quantitative phase evaluation was carried out using the Siroquant software package.

2.5. Data analysis

To evaluate the similarity between the chemical composition of urban sediments and the average composition of the Upper Continental Crust (UCC), and to identify geochemical anomalies, the Enrichment Factor (EF) was calculated. The elemental concentrations reported by Rudnick and Gao (2014) for the UCC were used as the reference values. Using Al as the conservative reference element for normalization, the EF was calculated according to Sutherland et al. (2000) using the following equation:

$$EF = \frac{C_i/C_{ref}}{UCC_i/UCC_{ref}}$$

1

where C_i and UCC_i are the concentrations of element i in the sediment sample and the UCC, respectively (mg/kg); C_{ref} and UCC_{ref} are the concentrations of the reference element (Al) in the sediment sample and the UCC, respectively (mg/kg).

Principal Component Analysis (PCA) was applied to investigate the multivariate structure of the geochemical dataset and to identify the major factors controlling variations in the chemical composition of urban sediments, group elements exhibiting similar distribution patterns, and distinguish potential natural and anthropogenic sources. In addition, PCA provides information on the relative contribution of individual factors to the overall variability of the dataset.

Hierarchical cluster analysis was performed to identify relationships among chemical elements. This procedure was carried out using the Complete Linkage algorithm with Pearson's correlation distance ($1 - r$) as the similarity measure, generating dendrograms that illustrate the degree of similarity among elements and the hierarchical sequence of cluster formation. Both PCA and hierarchical cluster analysis are widely used in geochemical studies of urban sediments to identify geochemical associations and infer natural and anthropogenic sources of elements (Han et al. 2006; O'Shea et al. 2020; Papazotos et al. 2024).

One of the important landscape factors playing significant role in sediment generation is gradient slope (Silva et al. 2026; Nekhodtsev et al. 2024). This factor was considered using the elevation above sea level of each sampling site extracted from the Copernicus GLO-30 Digital Elevation Model using QGIS software. The terrain slope (Δh) was then calculated for every pair of sampling sites within each city using the following equation:

$$\Delta h = \frac{abs(H2 - H1)}{L} \bullet 100\%$$

2

where H_1 and H_2 are the elevations above sea level (m), and L is the horizontal distance between the sampling sites (m).

3. Results

A total of 300 urban surface-deposited sediment samples were obtained across the surveyed areas, with 30 to 40 specimens collected per city. The monitoring network featured a sampling density of 3 sites per square kilometer, covering a cumulative residential area of approximately 100 km².

3.1. Landscape

Based on an expert assessment of the landscape survey, functional zones are differentiated by contribution to the catchment area associated with surface micro-depressions where sediment samples were collected (Fig. 2). On average, transport-related sectors, encompassing roads, driveways, and parking lots, account for approximately 60% of the total drainage area across the surveyed cities.

The relief across the studied urban areas exhibits distinct terrain slope differences (Fig. 3a). The lowest mean slopes (approximately 0.5%) were observed in Kamensk-Uralsky, Alapaevsk, and Verkhnyaya Pyshma. Kachkanar demonstrated a substantially greater value than the other cities, with a mean terrain slope exceeding 2%. Moreover, Kachkanar showed the highest maximum terrain slope between sampling sites, reaching 10%, indicating a highly dissected and hilly terrain. The area of disturbed surfaces also varies across the cities (Fig. 3b). The maximum values were recorded in Kachkanar (more than 30% of the sampling site area), while the lowest proportions were observed in Verkhnyaya Pyshma (20%).

3.2. Mineralogical composition of urban surface-deposited sediment

The investigated urban sediment matrices are dominated by major rock-forming minerals, including quartz, K-feldspar, plagioclase, and amphibole, which were identified in nearly all analyzed specimens (Fig. 4). Most samples also contain secondary alteration minerals, specifically serpentine and chlorite.

Several minerals exhibited a localized distribution and were identified only in individual cities. Magnetite and the rock-forming clinopyroxene (diopside) were detected exclusively in sediment samples from Kachkanar. Amphibole reached its highest abundance in Pervouralsk, whereas serpentine reached its highest content in Asbest. Andradite (a garnet-group mineral) and gehlenite were found exclusively in samples from Serov.

Marked inter-city variations were observed in quartz content. Ranked by increasing mean quartz abundance, the cities follow the order: Kachkanar – Pervouralsk – Asbest – Verkhnyaya Pyshma – Serov – Nevyansk – Kamensk-Uralsky – Alapaevsk. This pattern reflects the affiliation of the cities to different structural-formational megazones.

Calcite and dolomite, the principal carbonate minerals of sedimentary rocks, were identified in all cities except Kachkanar. Based on the combined content of these minerals, the cities are ranked in increasing order: Kachkanar – Asbest – Verkhnyaya Pyshma – Alapaevsk – Pervouralsk – Nevyansk – Serov – Kamensk-Uralsky. This trend is consistent with the distribution of pre-Neogene formations shown on geological maps and with the occurrence of sedimentary strata in the geological sections of the respective areas.

Using the mineralogical composition of individual sediment samples and city-averaged mineralogical compositions, the within-city (VarWC) and between-city (VarBC) variances were estimated. Quartz, which was present in all samples, was selected for this analysis. The results showed that VarWC was four times lower than VarBC.

3.3. Chemical composition of urban surface-deposited sediment

The results of the chemical analyses and the calculated EF values for the sediment samples are presented in Table 2 and Fig. 5. To facilitate comparison, Table 2 reports the mean Al concentrations and the EF values for each element, calculated relative to the UCC composition (Rudnick and Gao 2014). As shown in Table 2, the highest *EF* values were observed for Ni and Mg, with the most pronounced anomalies occurring in Asbest and Alapaevsk. Among the elements with lower atomic mass, the highest EF values were recorded in Kachkanar and Pervouralsk, both located within the Tagil Megazone. In contrast, these cities exhibited a pronounced depletion of the incompatible elements (Rb, Th, and U), whereas the Trans-Ural Megazone cities showed EF values for these elements close to unity, reflecting near-background UCC levels.

Table 2

Mean Al concentration (mg/kg) and EF values of chemical elements in urban surface-deposited sediments relative to the UCC composition (Rudnick and Gao, 2014) with coefficients of variations (in parenthesis).

Me	Kachkanar	Pervouralsk	Asbest	V. Pyshma	Serov	Nevyansk	Kam.- Ural.	Alapaevsk
Concentration, mg/kg								
Al	40400 (0.14)	57000 (0.17)	30800 (0.22)	46800 (0.15)	39400 (0.15)	48750 (0.17)	34600 (0.23)	32900 (0.26)
EF of light elements								
Mg	5.4 (0.21)	3.1 (0.29)	15 (0.31)	3.2 (0.49)	2.8 (0.50)	1.8 (0.49)	2.5 (0.36)	8.0 (0.55)
Ti	2.1 (0.12)	1.8 (0.19)	0.65 (0.20)	0.96 (0.24)	1.3 (0.12)	1.0 (0.17)	0.97 (0.10)	1.1 (0.16)
V	7.1 (0.23)	4.4 (0.22)	1.7 (0.21)	1.9 (0.28)	4.2 (0.56)	2.4 (0.21)	1.3 (0.17)	2.1 (0.19)
Mn	3.1 (0.23)	2.4 (0.23)	2.5 (0.31)	1.7 (0.23)	12 (0.65)	2.7 (0.27)	1.5 (0.46)	11 (0.80)
Fe	34 (0.25)	19 (0.14)	25 (0.26)	15 (0.26)	32 (0.24)	14 (0.23)	9.8 (0.16)	23 (0.25)
Co	5.3 (0.18)	2.7 (0.16)	8.8 (0.34)	3.1 (0.40)	4.2 (0.37)	2.3 (0.32)	2.0 (0.25)	5.7 (0.42)
Ni	4.5 (0.38)	4.9 (0.55)	54 (0.34)	13 (0.58)	7.9 (0.93)	5.8 (0.64)	7.6 (0.40)	32 (0.54)
EF of heavy elements								
Rb	0.10 (0.36)	0.19 (0.46)	0.69 (0.40)	0.63 (0.20)	0.46 (0.40)	0.30 (0.48)	0.75 (0.19)	0.95 (0.26)
Sr	1.2 (0.14)	0.94 (0.14)	0.78 (0.17)	1.6 (0.12)	1.3 (0.18)	1.6 (0.29)	1.2 (0.23)	1.7 (0.44)
La	0.28 (0.54)	0.34 (0.29)	0.75 (1.6)	0.67 (0.27)	0.85 (0.21)	0.66 (0.23)	2.2 (1.5)	1.3 (0.26)
Ce	0.23 (0.46)	0.36 (0.30)	0.50 (0.33)	0.61 (0.19)	0.82 (0.19)	0.75 (0.19)	0.95 (0.15)	1.1 (0.19)
Th	0.09 (0.40)	0.19 (0.39)	0.62 (0.51)	0.45 (0.24)	0.57 (0.21)	0.31 (0.34)	0.77 (0.17)	1.1 (0.36)
U	0.26 (1.1)	0.31 (0.31)	1.0 (0.45)	0.83 (0.25)	0.94 (0.16)	0.78 (0.27)	1.7 (0.28)	1.5 (0.24)

