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Economic Development and Responsible Supply Chains in the Mining Sector of the Democratic Republic of Congo (II)

Background Values of Trace Metals in the Soil of the Katangan Copperbelt, DR Congo

November 2025

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Authors:
Laurent Kidinda Kidinda, Eric Irung Bwanaching, Valentine Le Grand de Mercey
(Federal Institute for Geosciences and Natural Resources, BGR)
Martin Mpinda Tushiminine (Environmental Agency SARL, Université Nouveaux Horizons–UNH)

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Website:
www.bgr.bund.de

Contact:
Dr. Philip Schütte, Dr. Andreas Möller
Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)
Stilleweg 2, 30655 Hannover, Germany
E-mail: philip.schuette@bgr.de, andreas.moeller@bgr.de

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*Laurent Kidinda Kidinda, Martin Mpinda Tushiminine,
Eric Irung Bwanaching, Valentine Le Grand de Mercey*

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Summary

As part of their technical cooperation, the Federal Institute for Geosciences and Natural Resources (BGR, Germany) and its partners in the Ministry of Mines of the Democratic Republic of Congo (DRC) are working to strengthen economic development and transparency in the mining sector and to improve its environmental management. Within this framework, the partners agreed to produce reference data on metal concentrations in the soil of the Katangan Copperbelt (KCB).

In the DRC and in the KCB, generic threshold values developed for other regions of the world are still widely used to interpret trace-metal concentrations in soil. This direct transposition is problematic: it can lead to overestimating concentrations that are in fact normal, or underestimating concentrations that are genuinely of concern. Given the specific geology of the KCB, which is often naturally enriched in trace metals such as copper (Cu) and cobalt (Co), it is essential to determine the concentrations that correspond to the pedo-geochemical background (PGB), i.e. those mainly controlled by rock weathering, soil-forming processes and, potentially, natural atmospheric inputs. This work therefore establishes, for the first time at the scale of the KCB, PGB values for a suite of trace metals. The main objective is to propose “normal” reference ranges that can be used to distinguish concentrations driven by natural processes from those that may reflect anthropogenic inputs.

To this end, two soil sampling campaigns (Haut-Katanga Province in 2023 and Lualaba Province in 2025) were carried out within the BGR/DRC project using a common sampling design and analytical protocol. The study area covers approximately 36,000 km^2 between Lubumbashi and Kolwezi. Sampling locations were chosen to represent the diversity of environmental conditions (geology, soils, land use, altitude), while excluding areas clearly affected by human activities (e.g. mining sites, built-up areas, roadsides). Lithostratigraphic units (groups of geological formations) in the KCB were used as the main stratification factor, each unit being treated as a coherent geographical entity. Within each unit, variations in land use, soil type and elevation were taken into account. In total, 200 sites representative of the KCB were selected. At each site, two composite samples were collected, from topsoil (0–25 cm) and subsoil (25–50 cm). Laboratory analyses focused on a set of trace metals (Table 1), using a standard near-total geochemical extraction (four-acid digestion: HF–HNO_3–$HClO_4$ + HCl). For each lithostratigraphic unit and for both soil horizons (0–25 cm and 25–50 cm), PGB values were determined using percentile-based statistics. The median (50^{th} percentile, P50) was used as the central value, and the 90^{th} percentile (P90), together with its 95 % confidence interval (CI), was taken as the upper limit of the PGB range.

The resulting PGB values vary by lithostratigraphic unit and soil horizon. Table 1 summarizes, for each trace metal, the lithostratigraphic unit and depth where the highest PGB range was observed, together with the associated 95 % CI for P90.

Table 1. Ranges of pedo-geochemical background values identified as the highest among all measured trace metals.

Trace metal	Background value (P50–P90) [ppm]	95% CI (P90) [ppm]	Lithostratigraphic unit	Depth [cm]
Arsenic (As)	23–53	29–53	Mwashya & Roan	25–50
Barium (Ba)	245–543	310–613	Lower Kundelungu	25–50
Beryllium (Be)	2–4	2–4	Lower Kundelungu	25–50
Cobalt (Co)	16–41	21–72	Lower Kundelungu	25–50
Chromium (Cr)	561–734	561–761	Cenozoic cover	0–25
Copper (Cu)	31–134	62–173	Kundelungu	25–50
Manganese (Mn)	216–940	469–1250	Kundelungu	25–50
Molybdenum (Mo)	4–6	5–10	Katangian	25–50
Nickel (Ni)	45–79	52–92	Katangian	0–25
Lead (Pb)	11–29	9–36	Cenozoic cover	25–50
Strontium (Sr)	9–35	16–40	Holocene alluvium	0–25
Vanadium (V)	204–415	233–488	Cenozoic cover	25–50
Zinc (Zn)	34–85	55–105	Lower Kundelungu	25–50

The PGB values thus determined can be used in several contexts:

(i) For industrial mining, the PGB values provide an operational frame of reference for distinguishing trace-metal concentrations that are compatible with the pedo-geochemical background from those that likely reflect industrial inputs in the KCB. They do not constitute health-based guideline values or regulatory thresholds. In Environmental and Social Impact Assessments (ESIAs), their primary role is to characterize the baseline condition. During operations, they can support monitoring of soil chemical properties around industrial sites, waste-rock dumps and tailings storage facilities (TSFs). In geochemical exploration, using P90 (and its 95 % CI) as a reference helps to reduce false positives in naturally enriched settings. For rehabilitation, closure and post-closure, PGB values can inform realistic, site-specific performance criteria. In all cases, they provide regional context and must not replace local baseline studies defined as part of ESIA processes.

(ii) In the ASM sector, PGB values can be used on a voluntary basis to assess the initial condition of Artisanal Exploitation Zones (*Zones d'Exploitation Artisanale* – ZEAs) and related sites (crushing/washing areas, waste-rock storage areas, discharge sites). This use is not required by the Mining Code, but it offers methodological support for good environmental practice. In a participatory monitoring framework, cooperatives and, where relevant, NGOs and local communities could, under the supervision of a technically competent organization (e.g. a university, an accredited laboratory or a consulting firm), establish networks of control points around ZEAs and associated sites to track changes in trace-metal concentrations over time. In this approach, PGB values for the KCB provide regional context for interpreting the local baseline, but do not replace a site-specific baseline.

(iii) For public authorities, PGB values can provide the Ministry of Environment and Sustainable Development (*Ministère de l'Environnement et Développement Durable* – MEDD), through the Congolese Environment Agency (*Agence Congolaise de l'Environnement* – ACE), with a practical basis for reviewing ESIAs and Environmental and Social Management Plans

(ESMPs) for mining or industrial projects in the KCB, and for distinguishing soil trace-metal concentrations compatible with the PGB from those suggesting additional anthropogenic inputs. The PGB values can offer the Ministry of Mines, through the Directorate for the Protection of the Mining Environment (*Direction de la Protection de l'Environnement Minier* – DPEM), a technical benchmark for interpreting environmental monitoring results on soil chemistry, in order to better identify trace-metal concentrations of anthropogenic origin.

(iv) In research, PGB values can: (1) provide a geochemical baseline for selecting reference and enriched sites in ecotoxicological and phytoremediation studies; (2) be used as contextual explanatory variables in multivariate analyses combining soil composition, additional contamination and biological responses; and (3) serve as a starting point for future work combining information on total concentrations, speciation, bioavailability and biological effects.

The study is accompanied by an interactive map (https://doi.org/10.17632/ds3582v368.1) that compiles all results. Users can select the trace metal of interest (e.g. Cu, Co) and soil horizon (topsoil: 0–25 cm; subsoil: 25–50 cm), view summary statistics (P50, P90, mean, standard deviation, coefficient of variation) and display results as spatial distribution maps. The interface allows users to locate a point using GPS coordinates and to consult the PGB values and other statistics for the lithostratigraphic unit at that location. Maps can be exported for direct inclusion in reports. Available in French, English and German, the interactive map is intended to facilitate uptake and use by a wide range of stakeholders.

For future work, the study recommends extending the sampling to the remaining part of the KCB not yet covered (between Sakania and Lubumbashi) and progressively rolling out the approach at national scale. Priority areas include not only zones of intense mining activity, but also areas with past or present industrial activities and major logistics corridors (for example along the future Lobito railway and other transport routes), in order to document a reference state before traffic increases.

It would also be useful to establish a working group or network of experts and practitioners dedicated to "background values", bringing together institutions from the DRC and, where appropriate, neighboring countries facing similar mining and industrial issues (e.g. Zambia). This network would be tasked with consolidating and exchanging experience on methods for determining background values, their potential uses, and good practices for documenting and communicating these values to decision-makers and operators.

In the longer term, the study proposes establishing a formal regulatory process in the DRC, led by the competent national authorities (e.g. MEDD/ACE and the Ministry of Mines/DPEM), to integrate PGB values into the national normative framework. This process could include creating a national expert group responsible for issuing technical opinions and proposing regulatory thresholds for soil chemical properties (reference values, guideline values, alert values), to be incorporated into implementing instruments (Mining Regulations, ministerial decrees, technical guidelines), in line with the environmental framework law and national pollution-control strategies.

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List of Abbreviations

Abbreviation	Meaning
ACE	Agence Congolaise de l'Environnement *Congolese Environmental Agency*
ADEME	Agence de l'Environnement et de la Maîtrise de l'Énergie
ASM	Artisanal and Small-scale Mining
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe *Federal Institute for Geosciences and Natural Resources*
DPEM	Direction de la Protection de l'Environnement Minier *Directorate for the Protection of the Mining Environment*
DRC	Democratic Republic of Congo
ESIAS	Environmental and Social Impact Assessments
ESMPs	Environmental and Social Management Plans
FAO	Food and Agriculture Organization (of the United Nations)
GIS	Geographic Information System
ICP-OES	Inductively Coupled Plasma - Optical Emission Spectrometry
ISO	International Organization for Standardization
KCB	Katangan Copperbelt
PCA	Principal Component Analysis
PGB	Pedo-geochemical Background
QA/QC	Quality Assurance/Quality Control
WRB	World Reference Base for Soil Resources
XRF	X-ray Fluorescence

1. General introduction

1.1 Cooperation framework

Since 2009, the Federal Institute for Geosciences and Natural Resources (BGR) of Germany and the Ministry of Mines of the Democratic Republic of Congo (DRC) have been collaborating within the framework of bilateral development cooperation programs aimed at promoting responsible mining and strengthened governance, for both industrial and artisanal operations. During the phases 2021–2024 (*Economic Development and Responsible Supply Chains in the Congolese Mining Sector I*) and 2024–2027 (*Economic Development and Responsible Supply Chains in the Congolese Mining Sector II*), BGR and its partners agreed to conduct studies designed to propose options for addressing environmental challenges in the mining sector. During the 2021–2024 phase, a study was initiated to determine pedo-geochemical background—PGB— "normal" values of trace metals in the soil of Haut-Katanga Province. This study was subsequently extended to Lualaba Province during the 2024–2027 phase of the project. The present report brings both components together and defines PGB values of trace metals at the scale of the Katangan Copperbelt (KCB).

1.2 Context and justification of the study

The Katangan Copperbelt (KCB) in the DRC hosts one of the world's largest reserves of copper–cobalt ore deposits. In 2024, this region contributed to positioning the DRC as the world's leading producer of cobalt (Co) and the second-largest producer of copper (Cu) in terms of mine production (U.S. Geological Survey, 2025). The Cu and Co thus exploited often coexist with other trace metals, and their concentrations vary due to the diversity and nature of the geological formations (Cailteux et al., 2007).

In practice, metal concentrations in the soil of the KCB are still too often assessed using generic international reference values derived from different geological environments. Such transposition may lead to overestimating naturally elevated situations, or conversely underestimating situations that are genuinely of concern (Reimann & Garrett, 2005). This situation can result in contradictory diagnoses, technical and legal uncertainties for authorities and operators, difficulties in prioritizing actions and in establishing informed dialogue with communities. These limitations stem mainly from the absence of local or regional reference values (i.e. background values) capable of reflecting the lithological and pedological variability specific to the KCB. In accordance with ISO 19258:2018, these values must be established on the basis of a representative sampling plan (excluding obvious point sources) and robust statistical treatment, in order to clearly distinguish natural concentrations from anthropogenic inputs. In this perspective, the present study aims to determine pedo-geochemical background (PGB) values of trace metals in the soil of the KCB and to provide the scientific and practical basis for an environmental reference framework for the DRC.