The geochemical relationships between the Sr/Rb and Al/V ratios differentiate sediment material derived from cities belonging to different Ural Structural and Formation Megazones (Fig. 5a). Cities within the

Trans-Ural Megazone are characterized by low Sr/Rb values and a wide range of Al/V ratios, whereas the opposite pattern is observed for the Tagil Megazone. The East-Ural Megazone cities exhibit substantial variability in both ratios, occupying an intermediate position on the scatter plot (Fig. 5a). The distribution of individual EF_{Rb} values across the investigated cities closely reflects the geostructural zonation of the study area (Fig. 5b). In the Tagil Megazone, most specimens display $EF_{Rb} < 0.25$, consistent with the ultramafic bedrock of the Tagil megasynclinalorium and the lower continental crust. In contrast, $EF_{Rb} > 0.75$, characteristic of the felsic UCC, occur predominantly in samples from the Trans-Ural Megazone. Sediments from the East-Ural Megazone exhibit a broad range of EF_{Rb} , spanning compositions from mafic to felsic, with most values exceeding 0.25.

Hierarchical cluster analysis reveals the specific relationships among the chemical elements within the urban sediment systems (Fig. 6). Correlation distance ($1 - r$, where r is the Pearson correlation coefficient) was used as the distance metric. The resulting dendrograms reveal both common patterns and city-specific differences in the associations of typomorphic (signature) elements. A stable Ni–Mg association ($1 - r < 0.3$) was identified in all cities except Asbest, with Co joining this cluster in the most of the cities. Across all study areas, this elemental association showed either negative correlations with other clusters ($1 - r > 1$) or no statistically significant correlations ($1 - r \approx 1$). In addition, a stable cluster comprising the incompatible elements (La, Ce, Th, Rb, and U) was consistently identified, although its composition varied slightly among the cities ($1 - r < 0.5$).

A specific feature of the elemental composition of sediment across individual cities is the occurrence of Al- and Fe-associated clusters. Aluminum forms close associations ($1 - r < 0.5$) with Ti in Kachkanar and Nevyansk and with Ti and V in Alapaevsk. Furthermore, Al clusters with the incompatible group (La–Ce–Th–Rb–U) in Verkhnyaya Pyshma, with Ti and the (La–Ce–Th–Rb) assemblage in Serov and Kamensk-Uralsky, and with Sr in Asbest and Pervouralsk. Iron is associated ($1 - r < 0.5$) with Mn in Verkhnyaya Pyshma; with V in Kachkanar, Nevyansk, and Kamensk-Uralsky. This macro-element is also associated with both Mn and V in Serov, with V and Co in Pervouralsk; and with Mg in Asbest. No statistically significant associations between Fe and the other elements were identified in Alapaevsk.

Principal component analysis reveals interrelationships among elemental concentrations, with the first three principal components explaining 74% of the total variance. Figure 7a shows the elemental loadings on these components. The first principal component (PC1) exhibits high positive loadings for Fe, V, and Ti, contrasting with high negative loadings for Ce, La, Rb, Th, and U, thereby reflecting the mafic-to-felsic geochemical gradient (with $PC1 > 0$ and $PC1 < 0$, respectively). The second principal component (PC2) contrasts the Ni–Mg and Al–Sr associations, whereas the third principal component (PC3) is dominated by variations in Mn concentration.

Figure 7b shows the distribution of individual sediment samples in the PCA score space, where samples from different cities form distinct, nearly non-overlapping groups. Kachkanar samples are located at the ultramafic end of the compositional spectrum, whereas those from Kamensk-Uralsky occupy the opposite, felsic end. Along PC1, the cities from the Tagil Megazone and the Trans-Ural Megazone form

completely separated groups characterized by positive and negative PC1 scores, respectively. Samples from the East-Ural Megazone are centered near zero along PC1. Along PC2, all samples from Asbest and most from Alapaevsk exhibit positive scores, whereas samples from the remaining cities are distributed around zero or have negative values. Along PC3, Kamensk-Uralsky is clearly distinguished by negative scores, whereas Alapaevsk and Serov display positive scores values.

3.4. Particle-size distribution of urban surface-deposited sediment

The particle-size distribution of the sediment samples is shown in Fig. 8. The studied cities differ markedly in their proportion of the fine fraction (D_{100}) (Fig. 8a), with city averages ranging from 10% to 20%. Within individual cities, however, the D_{100} values vary by nearly an order of magnitude across sampling sites. The highest mean and maximum contents of particles < 0.1 mm were recorded in Pervouralsk and Kachkanar; in Pervouralsk, the D_{100} values ranged from 7 to 45%.

Figure 8b illustrates the relationship between the particle-size and mineralogical characteristics of the sediment. The relative abundances of several minerals differ markedly between the fine and coarse fractions, allowing three mineral groups to be distinguished. Quartz and K-feldspar are depleted in the fine fraction relative to the coarse one. Chlorite, serpentine, and magnetite exhibit minor variations between the two size classes. In contrast, clinopyroxene, plagioclase, amphibole, and carbonate minerals are enriched in the fine fraction (< 0.1 mm). Thus, the minimum relative abundance in the fine fraction is characteristic of quartz, whereas the maximum is observed for sedimentary minerals. Inter-city variation in the relative quartz abundance in the fine fraction is generally minor, except for Kachkanar, where it is substantially lower.

The relationship between D_{100} and the bulk quartz content was evaluated using the entire urban sediment dataset. Figure 9 shows the mean D_{100} values for successive quartz content intervals. A distinct inverse relationship is evident, with the proportion of the fine fraction decreasing progressively with increasing quartz content in the sediment.

The relationship between the particle-size and geochemical characteristics of urban sediment is illustrated in Fig. 10, which plots the relationships between the Rb/Fe and Sr/Fe ratios and D_{100} . The Rb/Fe ratio changes markedly with increasing fine fraction content, varying by as much as a factor of eight, and closely follows a sigmoidal trend. In contrast, the Sr/Fe ratio exhibits a much weaker dependence on the D_{100} values, with a maximum variation of approximately 50%.

To evaluate how landscape features affect the sediment granulometry, a k_{USLE} factor was calculated as the product of the mean terrain slope (Fig. 3a) and the mean proportion of disturbed surfaces (Fig. 3b). This landscape proxy index heuristically captures the empirical link between sediment yield and catchment properties, as conceptualized in the Universal Soil Loss Equation (USLE) framework (Patowary and Sarma 2018; Shevchenko et al. 2024; Akatu et al. 2026). Figure 11 displays the relationship between

the mean D_{100} proportion and the k_{USLE} values across the studied cities. The observed trend indicates that the particle-size distribution of urban surface-deposited sediment is strongly governed by local landscape characteristics.

4. Discussion

4.1. Urban sediments preserve a city-specific lithogenic signature modified by anthropogenic inputs

The applied cross-city approach allows individual observations to be interpreted as manifestations of common processes rather than as isolated characteristics of particular cities. Data obtained in this study on the mineralogical and geochemical characteristics of urban surface sediments showed systematically that the material of this object is genetically linked to the lithogenic substrate and variety of used construction materials.

In all cities, the mineral composition includes all major minerals typical for the geological formations of the city location territory, indicated on detailed official geological maps. Cities of the Tagil megazone exhibit elemental characteristics associated with mafic and ultramafic rocks, whereas sediments from the Trans-Ural megazone approach the composition of more felsic upper-crustal material, with the East Ural megazone occupying an intermediate position. The ordering of cities according to quartz content reflects the regional geological gradient and virtually reproduces the textbook crystallization sequence of igneous rocks in the Earth's crust.

The comparison of within-city and between-city mineralogical variability serves as a quantifiable criterion for verifying the mineralogical uniformity within each urban area. Given that $VarWC < VarBC$ for quartz, this relationship indicates a relatively high homogeneity of urban sediments. This pattern suggests that the mineralogical composition of surface-deposited sediments is not controlled primarily by highly localized sources, but instead reflects persistent material inputs operating at the scale of the urban area. Notably, this finding aligns with and mathematically validates the conclusions of previous studies, which had evaluated within-city sediment uniformity based primarily on expert-based interpretation (O'Shea et al. 2020, Navarro-Ciurana et al. 2023, Yarmoshenko et al. 2024).

The lithogenic signal is modified by anthropogenic materials whose distribution is not necessarily restricted to their original place of production. The erosion, weathering, and wear of roads and building structures introduce minerals that may occur systematically across several cities and therefore become characteristic components of regional urban sediments. Similar conclusions have been reached in different cities where mineralogical analysis of urban sediments was applied (Amato et al. 2011; Gunawardana et al. 2012; Candeias et al. 2020). Le Pape et al. (2025) considered appearance of building materials in urban sediments as a mineralogical tracer of city wear.

Serpentine provides the clearest example. The large Bazhenovo chrysotile-asbestos deposit produces serpentinite crushed stone, a widely used by-product of mining for road and civil construction in the region. While in Asbest, serpentinite could enter the composition of sediments both as a result of natural weathering and erosion of open ground surfaces, and during mechanical wear of road construction materials, in other studied cities this construction material accounts for the ubiquitous detection of serpentinite in the surface sediments. The input of serpentinite material is also clearly reflected in the geochemical (elemental) composition of sediments: elevated concentrations of Mg, which is part of the mineral crystal lattice, and Ni, inherited by the processes of serpentinization of initial ophiolites, are noted in all studied cities.

Urban sediments in Kachkanar and Pervouralsk are also enriched with minerals from local bedrock deposits – clinopyroxene and amphibole, respectively – likely due to the use of mining by-products in construction. Amphibole detected in other cities may likewise originate from regionally distributed building materials. Also, the use of amphibole and serpentinite crushed stone as an anti-icing material in the region was previously observed (Seleznev et al, 2019). In Serov, the sediments contain andradite, gehlenite, and forsterite, which may be indicators of metallurgical slag inputs. Notably, forsterite was detected in only single sample, yet it constituted a substantial proportion (18%). Elevated Mn concentrations provide an additional geochemical expression of this anthropogenic material. This suggests widespread use of metallurgical slags for local road construction and anti-icing treatments. Due to its favorable mechanical properties, granite is widely used throughout the region in construction materials, including road pavements. Numerous deposits are situated within Sverdlovsk Oblast along the granite belt of the East Ural megazone. Consequently, a portion of the quartz and K-feldspar in the sediments likely originates from the weathering of granite within the roadbed and other infrastructure components.

These findings extend the interpretation of urban surface-deposited sediments beyond their conventional treatment as predominantly anthropogenic or traffic-derived material. The results indicate that urban sediments should instead be considered as mixed materials in which the geological substrate establishes an important compositional framework that is subsequently modified by urban material inputs. The anthropogenic component of urban sedimentogenesis cannot always be inferred from proximity to an emission source alone. Material circulation through construction, infrastructure maintenance, and reuse of industrial by-products can redistribute distinctive mineral assemblages among cities. Rather than treating anthropogenic material as a homogeneous category, its mineralogical composition can be used in geochemical studies to distinguish between local geological sources, regionally distributed construction materials. This provides a broader perspective on the provenance of urban sediments which preserve broad-scale geological information even within heavily modified urban environments.

4.2. Mineralogical controls are essential for urban geochemical spectra and baselines

The obtained close correspondence between mineralogical and elemental composition has an important implication for the interpretation of urban sediments geochemical spectra. Table 3 summarizes the geochemical characteristics obtained in this study, including EF for the incompatible element association, geochemical ratios, and principal components derived from PCA. The values of the geochemical ratios closely correspond to the Structural and Formation Zones of the Ural Fold Belt. These results reveal a clear consistent pattern across the regional geostructural gradient, shifting from mafic/ultramafic signatures in the Tagil Megazone to upper-crustal parameters in the Trans-Ural Megazone, with the East Ural Megazone occupying an intermediate state (Table 3).

Table 3
Main geochemical ratios and characteristics by Structural and Formation Zones

Parameter	TG	EU	TU
Average EF for incompatible elements	0.1–0.3	0.5–1.0	0.8–2.1
EF _{Rb} range (90% of points)	< 0.25	0.25–0.75	> 0.5
Sr/Rb	High	Medium	Low
Al/V	Low	Medium	High
PC1	> 0	About 0	< 0

This finding is important for the use of EF and other geochemical indices. UCC abundances are frequently used as reference values for evaluating enrichment in urban sediments and soils (Bourliva et al. 2016; Osipova et al. 2023; Kasimov et al. 2024; Gokey et al. 2025). However, the present results show that the applicability of such values depends on whether the mineralogical and lithogenic composition of the investigated urban environment is reasonably represented by the selected reference. In regions characterized by strong lithological contrasts or extensive use of mineral-derived construction materials, crustal averages may either overestimate or underestimate the expected local concentrations. The results therefore support a source- and mineralogy-based approach to establishing geochemical baselines. Before an elemental enrichment is interpreted as evidence of pollution, its relationship with the mineralogical composition and the geological setting should be considered. This is consistent with the broader need identified in RDS research to account for local geology and to select background values on the basis of the actual geochemical characteristics of the investigated environment (Haynes et al. 2020).

Element concentrations cannot necessarily be interpreted independently of the minerals that host them. In the present study, the elemental composition is largely controlled by the mineralogical assemblage formed through the combined contribution of parent rocks and anthropogenic materials. This is particularly evident for the Ni-Mg association associated with serpentine. Elevated Ni concentrations occur across the studied cities, but the mineralogical evidence indicates that this pattern is largely related to the occurrence of serpentine rather than representing a uniform anthropogenic Ni source. Similar relationships between elemental associations and mineral phases demonstrate that an elevated

concentration relative to a generic crustal reference does not necessarily indicate anthropogenic contamination. The implication extends beyond the specific cities studied here. A mineralogical baseline provides a means of distinguishing geogenic and material-derived enrichment from genuinely anomalous anthropogenic inputs and can therefore improve the interpretation of subsequent assessments of pollutant accumulation and environmental risk.

4.3. Mineral stability controls the formation of the fine sediment fraction

Urban sediments in studied cities, as expected, contain a high proportion of the dust fraction. However, significant variations are observed between the cities, prompting an investigation into the factors driving these differences. In general, the relationship between the granulometric, mineral, and elemental compositions within the urban sedimentation cascade is highly complex. Nevertheless, it was possible to identify several compelling patterns that clarify the ongoing processes and mechanisms of fine fraction formation. The findings indicate that varying mineral resistance to weathering within the urban environment leads to a consistent repartitioning of mineral concentrations between the dust and coarser fractions. Quartz, a highly resilient rock-forming mineral, exhibits a decrease in concentration within the fine fraction across the studied cities by a factor of 1.5 to 2. Consequently, the proportion of the dust fraction is lower in quartz-rich samples. This relationship also underpins the dependence of D_{100} on the Rb/Fe geochemical ratio. As an incompatible element, Rb crystallizes in felsic, quartz-bearing rocks, whereas Fe is associated with mafic rocks, which are less stable under urban weathering conditions. Thus, the Rb/Fe ratio serves as an indicator of an expanding dust fraction. Meanwhile, the minor variability of the Sr/Fe ratio relative to D_{100} highlights the limited leaching of highly mobile Sr within urban sediments.

These results indicate that grain-size distribution should not be regarded solely as a physical property imposed on an otherwise chemically homogeneous sediment. Instead, particle-size composition is partly an emergent property of the mineralogical composition and weathering history of the sediment. This provides a process-based explanation for why cities with different geological and mineralogical settings can develop systematically different proportions of fine material.

4.4. Landscape conditions regulate fine-particle production across cities

Mineralogical composition alone does not explain the observed variation in the fine fraction. The cross-city comparison indicates that landscape conditions provide an additional control on sediment production. In particular, terrain gradient and the proportion of disturbed surfaces are found to accelerate the weathering of soils and pavements.

The k_{USLE} index, combining mean terrain slope and the proportion of disturbed surfaces, provides a simple proxy for these landscape controls. The strong relationship between mean D_{100} and k_{USLE} is consistent with the interpretation that exposed and disturbed surfaces enhance weathering and

sediment production, while terrain gradients facilitate sediment mobilization. This speculation complements the mineralogical interpretation developed above, in the sense that the fine fraction is therefore controlled by the interaction between material properties and the physical environment in which sedimentogenesis occurs.

The relevance of landscape controls has also been demonstrated in other urban environments (Nekhodtsev et al. 2024; Brezov et al. 2025; Akatu et al. 2026; Silva et al. 2026). The present results extend these observations by demonstrating their consistency across a network of cities analyzed using a common framework. The relationship also suggests that geochemical and mineralogical characterization can be linked with sediment-yield approaches such as RUSLE to develop a more process-oriented assessment of urban sediment production.

4.5. Conceptual process-based framework for urban surface-deposited sediments

The conducted study allows for the formulation of a process-based framework for investigating urban surface-deposited sediments, shifting the focus from purely geochemical properties to the underlying processes that determine them.