1.3 Objectives of the study

The overall objective of the study is to establish a regional reference of PGB values for trace metals in the soil of the KCB, in order to support environmental monitoring and assessment and political decision-making. The specific objectives are to:

1. Measure trace-metal concentrations in soil in order to understand their variability as a function of lithostratigraphic units (geological formations) along the KCB.
2. Calculate PGB values for different lithostratigraphic units and soil depths, in order to provide a regional basis for comparison in environmental assessment.
3. Map the spatial distribution of trace metals at the scale of the KCB, in order to visualize natural differences and support environmental monitoring.

1.4 Target audiences

This study is intended for several categories of audiences who may make use of the PGB values produced (Figure 1). Decision-makers may draw on them as a scientific basis to inform, where appropriate, the development of regulatory standards relating to soil chemical properties, in addition to human health and ecotoxicological risk analyses. Government technical services, such as the Directorate for the Protection of the Mining Environment (*Direction de la Protection de l'Environnement Minier*—DPEM) and the Congolese Environment Agency (*Agence Congolaise de l'Environnement*—ACE), will use PGB values for environmental assessment and monitoring before, during and after projects. Mining operators and other industrial actors will find in them a reference for assessing and monitoring soil chemical properties, setting rehabilitation targets, managing contaminated soils, identifying natural anomalies useful for geochemical exploration, and meeting compliance, audit and due-diligence requirements. Researchers will use PGB values to interpret soil measurements and better understand relationships between living organisms and metals. International organizations will rely on them for the interpretation of soil measurements as well as for compliance, audits and due diligence. Finally, civil society may also refer to PGB values for compliance (audits, due diligence) and for managing disputes and controversies.

Figure 1. Target audience that may be interested in the PGB values produced in this study.

2. Fundamental concepts

2.1 Definitions and conceptual distinctions

2.1.1 Historical development of the concept

The concept of "background" originates in exploration geochemistry, where it refers to the normal range of metal concentrations. Values above this range are treated as anomalies that may indicate an ore deposit (Hawkes & Webb, 1962). From the 1980s onwards, the concept was transferred to environmental sciences to serve as a comparative reference in assessments. This disciplinary shift has encountered several challenges: spatial and temporal diversity and heterogeneity of matrices (soils, sediments, waters), multiplicity of substances and their diffuse anthropogenic sources, and varied regulatory objectives. The gap between a concept originally designed to detect natural anomalies and the needs of environmental assessment led to terminological inconsistencies that now complicate the definition, estimation and use of background values (Reimann et al., 2005).

2.1.2 Terminological divergences

When describing concentrations or values of substances in soil (in particular metals), several related concepts have emerged in the scientific and normative literature. Terms such as *geochemical background, natural background concentration, background values* and *geochemical baseline* are widely used, and are sometimes treated as synonyms meaning simply "the normal concentration". However, there are important nuances. ISO 19258:2018, for example, explicitly distinguishes between concentration and value. A *background concentration* is a measured concentration on representative samples, whereas a *background value* is a statistic derived from these concentrations (e.g. mean or percentile). Another key nuance concerns the adjectives *geochemical* and *pedo-geochemical*. Some studies use *geochemical background* when describing the content of the parent material, and *PGB* when referring to the soil itself (ADEME, 2018).

The term *baseline* is another source of confusion because it is used in two different ways. For Darnley (1997), a *baseline* is a spatial geochemical reference describing the current state of the environment and allowing comparison between regions and the detection of future changes, without assuming a pristine state or excluding diffuse anthropogenic inputs. ADEME (2018), by contrast, uses *baseline* for values calculated by statistical treatment of concentration ranges representative of background conditions. In that framework, the *baseline* is used to distinguish natural pedo-geochemical background from anthropogenically influenced pedo-geochemical background and to identify anomalies. However, under ISO 19258:2018, any statistical characteristic (e.g. mean, median) calculated from pedo-geochemical background concentrations is considered a *background value*, not a *baseline*. These discrepancies underline the need for conceptual harmonization. Without explicit definitions, it is difficult to align sampling strategies, laboratory analyses and statistical treatments.

2.1.3 Harmonized definitions of concepts

Drawing on the scientific literature and relevant standards, this study proposes a harmonized set of definitions for reference values for trace metals in soil (Figure 2). The aim is to establish a shared vocabulary and to clarify how these terms are used in this report.

A background concentration is the concentration of an element characteristic of a given soil type in a given area or region, resulting from both natural sources and diffuse anthropogenic sources such as atmospheric deposition. **A background value**, by contrast, is a statistical descriptor (e.g. mean, percentile, standard deviation) calculated from these background concentrations (ISO 19258, 2018).

Geochemical background refers to the concentrations or values of an element in a reference material such as rock. **Pedo-geochemical background** refers to the concentrations or values of a substance in soil. This background reflects natural geological and pedological processes (Darnley, 1997; ISO 19258, 2018). **Natural PGB** corresponds to concentrations or values explained solely by natural factors (lithology, weathering, natural deposits) and is often no longer measurable at the surface for many elements because of diffuse anthropogenic influences (Reimann et al., 2005). **Anthropogenic (or ambient) PGB** combines the natural component with the diffuse, ubiquitous, non-localized influence of human activities (urban atmospheric deposition, historical agricultural practices), without contribution from an identifiable point source (ADEME, 2018). Depending on the context, we therefore distinguish between **natural PGB** (value or concentration) and **anthropogenic PGB** (value or concentration).

In this report, **pedo-geochemical baseline** is used in a descriptive sense: it is a spatial and temporal reference that documents the current state of an environment, enabling comparison between areas and the monitoring of changes over time. This usage does not require a pristine state and remains valid in industrial settings at site scale, prior to the start of activities, to establish an initial reference condition (Darnley, 1997; Reeder, 2007).

Threshold values are administrative levels based on health and/or ecotoxicological criteria and on management choices. They must not be confused with background values, which describe geo-pedological variability (ADEME, 2018; ISO 19258, 2018; Reimann & Garrett, 2005).

A natural geochemical anomaly is a statistically significant deviation from the pedo-geochemical background, attributable to natural processes such as mineralization or lithogeochemical contrasts. **An anthropogenic anomaly** is a statistically significant deviation attributable to human sources, whether point sources (industrial sites, localized deposits) or diffuse sources (atmospheric fallout, historical practices). Correctly identifying an anomaly requires specifying in advance the chosen background reference, the scale of analysis and the detection method, in order to avoid confusing natural variability with anthropogenic impact (Hawkes & Webb, 1962; ISO 19258, 2018; Matschullat et al., 2000; Reimann & Garrett, 2005).

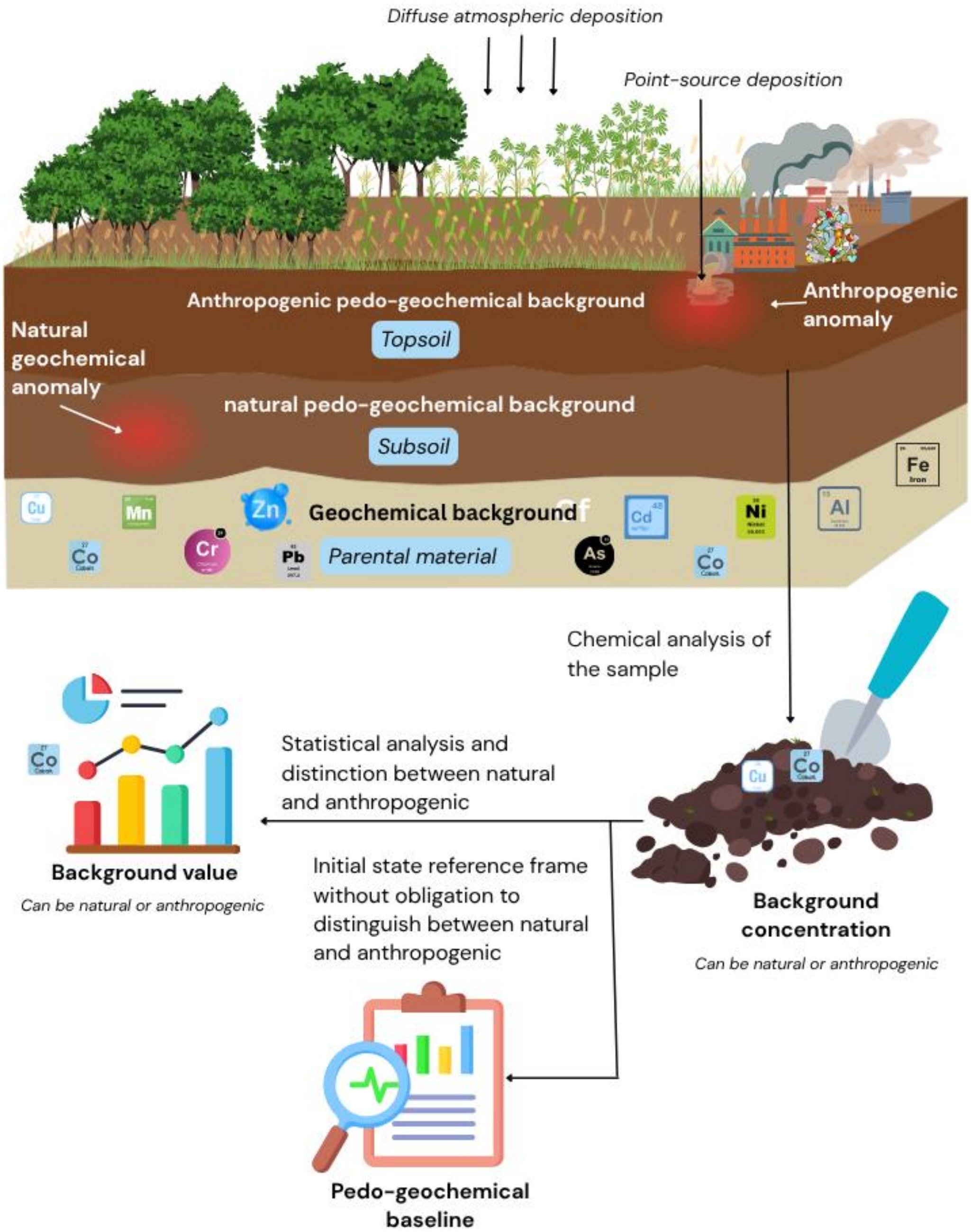

Figure 2. Conceptual framework for the definition of background values in soil.

2.2 State of the art

2.2.1 Bibliometric mapping

To date, there is a substantial body of work worldwide on background values (Figure 3). It includes scientific articles and project reports carried out at local, national and regional scales. These studies can be grouped into four main categories: 1) review articles that synthesize or critically discuss existing knowledge, concepts and approaches; 2) methodological articles proposing sampling protocols, laboratory analyses and statistical and geospatial treatments; 3) determination articles aiming to establish background values for a given medium or region; 4) application articles using these values for environmental monitoring or ecotoxicological assessment. Among the most influential and conceptually structuring contributions are Reimann et al. (2005, 2017), Reimann & Garrett (2005), Matschullat et al. (2000) and Salminen & Gregorauskien (2000). Alongside these publications, the ISO 19258 (2018) standard, the ADEME (2018) report and the large-scale FOREGS[1] (Forum of European Geological Surveys) and GEMAS[2] (Geochemical Mapping of Agricultural and Grazing land Soils of Europe programs provide key reference frameworks. Together, these works form the methodological and conceptual foundation for this report.