Taken together, the results of this study support a conceptual model in which urban surface-deposited sediments develop through the interaction of three major controls: lithogenic substrate, anthropogenic material inputs, and landscape conditions. The lithogenic substrate provides the initial mineralogical and geochemical framework; construction materials, mining products, and industrial by-products modify this framework and introduce additional mineral signatures; and landscape conditions regulate the weathering, production, and accumulation of sediment, particularly the fine fraction. The specific mineral assemblage reflects its local geological and anthropogenic setting, whereas the relationships among lithogenic inheritance, anthropogenic material inputs, mineral stability, and landscape controls are more general. The process-oriented interpretation provides a framework for understanding why city-specific sediment signatures can coexist with broader, transferable sedimentogenetic mechanisms. Finally, such approach allows to understand how sediment composition and properties reflect regional geology, industrial history, the types of construction materials used, as well as landscape attributes and the quality of urban environment maintenance.

While broader geoecological impacts involve heavy metal accumulation and airborne particulate matter hazards, their accurate interpretation can be advanced applying the approach developed here. From an environmental assessment perspective, the process-based framework emphasizes that mineralogical characterization is not merely complementary to chemical analysis. It is required for interpreting elemental baselines and understanding the formation and behavior of the fine sediment fraction. Establishing the provenance and mineralogical composition of urban sediments can consequently provide a more robust basis for distinguishing natural or material-derived geochemical variability from anthropogenic contamination and for evaluating subsequent pollutant transport and environmental risk. The process-based framework establishes the essential mineralogical and lithogenic baseline, providing

a mandatory prerequisite for future ecotoxicological assessments of pollutant transport and related public health risks.

5. Conclusion

In the urban environment, natural sedimentation processes occur within a multicomponent urban matrix. The geochemical characteristics of urban surface-deposited sediments are governed by complex interactions between the natural lithogenic substrate, anthropogenic drivers, and socio-economic conditions, including construction, industrial activity, and municipal management. Acting cumulatively, these drivers turn sediments into a comprehensive geochemical archive. By integrating environmental signals from diverse landscape compartments, such as roads, driveways, sidewalks, and green spaces, these matrix-deposited materials provide critical, holistic insights into the state of the urban environment.

Urban development shapes a unique mineralogical signature within the surface sediments of each city. This composition is genetically linked to the local lithogenic parent material, the construction components used, and by-products derived from both local and distant industrial enterprises and raw material processing facilities. The final mineral combination and its proportions do not fully match any natural rock type or naturally occurring mineral assemblage.

The polygenetic mineral composition directly controls the baseline characteristics of the sediments. Establishing these unique localized background conditions is essential for accurately calculating indices of environmental geochemistry (e.g., EF and I_{geo}).

The mineralogical profile substantially determines the grain-size distribution and the subsequent generation of particulate matter during dust resuspension. Concurrently, specific landscape attributes that accelerate sediment production have been identified.

The investigation revealed distinct patterns in the geochemical characteristics of the urban environment. These include: (i) an intra-city homogeneity in the mineral and baseline chemical composition of surface sediments; (ii) a direct dependence of the fine-fraction accumulation on the environmental resilience of the constituent minerals; and (iii) a comprehensive interrelation among the mineralogical, chemical, and grain-size profiles of urban sediments.

A systemic understanding of the core physicochemical properties of surface-deposited urban sediments, specifically their mineralogical, chemical, and grain-size compositions, serves as a fundamental prerequisite for effectively investigating the environmental implications of urban sedimentogenesis. Shifting the focus toward a process-based model that integrates geochemistry, mineralogical provenance, and landscape metrics provides a robust baseline mandatory for future ecotoxicological assessments of pollutant transport, airborne particulate matter hazards, and related public health risks. The most pressing ecological concerns focus on the accumulation and lateral transport of pollutants derived from industrial and vehicular sources, alongside their adverse impacts on urban infrastructure, adjacent aquatic systems, and public health.

Declarations

CRedit authorship contribution statement: Ilia V. Yarmoshenko: Conceptualization, Formal analysis and investigation, Methodology, Writing – original draft. Andrew V. Shevchenko: Data curation, Formal analysis and investigation, Visualization, Writing – original draft. Georgy P. Malinovsky: Formal analysis and investigation, Visualization, Writing – original draft, Writing – review and editing. Andrian A. Seleznev: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review and editing.

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Figures

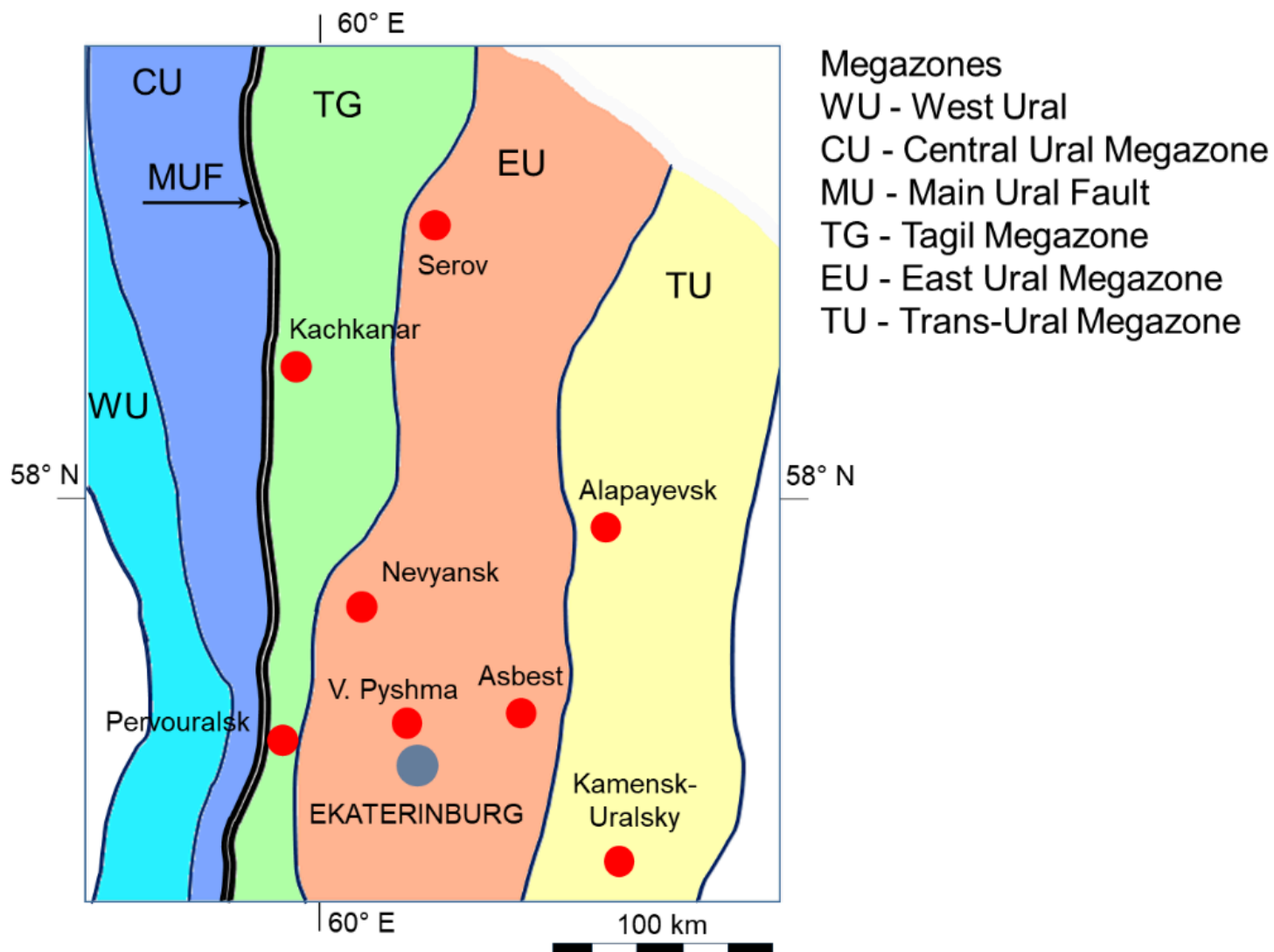


Figure 1

Schematic map of the Structural and Formation Zones of the Ural Orogen and the locations of the investigated cities