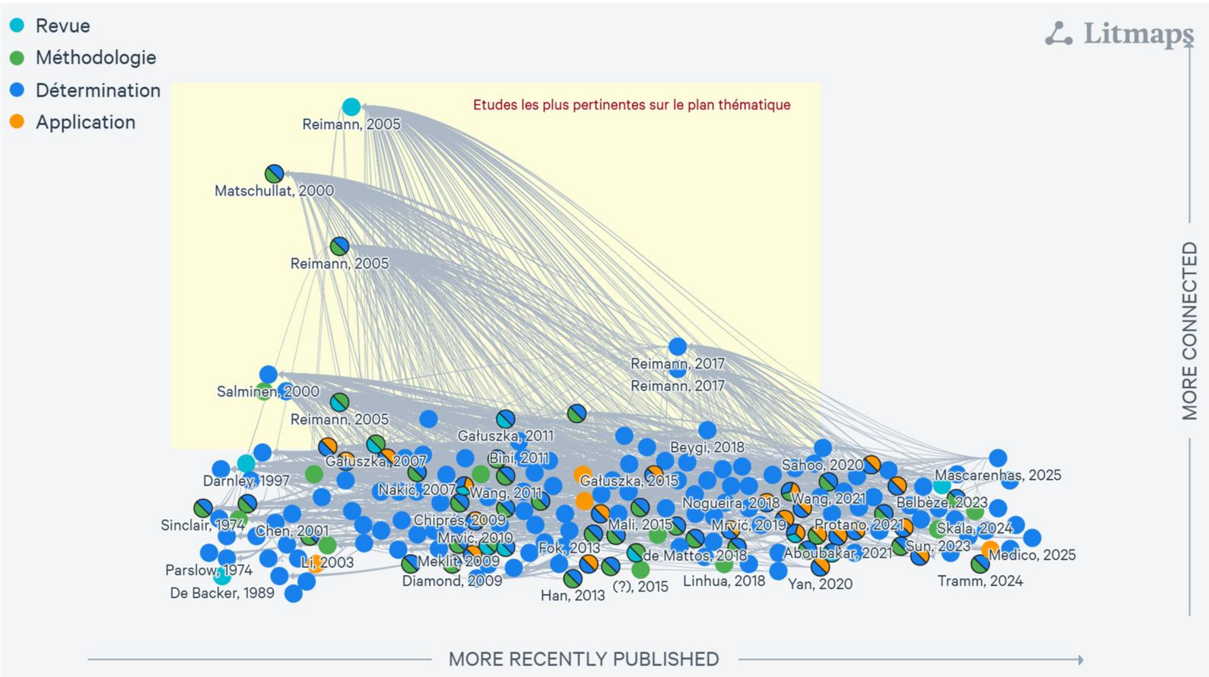

Figure 3. Bibliometric mapping of studies on background values. The studies were compiled from various bibliographic databases and imported into Litmaps to visualize citation links and thematic connectivity.

Most studies on background values have been carried out in China, Brazil, the United States, and Western and Northern Europe (Figure 4). In Africa, the Middle East, Central Asia and parts of South Asia, background values remain sparsely documented. Among the studies conducted globally, relatively few have national coverage. In the DRC, two studies have addressed reference values for trace metals in soil (Mpinda et al., 2021; Shutcha et al., 2018). Mpinda et al. (2021) establish baselines for 11 trace metals, while Shutcha et al. (2018) estimate background values in the Lubumbashi area by focusing on risk zones and using a small set of "uncontaminated soils" (n = 18) as a reference. These studies provide useful information but have several limitations: heterogeneous analytical protocols, restricted spatial coverage, and the absence of a sampling

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[1] https://ssp-infoterre.brgm.fr/fr/base-de-donnees/foregs

[2] https://eurogeosurveys.org/projects/gemas/

design that clearly separates natural and anthropogenic components. In their current form, they do not aim to define regional PGB values.

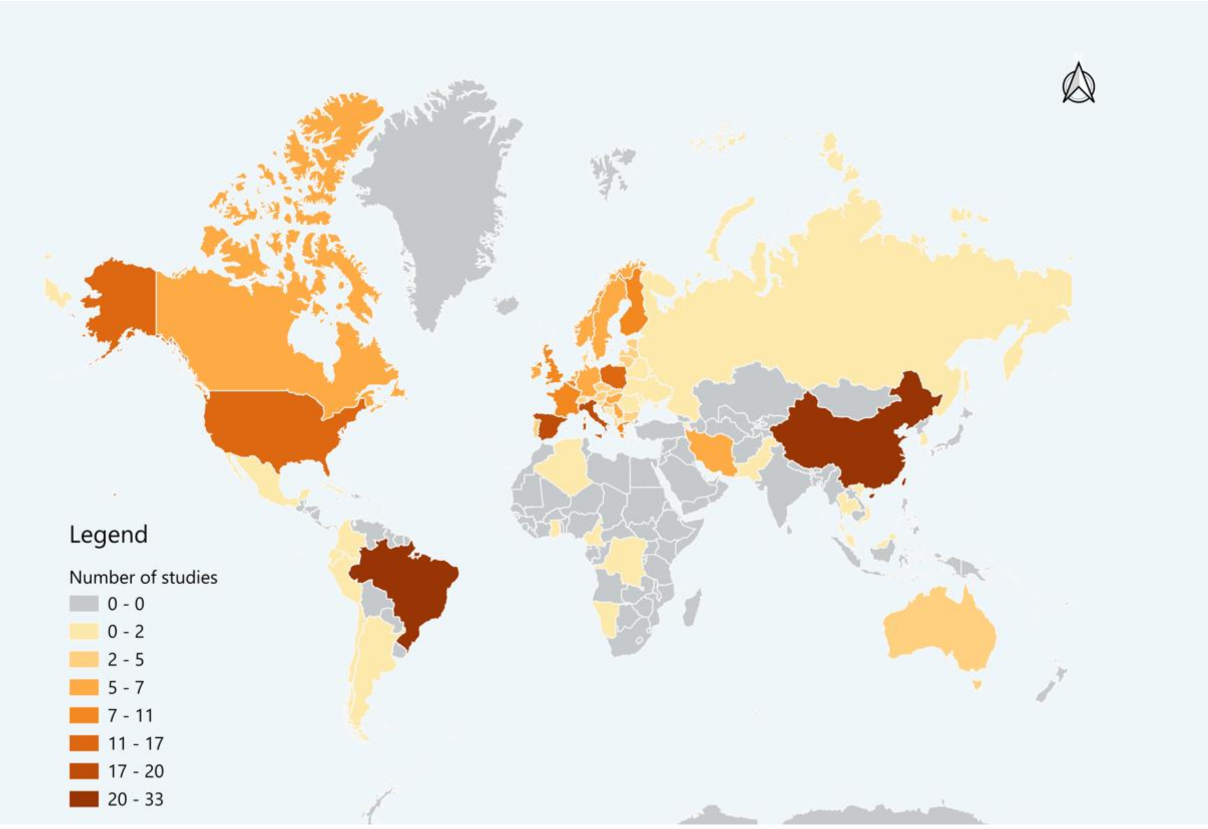

Figure 4. Choropleth map showing the global distribution of studies on background values by country. For studies without sampling (e.g. review articles), the country is assigned on the basis of the first affiliation of the first author.

2.2.2 Methodological considerations

Clearly stating the study objectives and defining coherent geographical entities (e.g. by geology, soil type, land use) are essential steps to ensure representative sampling (ADEME, 2018; ISO 19258, 2018; Reimann et al., 2017). To estimate upper percentiles robustly, around 25–30 samples per coherent geographical entity are generally recommended (ADEME, 2018; Ander et al., 2013; Utermann et al., 2008).

The choice of sample preparation (for example, < 2 mm) and extraction chemistry defines the operational fraction that is measured. “Total” and “pseudo-total” digestions are not directly comparable to partial extractions (ISO 19258, 2018; Papastergios et al., 2011). Comparability between studies requires harmonized analytical protocols, transparent reporting of detection limits and a complete quality assurance/quality control (QA/QC) scheme (Salminen & Gregorauskien, 2000; Tarvainen et al., 2009). The link between intended use (monitoring, mapping, risk assessment) and analytical choices must be explicitly stated (ADEME, 2018; ISO 19258, 2018).

All statistical analysis starts with harmonizing and cleaning the database. Values below the limit of quantification (LOQ) should not be replaced mechanically (e.g. by "LOQ/2"). Methods appropriate for censored data should be used instead: Regression on Order Statistics (ROS), the Kaplan–Meier (KM) estimator or Maximum Likelihood Estimation (MLE), depending on the proportion of values below the limit of detection (LOD) (Tramm et al., 2024).

If coherent geographical entities were not defined at the soil-sampling stage, they must be delineated before any statistical analysis; otherwise, natural variability is confounded with anthropogenic inputs (ADEME, 2018; ISO 19258, 2018). Atypical values must be traced back from the field to the laboratory. Exclusion is justified only in the case of a proven error or when a value clearly reflects a point source that falls outside the objective of characterizing background conditions (Reimann et al., 2005). To separate geochemical anomalies from PGB, practitioners can use graphical tools (e.g. Q–Q plots, histograms, box plots), fractal filtering and singularity analysis (Borojerdnia et al., 2020; Cheng et al., 1994; C. Li et al., 2003).

In pedo-geochemical datasets, distributions are rarely Gaussian; the common default assumption of log-normality should therefore be avoided (Reimann & Filzmoser, 2000). Background values based on the mean and standard deviation are usually unreliable. It is preferable to use robust estimators (such as high percentiles) together with graphical diagnostics like cumulative distribution functions (CDFs) and Q–Q plots to characterize background values (Borojerdnia et al., 2020; Reimann et al., 2005). Background is a contextual distribution, not a single number. Reporting should therefore favor ranges (e.g. median, 90^{th} /95^{th} percentiles), accompanied by uncertainty intervals, rather than a single point value (Gałuszka, 2007).

3. Methodological approach

3.1 Organization of the study and stakeholders

The study was conducted in two complementary phases. The first sampling campaign took place in April 2023 in Haut-Katanga Province; the second in July 2025 in Lualaba Province. The same field teams applied a single, consistent methodology for soil sampling and soil-profile description, and samples from both campaigns were analyzed by the same laboratory using a harmonized analytical protocol and shared QA/QC procedures. Both phases were carried out in close collaboration with the DPEM and the ACE, which participated in the soil-sampling campaigns in Haut-Katanga and Lualaba. In parallel, the study included a capacity-building component in the form of on-the-job training for students from the University of Lubumbashi, Nouveaux Horizons University (Haut-Katanga), the University of Kolwezi and the Higher Institute of Applied Techniques of Kolwezi (Lualaba). The objective was to stimulate interest among future local researchers and to help build a center of expertise in environmental geochemistry (Figure 5).

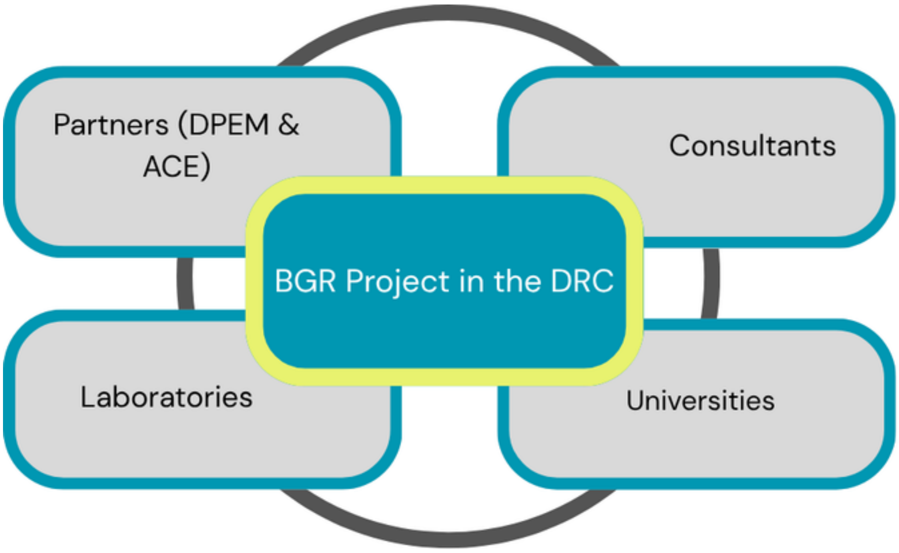

Figure 5. Stakeholders that contributed to the implementation of this study.

3.2 Study area

3.2.1 Location

The study area covers approximately 36,000 km^2 within the Katangan Copperbelt (KCB) (Figure 6), in south-eastern DRC, between the cities of Lubumbashi (capital of Haut-Katanga Province) and Kolwezi (capital of Lualaba Province). It lies within the Lufilian Arc, which hosts the Congolese segment of the Central African Copperbelt (Kampunzu & Cailteux, 1999). Since the early 20th century, the KCB has been the historic heart of the Congolese mining industry, based on Cu–Co deposits of global importance. Over time, extraction and processing methods have evolved (from open-pit to underground mining, from pyrometallurgy to hydrometallurgy), generating material flows (waste rock, tailings, slag), atmospheric emissions (metal-bearing dust, smelter plumes) and liquid effluents (Lerat, 1961). In such a context, estimating PGB values requires a robust sampling design capable of separating background concentrations from inputs related to mining and metallurgical activities.

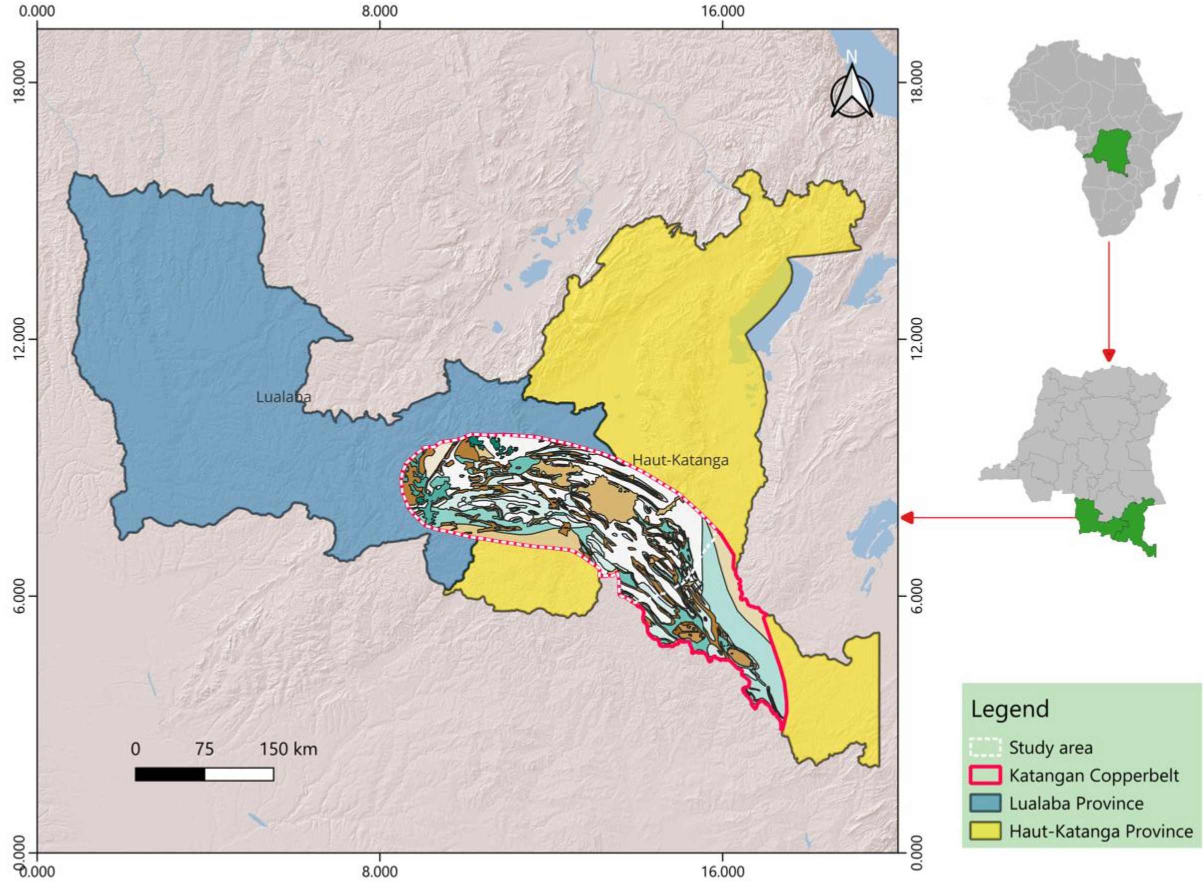

Figure 6. Location map of the study area.

3.2.2 Climate

Situated at elevations above approximately 1,200 m, the study area belongs to the Cwa/Aw climate types according to the Köppen–Geiger classification and experiences rainfall concentrated between October and April, with a frequent peak in December–January (Beck et al., 2018). Over the area that includes in particular the urban basins of Lubumbashi and Kolwezi, mean annual temperatures are around 20–22 °C, monthly maxima typically peak in October–November at around 31–33 °C, while the lowest night-time minima occur in June–July at around 9–12 °C.

3.2.3 Land use

The landscape of the study area forms a mosaic where fields and fallows associated with Miombo woodland (dominated by *Brachystegia–Julbernardia–Isoberlinia*) coexist. To this are added grassy and shrubby savannas and wetlands (marshy grasslands, dambos). This heterogeneous land cover is likely to influence trace-metal contents through distinct mechanisms: diffuse inputs (dust, atmospheric deposition), agricultural practices, erosion–runoff during the rainy season, or resuspension of particles during the dry season. In this context, it is essential to implement stratified sampling that covers the main land-use units while excluding areas directly affected by intensive human activities.

3.2.4 Geology

At the operational scale of this study, there is no harmonized, detailed spatial dataset for the lithology of the KCB. However, the regional lithostratigraphy has been described in numerous works (Batumike et al., 2007; Cailteux & De Putter, 2019; Twigg & Hitzman, 2025). Lithostratigraphically, the study area belongs to the Katanga Supergroup, whose classic succession (Roan, Nguba, Kundelungu) is widely exposed on the Katangan Plateau (Figure 7). The lower part comprises formations of the Roan, which host the main stratiform Cu–Co mineralization. These include the Mines Subgroup and the Mwashya, often associated with carbonate, dolomitic and argillaceous–shale levels that control the occurrence and remobilization of metals. This series is overlain by the Nguba, where the Grand Conglomérat (Cryogenian diamictite) records Paleoproterozoic glacial episodes. At the top, the Kundelungu (including “lower” facies and undifferentiated levels) consists of later detrital, carbonate and pelitic successions. On the margins or lower slopes of reliefs, Cenozoic formations (Neogene–Quaternary) and Holocene alluvium fill recent valleys and plains. Locally, outcrops of Kibaran basement (Mesoproterozoic) and broadly defined “Katangian” units complete the regional architecture. This geological framework justifies stratifying the sampling and calculating PGB values that are specific to each lithostratigraphic unit.

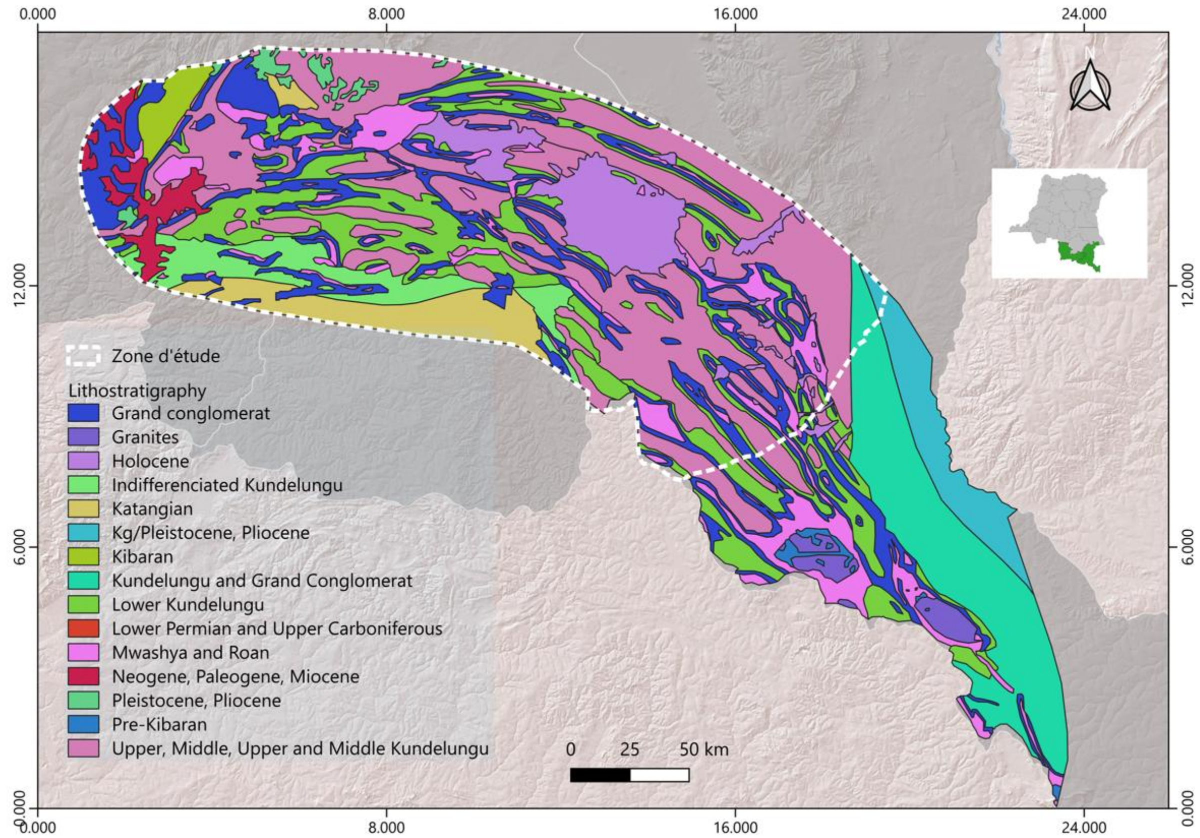

Figure 7. Geological map of the KCB and boundaries of the study area.

3.2.5 Soils

In the study area, Plinthosols constitute a structuring element of the soil landscape (Ferralsols, Acrisols and Alisols), reflecting intense lateralization processes under a tropical climate with alternating wet and dry seasons. Regional observations highlight haplic Plinthosols under natural vegetation, as well as plinthic Arenosols developed on the Dilungu landforms and on the margins of wetlands. On interfluves and upper slopes, Ferralsols (often haplic or rhodic) dominate; they are highly weathered, acidic, with low to moderate cation-exchange capacity (CEC) and rich in Fe and Al sesquioxides. Plinthic Arenosols and Regosols, found on coarse or reworked materials and at the edges of wetlands, are poor in clay and organic matter, which limits their retention capacity. Eutric Cambisols develop mainly on slopes and active glacis, where erosion and deposition dynamics are pronounced. In valley bottoms, Gleysols and Fluvisols associated with dambos reflect hydromorphic environments subject to seasonal waterlogging.

3.3 Sampling method

3.3.1 Selection of sampling points

To obtain representative soil samples of the study area, we used the Conditioned Latin Hypercube Sampling (cLHS) method. This stratified random sampling technique is recognized for its ability to reproduce the variability of environmental covariates in the study area (Minasny & McBratney, 2006), and has the advantage of explicitly including several variables known to influence trace-metal concentrations in soil (ADEME, 2018).