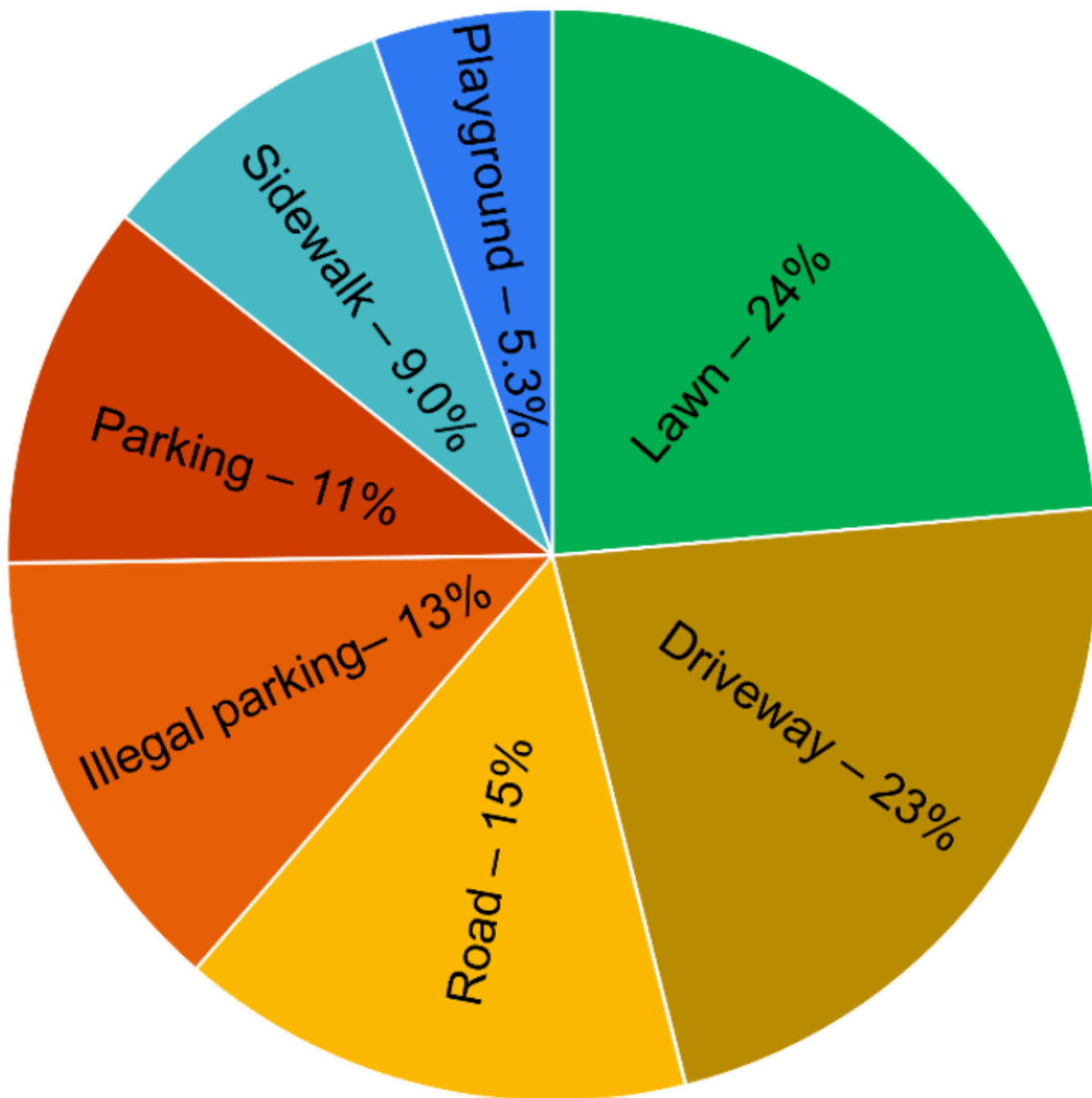


Figure 2

Mean proportion of different functional zones within the catchment area contributing to sampling site, based on expert assessment of the landscape survey

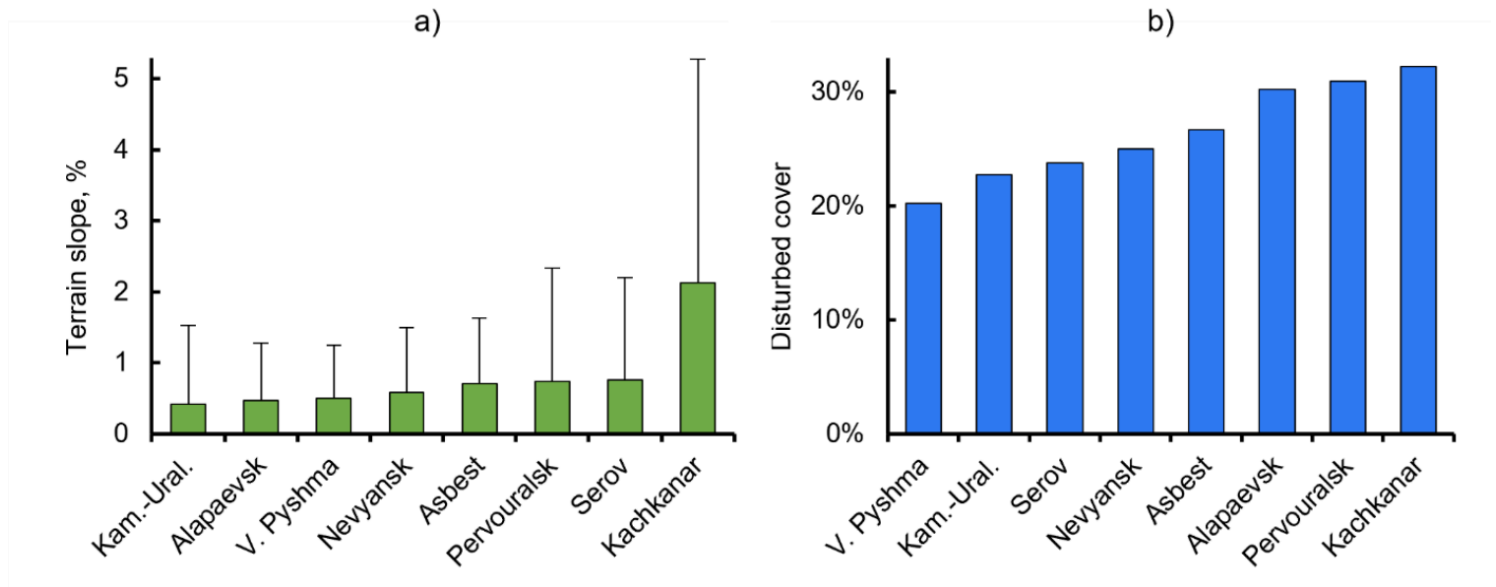


Figure 3

(a) Terrain slope between sampling sites by cities; bars represent the arithmetic mean and whiskers show the 95th percentile; (b) Proportion of area with disturbed surfaces at the sampling sites

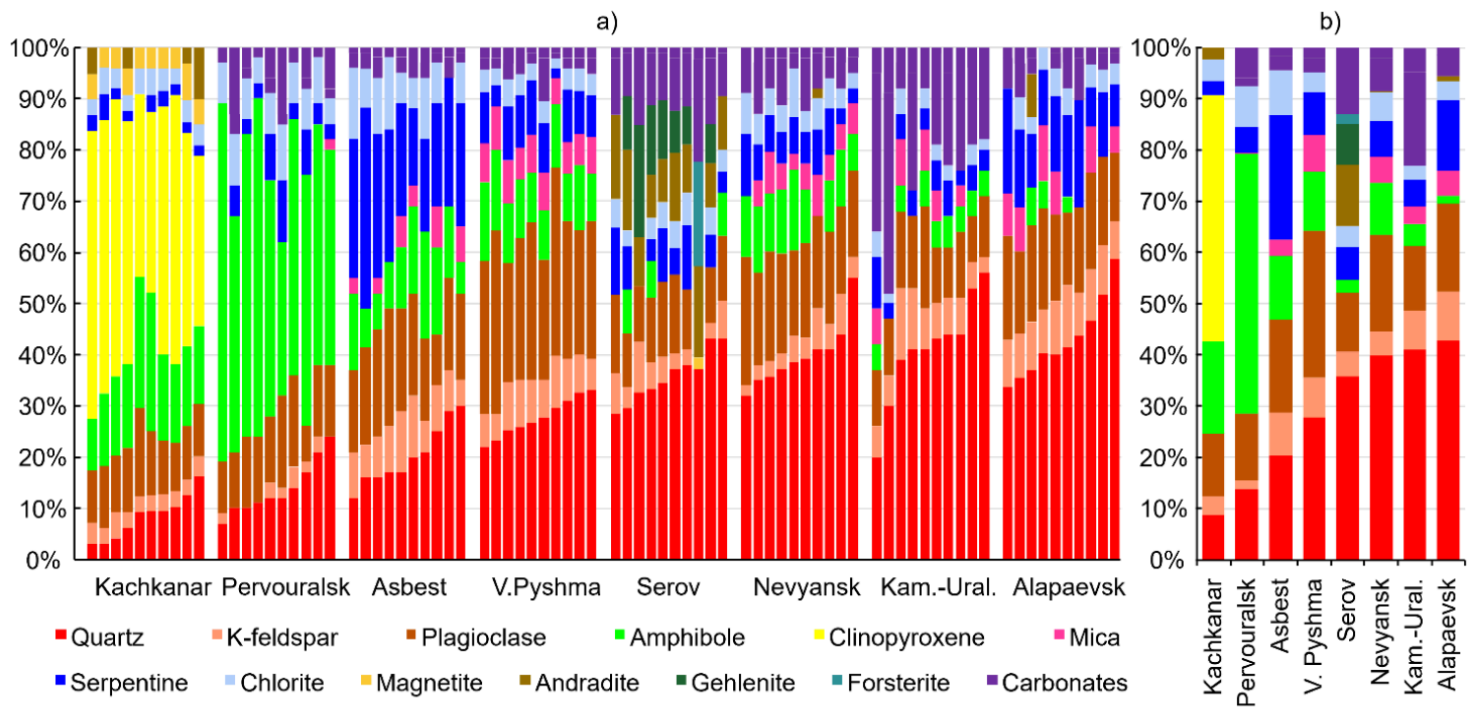


Figure 4

Mineralogical composition of surface-deposited sediments in the studied cities: (a) individual samples and (b) city mean compositions