To implement cLHS in R, four raster datasets and two shapefiles were generated using QGIS. These comprised land-use data, a digital elevation model, lithostratigraphic units and soil types. Additional data on the location of mining and processing sites, as well as primary and secondary roads, were used to refine the sampling design. In this study, lithostratigraphy was treated as the main stratification variable. Lithostratigraphic units were therefore considered as coherent geographical entities. Within each unit, sampling points were selected based on a set of environmental covariates to maximize representativeness. For each candidate cell, we considered land-use class, soil type (as mapped at regional scale) and elevation from the digital elevation model (Table 2). These covariates were incorporated into the cLHS algorithm as raster layers so that the combination of land-use classes and soil types, as well as the full altitudinal gradient, would be covered in a balanced way within each lithostratigraphic unit. A series of masks was then applied to restrict the areas eligible for sampling, excluding: mining and processing sites (with a 5 km buffer around mining areas), water bodies, built-up and industrial zones, and cells located less than 100 m from a road. Conditioned Latin Hypercube Sampling was applied within each geological formation, with a fixed, predefined number of points per lithostratigraphic unit, for a total of exactly 200 sites. More sites were allocated to dominant units such as the Kundelungu to better capture their variability in environmental covariates.

A post hoc analysis of sampling representativeness was carried out using Kolmogorov–Smirnov tests to assess the similarity of distributions, and principal component analysis (PCA) to visualize how well the sample covers the covariate space. These checks confirmed that the sampling design reproduces the environmental variability of the study area satisfactorily.

Table 2. Main GIS layers used to design the sampling plan.

Layers	Description	Years	Sources	Link
Lithostratigraphic units	Polygon vector layer representing the major lithostratigraphic units of the KCB, at a scale of about 1:2,500,000. The nomenclature is based on the classification of Cailteux (1994, 2003).	2008	National Geological Service of Congo (SGNC); Royal Museum for Central Africa (RMCA), Tervuren	https://sgnc.cd/cartes-geologiques/ https://geocatalogue.africamuseum.be/geonetwork/geonetwork/api/records/BE-RMCA-EARTHS-014626
Mining sites	Point vector layer locating the main industrial mines, some artisanal mining sites and processing facilities (plants, washing plants, tailings storage facilities).	2023 & 2025	World Bank and BGR data	https://www.google.com/maps/d/viewer?mid=1UaZsL2myAOXXO3_ymWcIe-I3myY&usp=sharing

Layers	Description	Years	Sources	Link
Land use	Raster land-use/land-cover layer, derived from supervised classification of 16 Landsat (OLI/TIRS) images. Spatial resolution of 30 m.	2023 & 2025	United States Geological Survey	https://www.usgs.gov
Digital elevation model	Elevation raster layer derived from data from the EarthExplorer platform, with a spatial resolution of about 30 m.	2023 & 2025	United States Geological Survey	https://www.usgs.gov
Soil types	Layer derived from the Soil and Terrain Digital Database (SOTER) for Central Africa, describing major soil units at regional scale (order of 1:1,000,000–1:2,000,000).	2007	Central Africa SOTER database; French Association for Soil Study (AFES) for dissemination and documentation	https://www.afes.fr

3.4 Soil sampling technique

3.4.1 Collection and preparation of composite samples

The Composite sampling followed the method recommended by Aynekulu et al. (2011). For each of the 200 pre-georeferenced sampling points, a plot of approximately 50 × 50 m was defined. The characteristics of each plot were recorded using the descriptive sheet (Annex 1), including, among others, location, altitude, land use, topography, slope and visible signs of erosion. A composite sample was then formed from 4 sub-points. The first sub-point coincided with the initial georeferenced point. The second was located 12 m away from the first. The third and fourth sub-points were positioned 120° and 240°, respectively, from the second sub-point (Figure 8). At each sub-point, two soil samples were collected: one from the topsoil (0–25 cm) and one from the subsoil (25–50 cm) using a hand auger. To focus on mineral soil, only the mineral horizon was sampled; the litter layer and organic horizon were excluded. The soil from the four sub-points was then mixed and homogenized to obtain a composite sample (> 500 g) for each depth separately. To support quality assurance and quality control of the laboratory analyses, an additional soil sample (about 1 kg) was thoroughly homogenized and used as an internal control sample. Between sampling plots, all equipment (augers, basins, knives) was carefully cleaned to avoid cross-contamination. Collecting the 200 sites mobilized a team of three field technicians and at least two assistants, working at an average rate of around four sites per day (Figure 9).

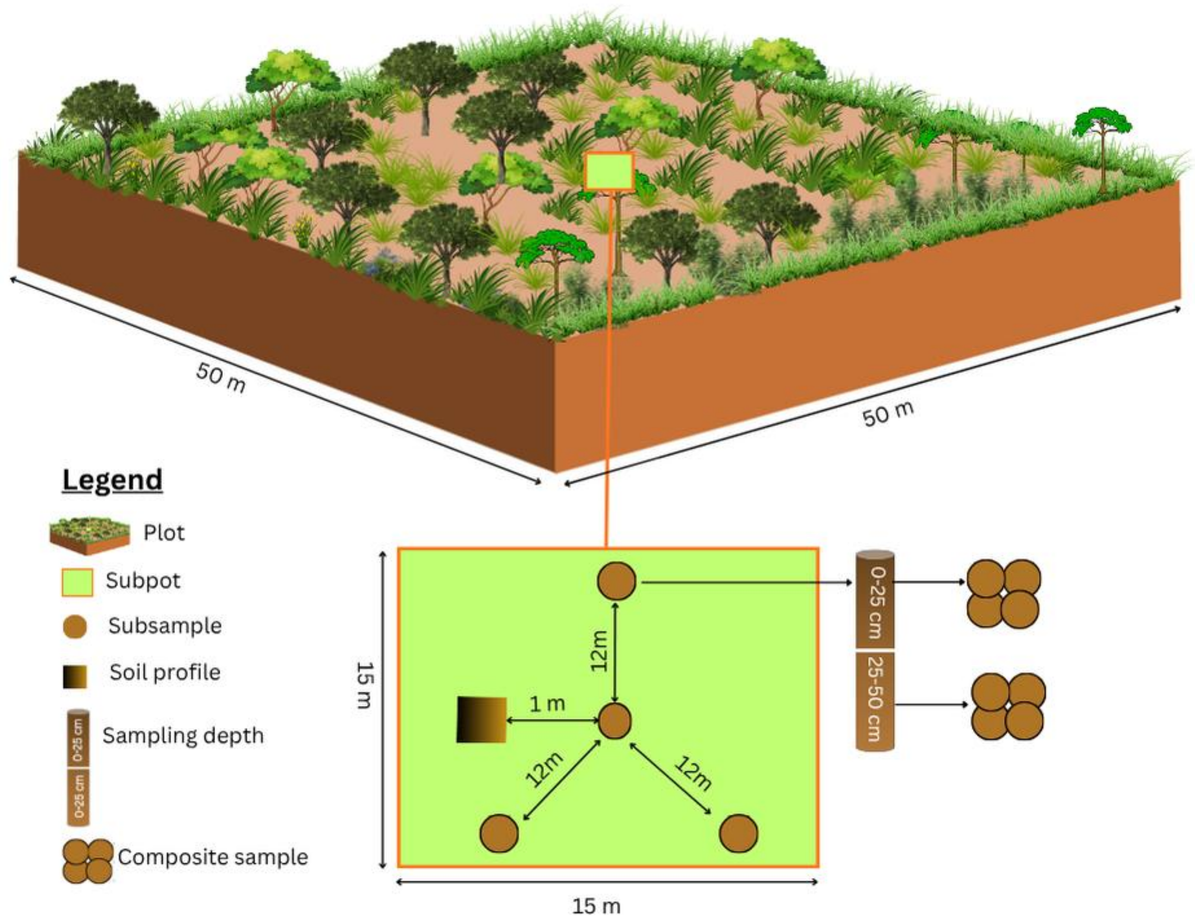

Figure 8. Illustration of the sampling technique applied at each point.

Several types of areas were deliberately avoided during sampling: areas under trees; industrial areas; road verges and edges; the immediate vicinity of livestock farms and intensive agriculture; ridges, furrows, embankments and dumps; recently planted forest stands; areas affected by major deforestation or fire; riverbanks; and locations with restricted access. When an initially selected point fell within one of these zones, an alternative point was chosen.

Figure 9. Field photographs illustrating the collection of soil samples: (a) collection of soil samples using a hand auger; (b) 1) completion of the sampling-plot description sheet, 2) homogenization of the soil and preparation of composite samples, 3) description of the soil from a sample taken with a Pürckhauer auger; (c) soil profile illustrating a Plinthosol, one of the dominant soils in the region.

3.4.2 Description of soil profiles

In total, 120 soil profiles were described. The profile description point was located 1 m from the center of each sampling plot (Figure 8). Profiles were excavated to a depth of about 1 m using either a Pürckhauer auger or spades. Soils were described and classified according to the international system World Reference Base for Soil Resources (WRB)[3], 2022. On average, three soil samples were collected per profile, each from a distinct horizon.

3.4.3 Physico-chemical analyses of soils

Moist soil samples collected in the field were air-dried in a ventilated space, protected from direct sunlight and kept below 40 °C, in accordance with ISO 11464 (2006). The dried samples were gently disaggregated and cleared of coarse fragments (stones), foreign objects (e.g. glass pieces, bottle caps) and plant material (grasses, roots). The soil was spread in a layer no thicker than 5 cm on

[3] https://wrb.isric.org/documents/

aluminum trays, which do not absorb moisture and do not contaminate the samples. Once dry, the soil was ground and sieved through a 2 mm mesh.

3.5 Pretreatment of samples

In studies that aim to determine geochemical or pedo-geochemical background values, the use of a "total" digestion method to bring metals into solution is recommended (ADEME, 2018; Amalric & Moreau, 2025). Aqua regia digestion, as described in ISO 54321:2021, is widely used in laboratories and is recognized as "relevant" for assessing health and environmental impacts, but is classified as a "partial" or "pseudo-total" digestion method (Amalric & Moreau, 2025). For this study, trace-metal analyses (in 2023 and 2025) were carried out at Congolese Analytical Laboratory S.A.R.L. (COAL). Digestion used the four-acid method (near-total extraction): HF–HNO_3–$HClO_4$ + HCl (ISO 14869-1, 2001; U.S. EPA, 1996). Metal concentrations were measured using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). Among the analyzed elements, only 13 were retained for establishing PGB values: Ba, Co, Cr, Cu, Mn, Ni, Sr, V, Zn, Mo, Pb, As and Be. The selection criteria were:

(i) They are considered trace metals in a broad sense, a term used here to include metals and some associated metalloids present at trace levels in soil (Kabata-Pendias, 2010);
(ii) These trace metals are either directly linked to the geological and mining context of the KCB (Cu–Co mineralization and related releases) or are ecotoxicologically relevant because of their potential toxicity for organisms (Cailteux et al., 2007; Kabata-Pendias, 2010; Langunu et al., 2024; Pourret et al., 2016);
(iii) For each of these trace metals, at least 50 % of the samples had concentrations above the limit of quantification, allowing robust statistical estimation of their background distribution.

Other physico-chemical soil parameters were analyzed at the Agropedological Laboratory (LAP) of the University of Lubumbashi for the soil-profile samples. Soil texture was determined by particle-size analysis using the Bouyoucos hydrometer method (Beretta et al., 2014; Beverwijk, 1967). In brief, 50 g of soil sieved to 2 mm were dispersed in a 10 % sodium hexametaphosphate $(NaPO_3)_6$ solution and treated with 6 % hydrogen peroxide (H_2O_2) three times at 60 °C to remove organic carbon. Organic carbon was determined by dry combustion in a high-temperature reactor, followed by precise measurement of CO_2 (Nelson & Sommers, 2018). Soil pH was measured following Black (1994) by potentiometry with a glass electrode and pH meter on 20 g of soil sieved to 2 mm. The pH was measured at a soil (by weight) to solution (by volume) ratio of 1:2.5, either in 1 M potassium chloride (KCl) for pH_{KCl} or in water for pH_{water}. Cation-exchange capacity (CEC) and base saturation were determined using a barium chloride solution in accordance with ISO 11260 (2018). The barium chloride extracts were also used to determine exchangeable acidity (exchangeable Al^{3+} and H^+) in accordance with ISO 14254 (2018). A detailed description of the QA/QC procedures applied to trace-metal and physico-chemical analyses is provided in Annex 2.

3.6 Statistical analyses

3.6.1 Pretreatment

3.6.1.1 Definition of analytical strata

Statistical analysis and data presentation were structured into two strata, consistent with the sampling design: lithostratigraphic units and soil depth (topsoil and subsoil). Due to access constraints, some sampling points had to be relocated, which reduced the number of samples in some strata below the target threshold (n > 20) and required grouping of several lithostratigraphic units. Of the ten initial units, four regionally dominant units had sufficient samples at each depth (28–63 samples). The remaining six were grouped into three sets based on lithostratigraphic character and chemical similarity (Table 3; Annex 3).

Table 3. Definition of analytical strata

Initial lithostratigraphic units	Sampled points		Final lithostratigraphic units	Sampled points	
	0–25cm	25–50cm		0–25cm	25–50cm
Grand conglomérat	32	32	Grand conglomérat	32	32
HOLLOCENE: modern alluvium	33	32	Holocene alluvium	33	32
Kundelungu	63	60	Kundelungu	63	60
Lower Kundelungu	31	28	Lower Kundelungu	31	28
Kundelungu and Grand Conglomérat	1	1	Katangian	24	25
Undifferentiated Kundelungu	8	9			
Katangian	15	15			
Mwashya and Roan	10	10	Mwashya and Roan	10	10
NEOGENE, PALEOGENE AND MIOCENE	5	5	Cenozoic cover	7	7
PLEISTOCENE and PLIOCENE	2	2			

3.6.1.2 Management of censored data

The management of concentrations below the LOQ was adapted to the proportion of censored values by trace metal (Table 4). When no value was below the LOD, the data were kept unchanged. For a low proportion (1–4 %), substitution by LOQ/2 was applied (ISO 19258, 2018). For a moderate proportion (6–14 %), the Kaplan–Meier estimator was used to determine percentiles in order to preserve the data distribution (ADEME, 2018).

Table 4. Evaluation report of values below the limit of detection. Limit of quantification: Be =0.5 ppm; Co, Cr, Cu, Ni, Mo, Sr et V = 1 ppm; Zn, Pb =2 ppm; As, Mn = 5 ppm; Ba = 10 ppm.

Samples below LOQ	Trace metals	Action
0%	Ba, Co, Cr, Cu, Mn, Ni, Sr, V, Zn	Keep without modification
1-4%	Mo, Pb	Apply LOQ/2
6-14%	As, Be	Apply Kaplan–Meier

3.6.1.3 Management of geochemical anomalies

Geochemical anomalies were identified through exploratory data analysis combining several descriptive tools: Q–Q plots, histograms (Figure 10) and box plots (Matschullat et al., 2000). As an independent check, a concentration–number fractal filter was then applied to confirm the presence of anomalies (Borojerdnia et al., 2020; Cheng et al., 1994). The following trace metals showed anomalies at a single sampling point: As, Ba, Mo, Pb, Sr and Zn, while Cu and Mn showed anomalies at two sampling points. At any given site, anomalies occurred consistently in both the topsoil (0–25 cm) and subsoil (25–50 cm). The corresponding samples were therefore excluded from subsequent statistical analyses. Annexes 4 and 5 illustrate the distribution of trace-metal concentrations before and after removal of geochemical anomalies.

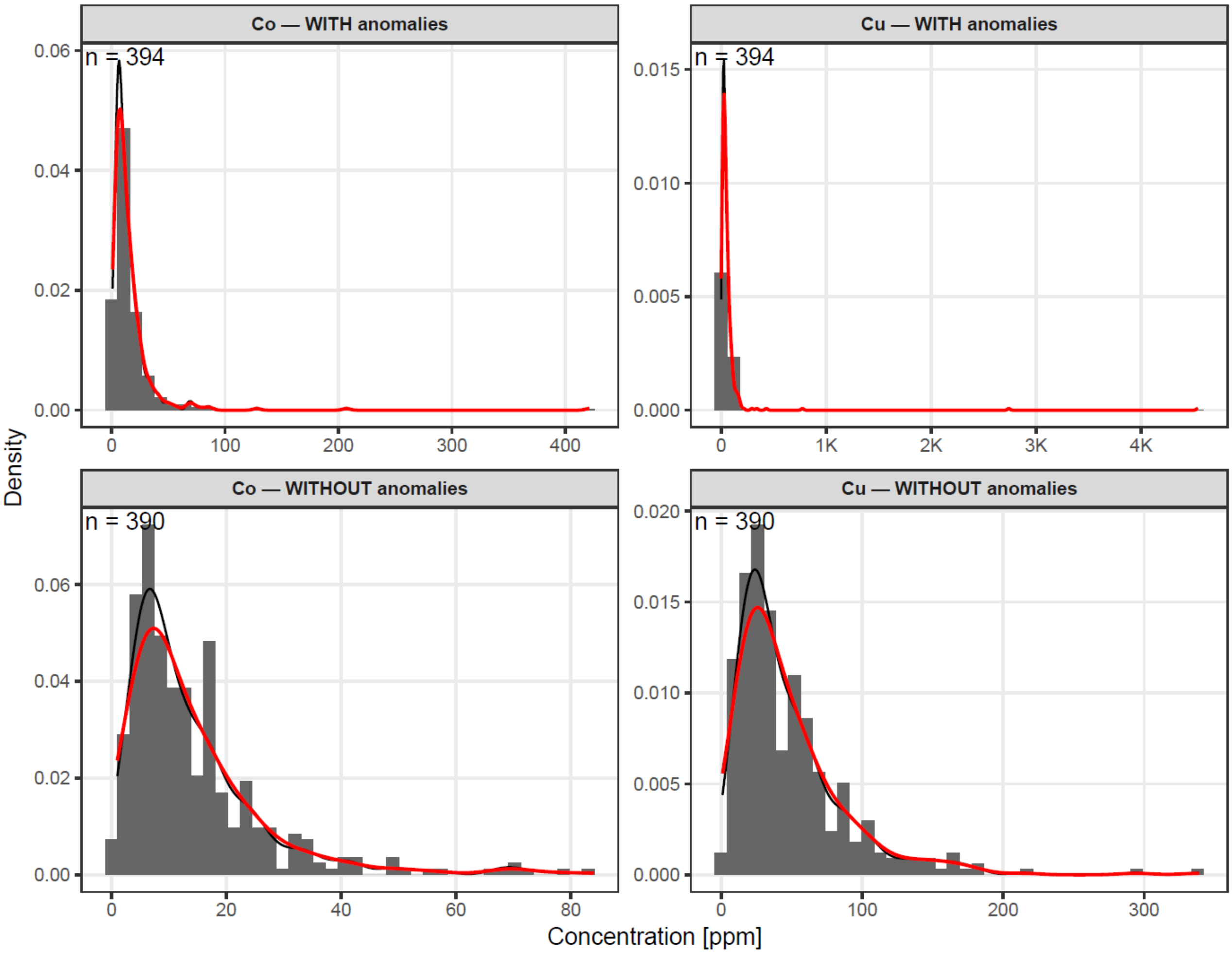

Figure 10. Histograms illustrating the distribution of Cu and Co concentrations before and after exclusion of geochemical anomalies.

3.6.1.4 Descriptive analyses and determination of pedo-geochemical background values

All statistical analyses were carried out in R, version 4.5.0 (R Core Team, 2024)[4]. For each stratum (lithostratigraphic unit × soil horizon), the following descriptive statistics were calculated: minimum, maximum, mean, standard deviation, coefficient of variation, interquartile range, geometric mean and geometric standard deviation. Because trace-metal concentrations typically deviate from a normal distribution and show heavy tails and extreme values (Reimann et al., 2005; Reimann & Filzmoser, 2000), percentiles were used to define PGB values. ISO 19258:2018 recommends using a high percentile as the PGB value. However, very high percentiles (e.g. 95th or 98th) can be highly uncertain when sample sizes are limited. This study therefore adopted the 90th percentile as the upper limit of the PGB and the median as the central descriptive measure. The 90th percentile is also commonly used in several European countries, including Germany (Cappuyns & Mallaerts, 2014; Utermann et al., 2008). A percentile is interpreted as follows: a randomly selected sample has an X % probability of having a concentration below the Xth percentile. In line with international practice, a 95 % confidence interval (CI) was estimated for the upper PGB limit (90th percentile) using a bootstrap approach with 10,000 resamplings per stratum (Efron & Tibshirani, 1994).

For operational use, 90th-percentile values were then mapped across the study area. For each lithostratigraphic unit, the 90th percentile derived from the sampled sites was projected onto outcrops of the same unit within the study area. This projection was then extended to the entire KCB, including unsampled sectors. This extrapolation assumes that PGB values are transferable within a given lithostratigraphic unit. In practice, this assumption is affected by uncertainties linked to lithological variability and other fine-scale environmental covariates. The mapped values should therefore be considered indicative only and cannot replace site-specific sampling for environmental decision-making.

[4] https://www.r-project.org/

4. Presentation of results

4.1 Descriptive analyses

The mean concentration of As varies between 9 ppm (Cenozoic cover, 0–25 cm) and 27 ppm (Lower Kundelungu, 25–50 cm), with maximum values reaching 209 ppm (Lower Kundelungu, 0–25 cm). As shows strong dispersion, with a coefficient of variation (CV) of up to 1.5 (Grand Conglomérat, 25–50 cm). At depth (25–50 cm), the mean concentration of As increases in all lithostratigraphic units (Table 5). The mean concentration of Ba varies between 109 ppm (Cenozoic cover, 0–25 cm) and 278 ppm (Katangian, 25–50 cm), with maximum values up to 820 ppm (Mwashya & Roan, 25–50 cm). Ba shows moderate to high dispersion, with a maximum CV of 0.9 (Mwashya & Roan, 25–50 cm). The mean concentration of Be varies between 1 ppm (Cenozoic cover, 0–25 cm) and 2 ppm (Lower Kundelungu, 25–50 cm), with maximum values up to 4 ppm (Lower Kundelungu, 25–50 cm). Dispersion of Be is low to moderate, with a maximum CV of 1.0 (Cenozoic cover, 25–50 cm). Overall, the mean Be concentration increases with depth in all lithostratigraphic units.

The mean concentration of Co varies between 6 ppm (Cenozoic cover, 0–25 cm) and 20 ppm (Lower Kundelungu, 25–50 cm), with maximum values up to 128 ppm (Kundelungu, 25–50 cm). Dispersion is moderate to high, with a maximum CV of 1.4 (Cenozoic cover, 25–50 cm). At depth, the mean Co concentration increases in all lithostratigraphic units. The mean Cr concentration varies between 163 ppm (Cenozoic cover, 0–25 cm) and 566 ppm (Lower Kundelungu, 25–50 cm), with maximum values up to 787 ppm (Grand Conglomérat, 0–25 cm). Dispersion of Cr is moderate, with a maximum CV of 0.7 (Grand Conglomérat, 25–50 cm). Overall, the mean Cr concentration decreases with depth in all lithostratigraphic units. The mean Cu concentration varies between 33 ppm (Holocene alluvium, 0–25 cm) and 65 ppm (Katangian, 25–50 cm), with maximum values up to 339 ppm (Lower Kundelungu, 25–50 cm). Dispersion is moderate to high, with a maximum CV of 1.1 (Lower Kundelungu, 25–50 cm). The depth gradient of Cu concentration depends on the lithostratigraphic unit.

The mean concentration of Mn varies between 95 ppm (Cenozoic cover, 0–25 cm) and 376 ppm (Kundelungu, 0–25 cm), with extreme maxima up to 1,965 ppm (Kundelungu, 0–25 cm) and 1,845 ppm (Holocene alluvium, 25–50 cm). Mn shows strong dispersion, with a maximum CV of 1.3 (Mwashya & Roan, 25–50 cm). With depth, its behavior is contrasting. The mean concentration of Mo varies between 1 ppm (Holocene alluvium, 0–25 cm) and 4 ppm (Katangian, 0–25 cm and 25–50 cm), with maximum values up to 11 ppm (Katangian, 25–50 cm). Mo shows moderate dispersion, with a maximum CV of 0.8. With depth, its behavior is contrasting. The mean concentration of Ni varies between 15 ppm (Cenozoic cover, 0–25 cm) and 50 ppm (Katangian, 25–50 cm), with maximum values up to 102 ppm (Katangian, 25–50 cm). Ni shows moderate dispersion, with a maximum CV of 0.6. At depth, the mean Ni concentration increases in all lithostratigraphic units.