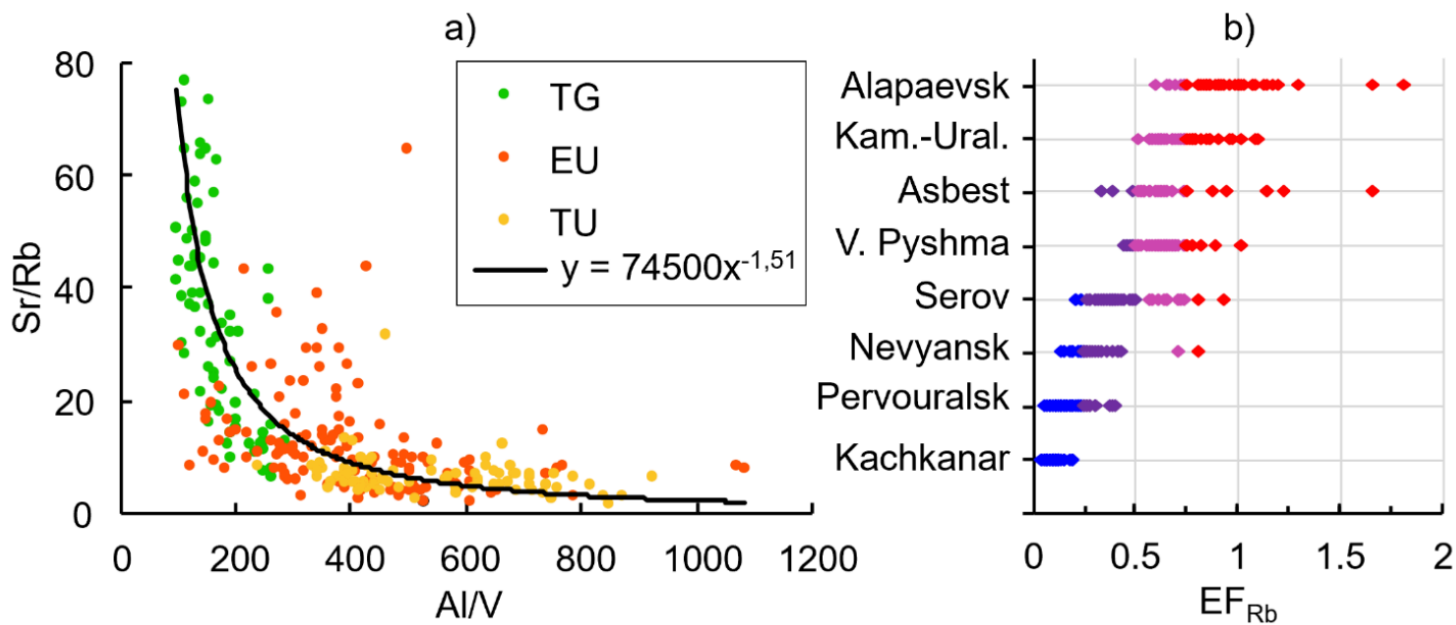


Figure 5

(a) Scatter plot of the Sr/Rb vs. Al/V ratios for sediment samples from cities belonging to different structural-formational megazones; (b) Distribution of individual EF_{Rb} values in sediments samples from the studied cities

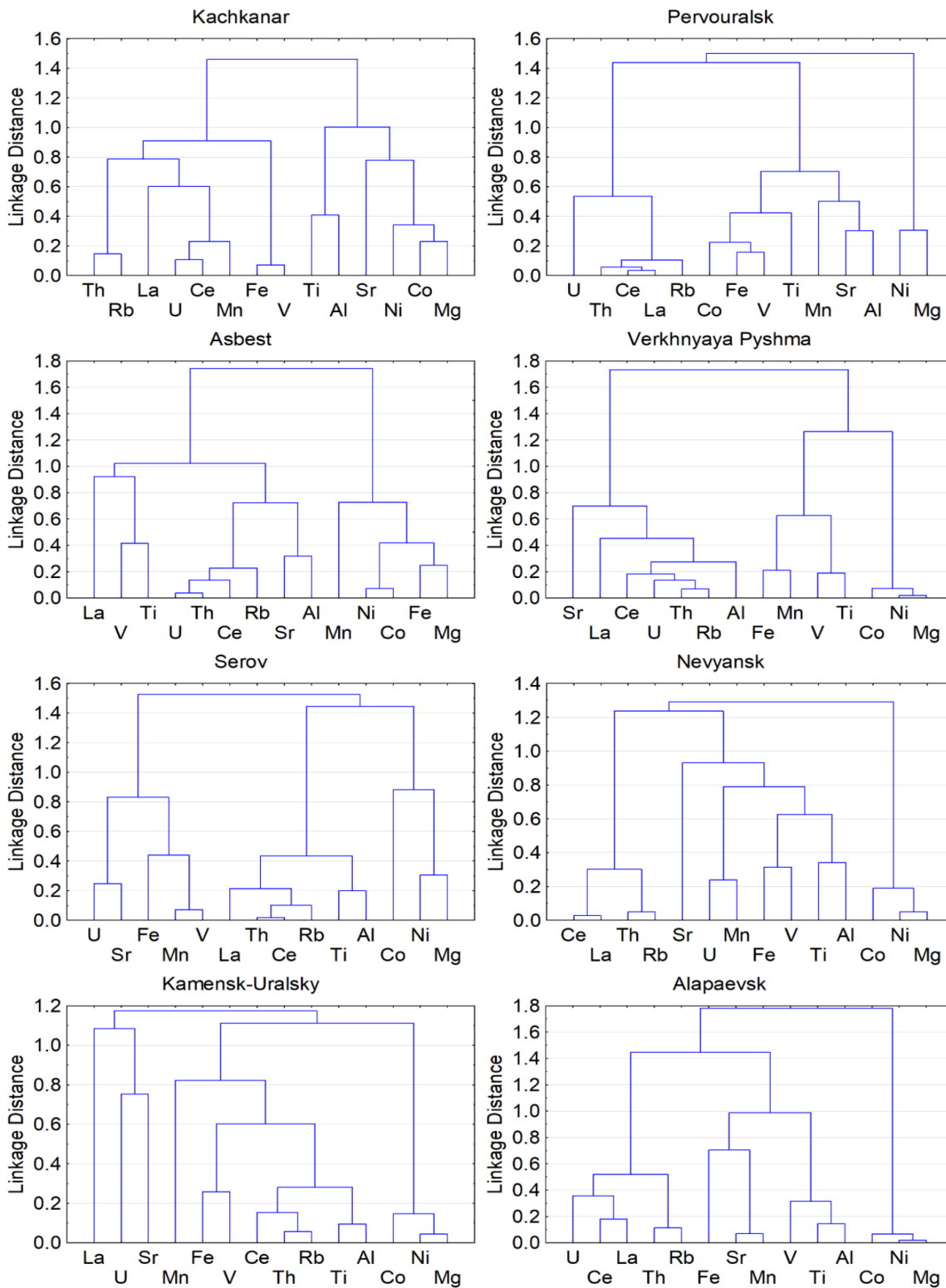


Figure 6

Hierarchical clustering dendrograms of chemical elements in sediment samples from the studied cities (Complete linkage, correlation distance, $1 - r$)