The mean Pb concentration varies between 8 ppm (Katangian, 25–50 cm) and 14 ppm (Cenozoic cover, 25–50 cm), with maximum values up to 72 ppm (Kundelungu, 25–50 cm). Pb shows moderate dispersion, which may locally be high, with a maximum CV of 1.1 (Katangian, 25–50 cm). With depth, its behavior is contrasting. The mean concentration of Sr varies between 9 ppm (Cenozoic cover, 25–50 cm) and 16 ppm (Mwashya & Roan, 0–25 cm), with maximum values up to 62 ppm (Grand Conglomérat, 0–25 cm). Sr shows moderate dispersion, with a maximum CV of 0.9. At depth, the mean Sr concentration decreases in all lithostratigraphic units.

The mean V concentration varies between 95 ppm (Holocene alluvium, 0–25 cm) and 271 ppm (Katangian, 25–50 cm), with maximum values up to 488 ppm (Cenozoic cover, 25–50 cm). V shows moderate dispersion, with a maximum CV of 0.8 (Cenozoic cover, 0–25 cm and 25–50 cm). At depth, the mean V concentration increases in all lithostratigraphic units. The mean Zn concentration varies between 14 ppm (Cenozoic cover, 25–50 cm) and 43 ppm (Lower Kundelungu, 25–50 cm), with maximum values up to 484 ppm (Holocene alluvium, 25–50 cm). Zn shows strong dispersion, with a maximum CV of 2.1 (Holocene alluvium, 25–50 cm).

Table 5. Statistical analysis results of trace metal concentrations as a function of depth and lithostratigraphic units.

Variable	Statistic	Holocene alluvium		Cenozoic cover		Grand Conglo-merate		Katangian		Kundelungu		Lower Kundelungu		Mwashya and Roan	
		0–25cm	25–50cm	0–25cm	25–50cm	0–25cm	25–50cm	0–25cm	25–50cm	0–25cm	25–50cm	0–25cm	25–50cm	0–25cm	25–50cm
As [ppm]	Minimum	<5	<5	<5	<5	<5	<5	5	5	<5	<5	<5	<5	<5	<5
	Mean	9	14	9	12	15	25	23	26	16	22	25	27	16	21
	Maximum	36	73	25	33	75	172	81	100	117	186	209	163	32	53
	Standard deviation	9	14	9	12	15	38	16	22	18	29	36	30	11	19
	Coefficient of variation	1.0	1.0	1.0	0.9	1.0	1.5	0.7	0.8	1.1	1.3	1.4	1.1	0.7	0.9
	Interquartile range	10	12	8	12	10	15	17	19	12	18	17	20	20	26
	Geometric mean	6	10	6	8	10	14	19	20	11	14	17	19	12	12
	Geometric standard deviation	2	2	3	3	2	3	2	2	2	3	2	2	2	3
Ba [ppm]	Minimum	20	30	10	10	30	20	80	80	20	20	30	50	70	70
	Mean	148	170	109	109	184	208	266	280	228	242	255	277	223	255
	Maximum	610	760	180	200	560	610	680	710	620	710	600	620	620	820
	Standard deviation	131	149	68	75	138	143	116	122	135	151	135	157	168	226
	Coefficient of variation	0.9	0.9	0.6	0.7	0.7	0.7	0.4	0.4	0.6	0.6	0.5	0.6	0.8	0.9
	Interquartile range	140	158	95	115	108	138	80	90	198	235	125	123	193	173
	Geometric mean	107	125	74	72	143	163	246	258	182	190	219	236	181	193
	Geometric standard deviation	2.3	2.2	3.2	3.2	2.1	2.1	1.5	1.5	2.1	2.2	1.9	1.8	1.9	2.2
Be[ppm]	Minimum	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	1	1	<0.5	<0.5	<0.5	1	1	1
	Mean	1	1	1	1	1	1	1	2	1	1	1	2	1	2
	Maximum	3	4	2	3	3	4	3	3	3	3	3	4	3	3
	Standard deviation	1	1	1	1	1	1	0	1	1	1	1	1	1	1
	Coefficient of variation	0.7	0.7	0.8	1.0	0.5	0.6	0.3	0.3	0.5	0.5	0.4	0.5	0.5	0.5
	Interquartile range	1	1	0	1	1	1	0	1	1	1	1	1	1	1
	Geometric mean	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Geometric standard deviation	2	2	2	2	2	2	1	1	2	2	2	2	2	2
Co [ppm]	Minimum	1	2	1	1	1	2	5	4	1	2	2	4	4	7
	Mean	11	15	6	9	9	13	16	17	15	18	16	20	12	14

Variable	Statistic	Holocene alluvium		Cenozoic cover		Grand Conglo-merate		Katangian		Kundelungu		Lower Kundelungu		Mwashya and Roan	
	Maximum	52	68	12	37	27	48	43	35	87	128	84	78	27	40
	Standard deviation	11	14	3	13	6	10	10	8	15	21	15	18	9	10
	Coefficient of variation	1.0	1.0	0.6	1.4	0.7	0.8	0.6	0.5	1.0	1.2	0.9	0.9	0.7	0.7
	Interquartile range	7	10	3	5	7	10	16	13	12	13	12	13	14	7
	Geometric mean	7	11	5	5	7	10	14	15	10	12	12	15	10	12
	Geometric standard deviation	2	2	2	3	2	2	2	2	2	2	2	2	2	2
Cr [ppm]	Minimum	48	27	303	280	31	34	90	85	45	30	81	54	181	52
	Mean	368	196	566	481	281	189	268	226	313	181	298	163	292	165
	Maximum	644	413	766	577	787	598	476	404	689	564	660	338	395	268
	Standard deviation	133	124	170	114	152	135	99	88	137	132	123	81	76	74
	Coefficient of variation	0.4	0.6	0.3	0.2	0.5	0.7	0.4	0.4	0.4	0.7	0.4	0.5	0.3	0.4
	Interquartile range	138	239	235	136	166	169	126	108	169	169	177	92	110	92
	Geometric mean	336	148	541	468	234	148	247	209	277	139	273	144	282	146
	Geometric standard deviation	2	2	1	1	2	2	2	2	2	2	2	2	1	2
Cu [ppm]	Minimum	6	8	5	1	7	3	19	20	4	3	11	12	12	11
	Mean	33	42	33	35	45	49	62	65	46	49	57	56	41	45
	Maximum	86	101	59	80	161	168	149	143	180	214	294	339	90	116
	Standard deviation	21	26	17	26	34	35	34	34	44	49	51	61	33	38
	Coefficient of variation	0.7	0.6	0.5	0.7	0.8	0.7	0.5	0.5	1.0	1.0	0.9	1.1	0.8	0.8
	Interquartile range	33	41	18	24	36	33	49	46	37	35	37	32	54	54
	Geometric mean	26	34	27	21	35	37	53	56	30	33	45	42	30	34
	Geometric standard deviation	2	2	2	4	2	2	2	2	3	2	2	2	2	2
Mn [ppm]	Minimum	39	40	49	37	48	41	61	52	53	31	36	39	52	27
	Mean	249	297	95	127	189	236	272	254	376	359	319	316	326	315
	Maximum	809	1845	141	254	464	1290	599	517	1965	1700	1615	1480	1075	1485
	Standard deviation	218	361	29	77	118	243	159	138	363	375	310	339	335	424
	Coefficient of variation	0.9	1.2	0.3	0.6	0.6	1.0	0.6	0.5	1.0	1.0	1.0	1.1	1.0	1.3
	Interquartile range	286	273	29	84	183	212	187	207	295	228	301	186	161	162
	Geometric mean	170	184	91	107	157	167	229	217	267	239	226	215	214	179

Variable	Statistic	Holocene alluvium		Cenozoic cover		Grand Conglo-merate		Katangian		Kundelungu		Lower Kundelungu		Mwashya and Roan	
	Geometric standard deviation	2	3	1	2	2	2	2	2	2	2	2	2	3	3
Mo [ppm]	Minimum	<1	<1	1	1	<1	1	1	1	<1	1.0	<1	<1	1	1
	Mean	1	2	2	3	2	3	4	4	2	3	2	3	2	3
	Maximum	4	5	5	7	5	6	9	11	6	9	5	6	3	6
	Standard deviation	1	1	2	2	1	2	2	2	1	2	1	1	1	2
	Coefficient of variation	0.6	0.7	0.8	0.8	0.6	0.6	0.5	0.6	0.6	0.7	0.6	0.5	0.5	0.5
	Interquartile range	1	1	1	2	1	2	2	2	1	1	2	2	1	3
	Geometric mean	1	2	1	2	2	2	3	3	1	2	2	3	2	3
	Geometric standard deviation	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Ni [ppm]	Minimum	6	8	8	5	9	8	15	15	7	8	8	11	16	17
	Mean	20	25	15	16	27	30	46	50	25	27	34	39	31	34
	Maximum	40	57	19	24	81	101	97	102	64	82	69	97	80	89
	Standard deviation	9	12	4	7	14	18	21	21	13	15	17	21	19	21
	Coefficient of variation	0.5	0.5	0.3	0.4	0.5	0.6	0.4	0.4	0.5	0.6	0.5	0.5	0.6	0.6
	Interquartile range	14	18	7	7	17	19	22	18	15	18	23	29	11	13
	Geometric mean	18	22	14	14	24	26	42	46	22	23	30	34	28	30
	Geometric standard deviation	2	2	1	2	2	2	2	2	2	2	2	2	2	2
Pb [ppm]	Minimum	<2	<2	4	<2	<2	<2	2	<2	<2	<2	<2	2	4	4
	Mean	9	12	10	14	9	11	10	8	12	13	11	13	10	10
	Maximum	22	30	23	36	20	26	37	40	41	72	42	50	23	20
	Standard deviation	6	7	8	12	5	7	8	9	7	12	9	10	6	5
	Coefficient of variation	0.7	0.6	0.7	0.9	0.6	0.6	0.8	1.1	0.6	0.9	0.8	0.8	0.6	0.5
	Interquartile range	9	10	8	15	7	10	9	9	9	11	9	10	7	5
	Geometric mean	7	9	8	9	8	8	7	5	10	10	9	10	9	9
	Geometric standard deviation	2	2	2	3	2	2	2	3	2	2	2	2	2	2
	Minimum	2	2	2	2	2	2	1	1	2	2	2	1	1	1
Sr [ppm]	Minimum	4	4	2	2	4	4	5	5	2	2	4	5	6	7
	Mean	14	13	11	9	15	13	12	12	15	13	15	14	16	14
	Maximum	42	43	31	16	62	49	26	25	41	39	45	33	47	27