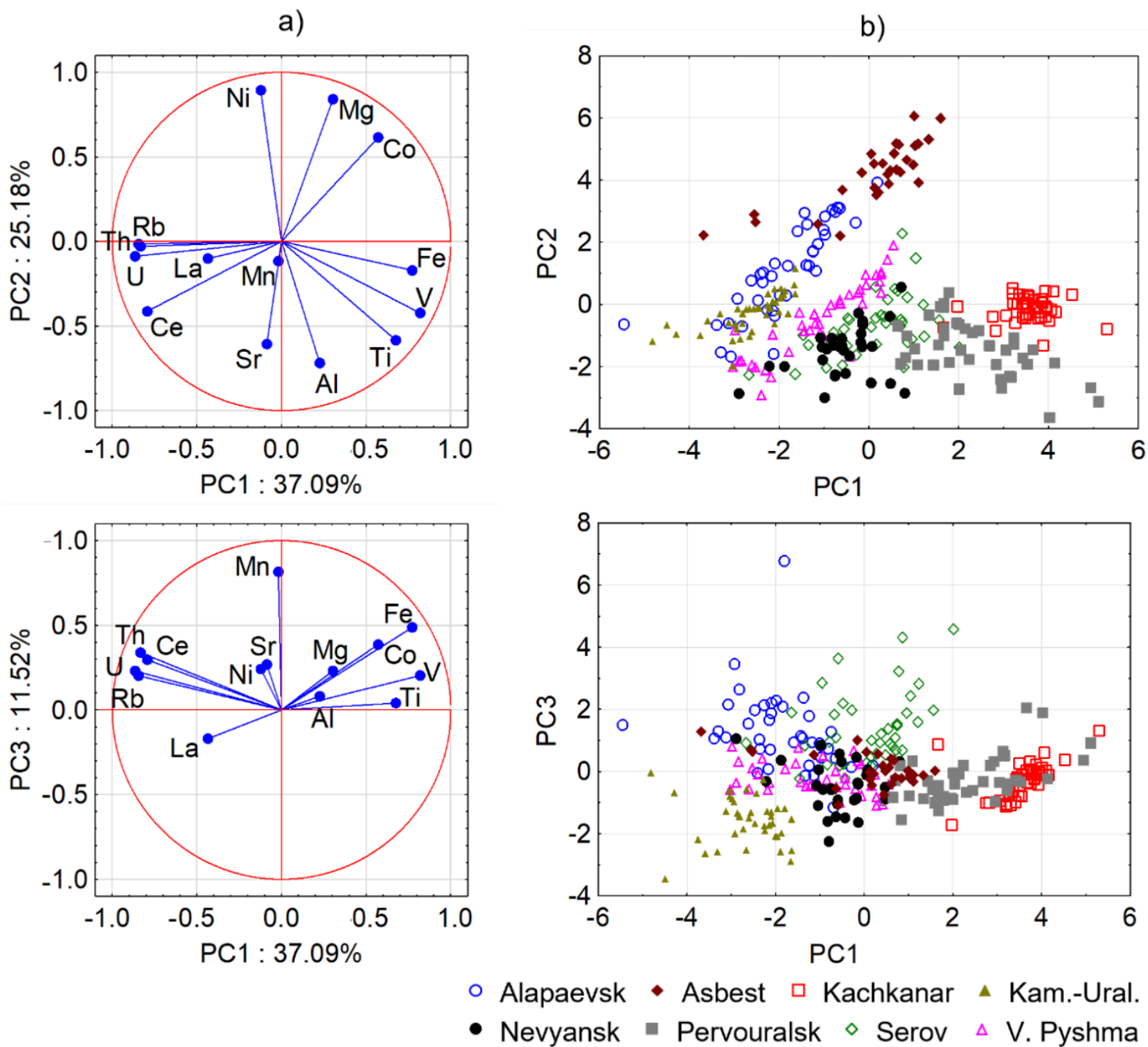


Figure 7

Principal component analysis (PCA) of urban surface-deposited sediment elemental composition: (a) loading plot of the analyzed elements; (b) PCA score plot of sediment samples from the studied cities

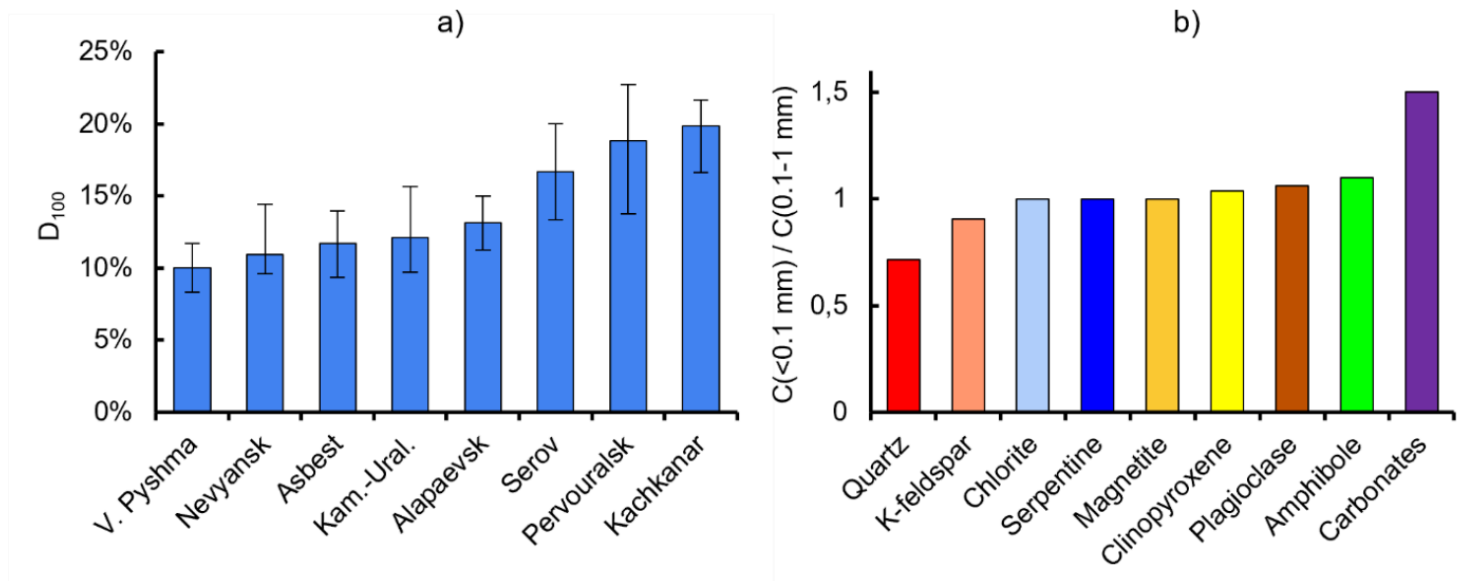


Figure 8

(a) Mean and maximum proportion of the fine fraction (D_{100} , <0.1 mm) in sediment samples from the studied cities; (b) Median ratio of mineral abundance in the fine (<0.1 mm) to coarse ($0.1-1$ mm) urban surface-deposited sediment fractions

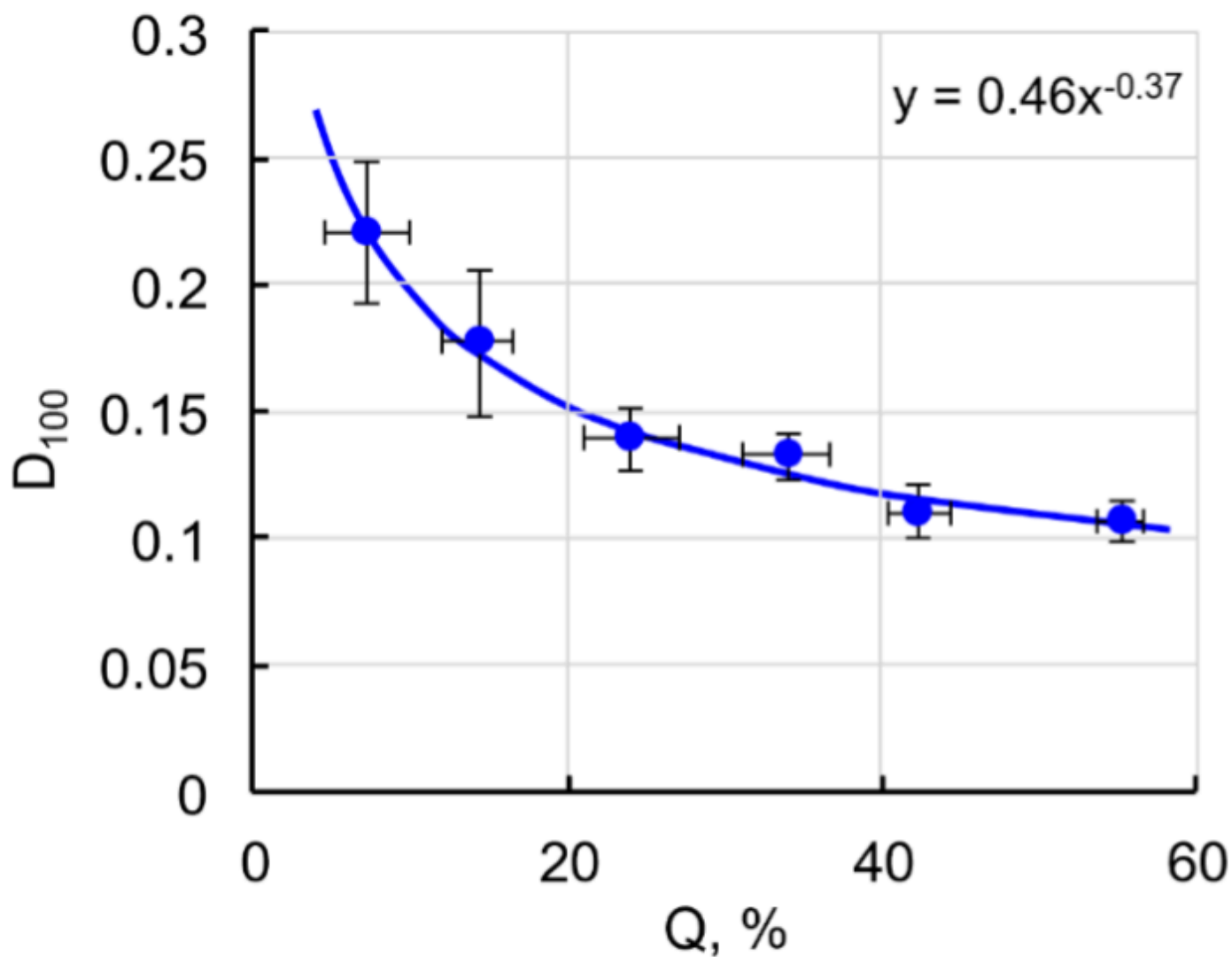


Figure 9

Relationship between the proportion of the D_{100} and the quartz content (Q) in sediment samples ($R^2 = 0.98$). Points – average values within intervals of Q; vertical whiskers – standard error of D_{100} ; horizontal whiskers – standard deviation of Q

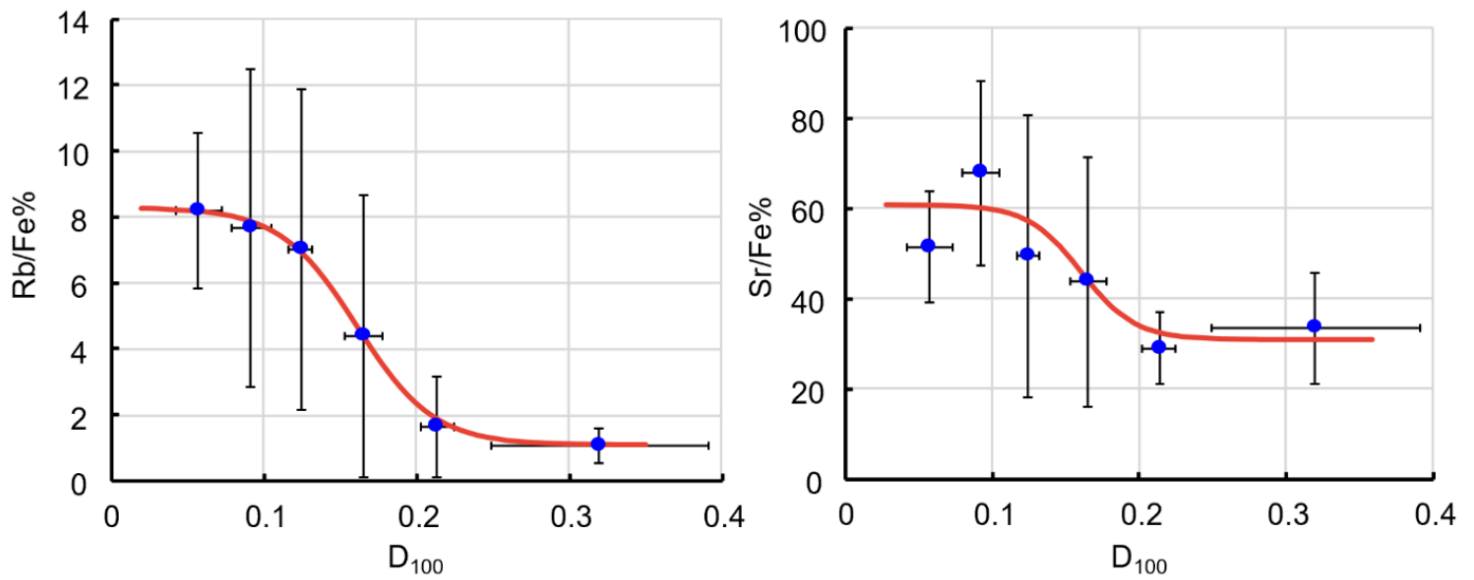


Figure 10

Relationships between the Rb/Fe and Sr/Fe ratios and the proportion of the D_{100} in sediment samples ($R^2=0.98$ and $R^2=0.77$ respectively). Points – average values within intervals of D_{100} ; vertical whiskers – standard error of geochemical ratio; horizontal whiskers – standard deviation of D_{100}

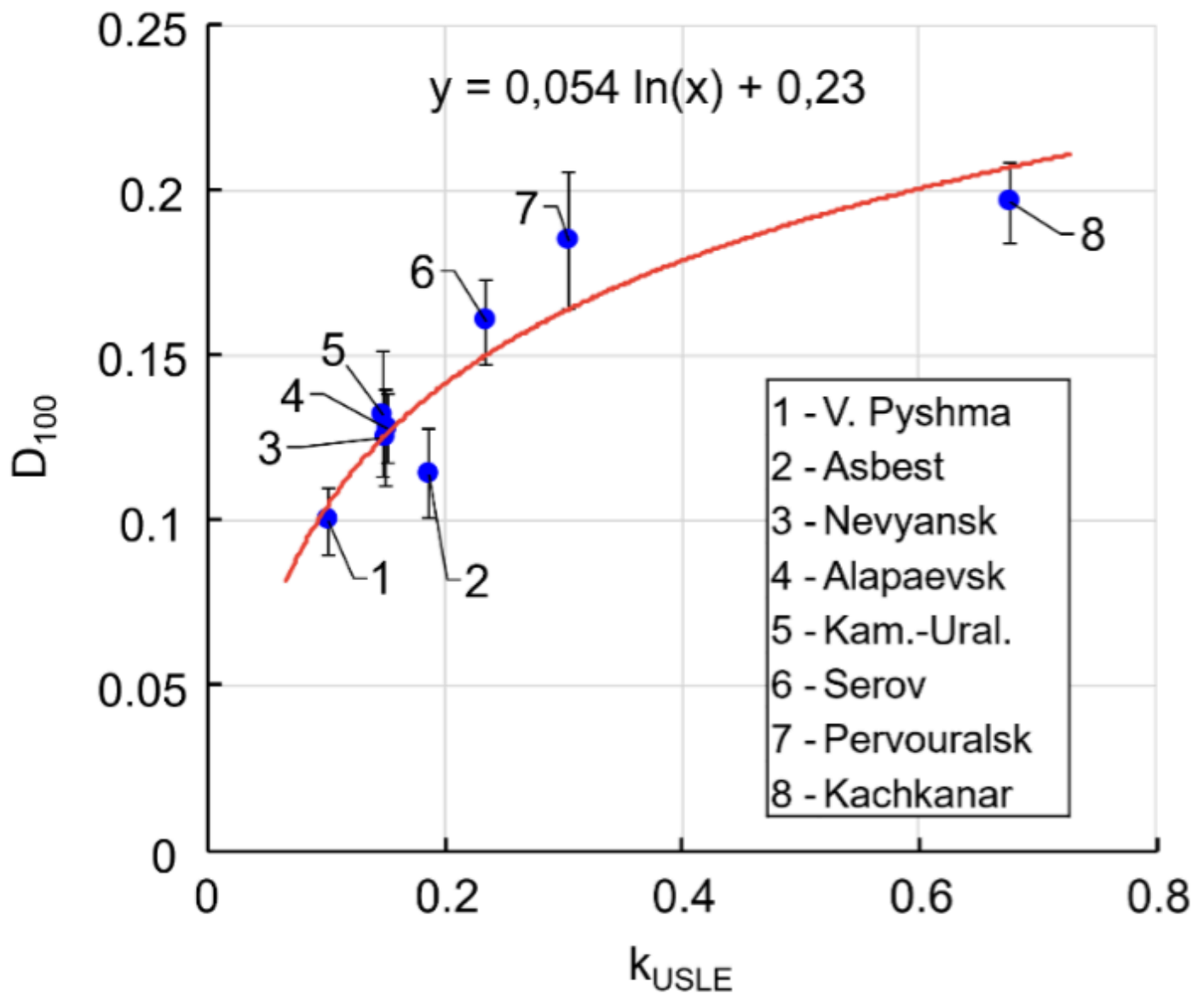


Figure 11

Relationship between the mean D_{100} value and the landscape coefficient k_{USLE} for the studied cities ($R^2=0.84$). Whiskers – 95% confidence intervals