Variable	Statistic	Holocene alluvium		Cenozoic cover		Grand Conglo-merate		Katangian		Kundelungu		Lower Kundelungu		Mwashya and Roan	
	Standard deviation	11	10	10	5	12	10	5	5	9	8	10	7	12	7
	Coefficient of variation	0.8	0.8	0.9	0.6	0.9	0.8	0.4	0.5	0.6	0.6	0.6	0.5	0.7	0.5
	Interquartile range	10	10	8	8	5	3	7	5	10	8	9	8	9	13
	Geometric mean	11	10	8	7	12	11	11	11	13	11	13	12	14	12
	Geometric standard deviation	2	2	2	2	2	2	1	2	2	2	2	2	2	2
V [ppm]	Minimum	23	24	20	19	27	25	100	111	23	24	52	68	55	68
	Mean	95	134	148	228	126	162	243	271	123	154	174	185	147	180
	Maximum	287	386	346	488	284	393	393	403	317	423	369	283	348	388
	Standard deviation	62	83	117	173	62	79	83	84	60	77	81	67	90	109
	Coefficient of variation	0.7	0.6	0.8	0.8	0.5	0.5	0.3	0.3	0.5	0.5	0.5	0.4	0.6	0.6
	Interquartile range	72	104	137	250	72	81	103	98	75	94	116	111	107	156
	Geometric mean	77	108	105	148	111	142	228	256	108	133	154	171	126	151
	Geometric standard deviation	2	2	3	3	2	2	1	1	2	2	2	2	2	2
Zn [ppm]	Minimum	6	6	6	3	12	8	6	7	9	6	6	12	12	10
	Mean	30	40	14	14	30	31	35	37	36	36	40	43	32	34
	Maximum	299	484	22	25	77	107	78	75	146	162	104	114	64	79
	Standard deviation	50	83	5	7	16	19	19	21	23	25	23	28	19	23
	Coefficient of variation	1.7	2.1	0.3	0.5	0.5	0.6	0.5	0.6	0.6	0.7	0.6	0.7	0.6	0.7
	Interquartile range	14	15	4	4	13	15	32	33	25	20	25	36	19	26
	Geometric mean	20	23	14	12	27	27	30	31	31	31	34	35	27	27
	Geometric standard deviation	2	2	2	2	2	2	2	2	2	2	2	2	2	2

4.2 Pedo-geochemical background values

4.2.1 Pedo-geochemical background of arsenic

In topsoil (0–25 cm), the PGB value of As ranges between 11 ppm (50th percentile) and 34 ppm (90th percentile) in the Kundelungu, which implies a 90 % probability of measuring an As concentration ≤ 34 ppm in this lithostratigraphic unit (Figure 11). The 95 % confidence interval (CI) of the 90th percentile is 21–47 ppm. In the Holocene alluvium, the PGB value of As lies between 6 and 21 ppm (CI: 12–32 ppm). In the Grand Conglomérat, the PGB value ranges from 10 to 32 ppm (CI: 17–50 ppm). Lower Kundelungu shows 18–35 ppm (CI: 26–58 ppm). The Katangian displays 20–41 ppm (CI: 28–81 ppm), Mwashya & Roan 14–32 ppm (CI: 28–32 ppm), and the Cenozoic cover 9–25 ppm (CI: 9–25 ppm). In subsoil (25–50 cm), the PGB value of As generally increases: Kundelungu 13–44 ppm (CI: 33–87 ppm); Holocene alluvium 10–28 ppm (CI: 18–73 ppm); Grand Conglomérat 13–35 ppm (CI: 26–157 ppm); Lower Kundelungu 19–51 ppm (CI: 32–163 ppm); Katangian 24–48 ppm (CI: 30–100 ppm); Mwashya & Roan 23–53 ppm (CI: 29–53 ppm); and Cenozoic cover 11–33 ppm (CI: 11–33 ppm).

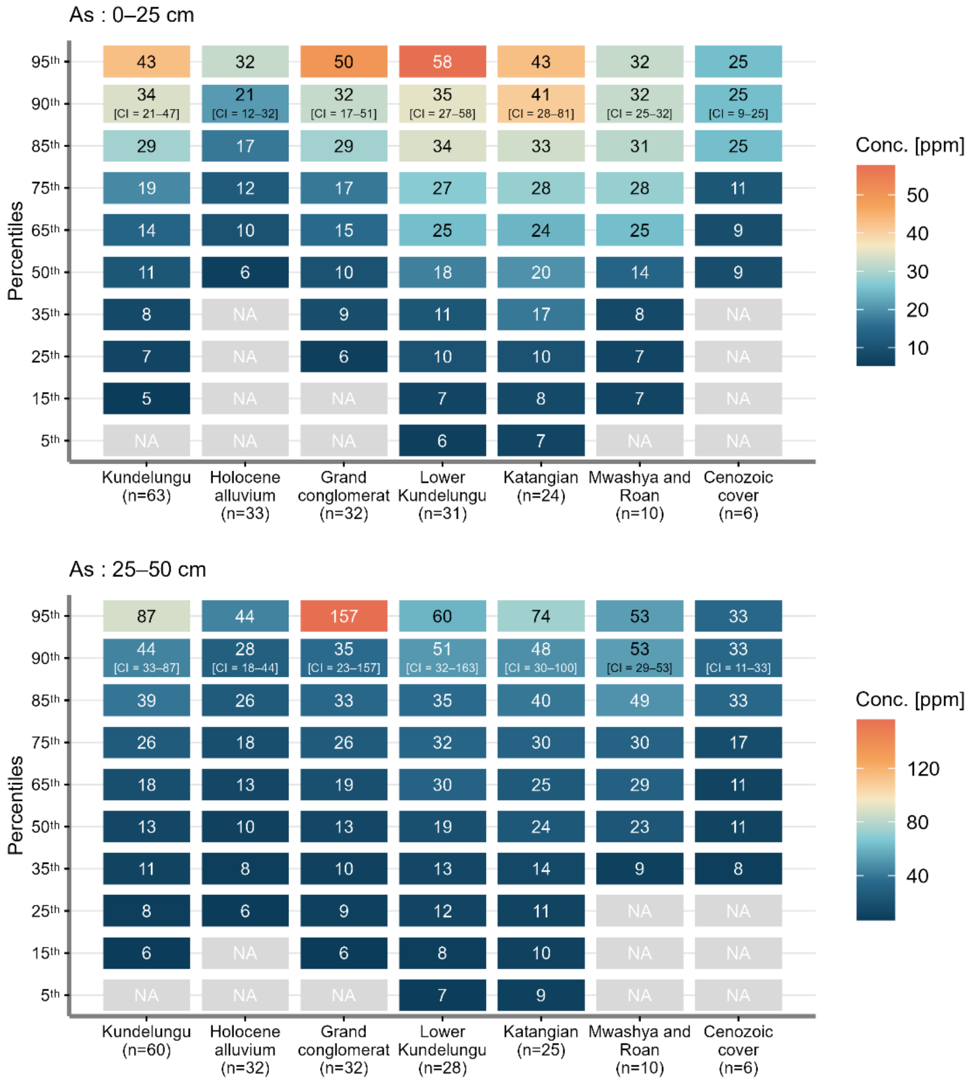

Figure 11. Pedo-geochemical background values of As per depth and in different lithostratigraphic unit. CI: 95 % confidence interval.

4.2.2 Pedo-geochemical background of barium

In topsoil (0–25 cm), the PGB value of Ba ranges between 210 ppm (50th percentile) and 399 ppm (90th percentile) in the Kundelungu, which implies a 90 % probability of measuring a Ba concentration ≤ 399 ppm in this lithostratigraphic unit (Figure 12). The 95 % CI of the 90th percentile is 330–456 ppm. In the Holocene alluvium, the PGB value of Ba lies between 90 ppm and 334 ppm, with a CI of 190–375 ppm. In the Grand Conglomérat, the PGB value ranges from 135 ppm to 345 ppm, with a CI of 228–530 ppm. Lower Kundelungu shows a PGB value between 240 ppm and 420 ppm, with a CI of 290–570 ppm. The Katangian displays values of 255–387 ppm (CI: 284–680 ppm), Mwashya & Roan 160–368 ppm (CI: 196–620 ppm), and the Cenozoic cover 140–168 ppm (CI: 124–180 ppm). In subsoil (25–50 cm), the PGB value of Ba generally increase: Kundelungu: 230–424 ppm (CI: 390–490 ppm); Holocene alluvium: 110–319 ppm (CI: 244–716 ppm); Grand Conglomérat: 160–350 ppm (CI: 284–530 ppm); Lower Kundelungu: 245–543 ppm (CI: 310–613 ppm); Katangian: 260–

402 ppm (CI: 302–598 ppm); Mwashya & Roan: 185–451 ppm (CI: 204–820 ppm); and Cenozoic cover: 100–182 ppm (CI: 122–200 ppm).

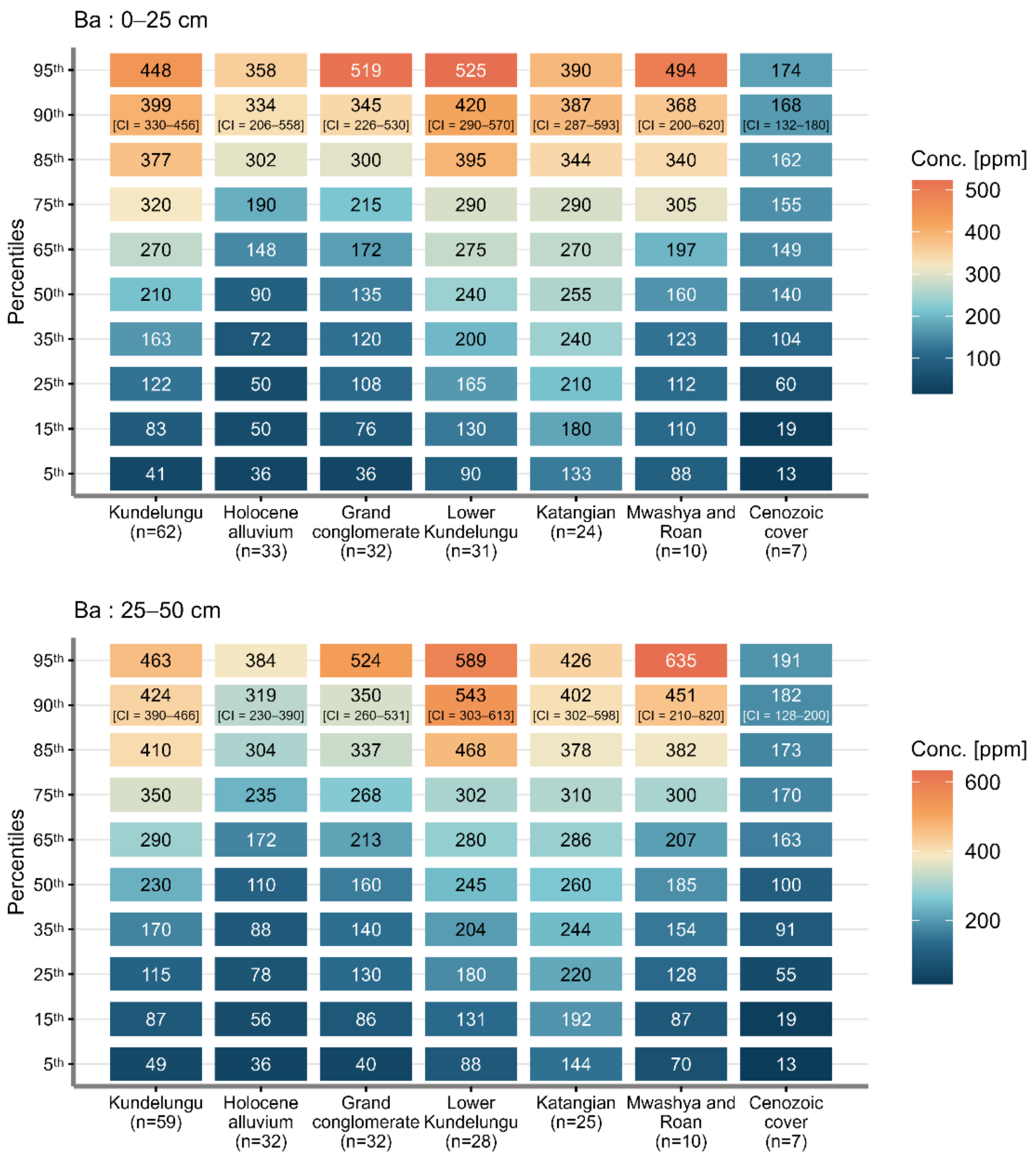

Figure 12. Pedo-geochemical background values of Ba at different depths and in different lithostratigraphic units. CI: 95 % confidence interval.

4.2.3 Pedo-geochemical background of beryllium

In topsoil (0–25 cm), the PGB value of Be ranges between 1 ppm (50th percentile) and 2 ppm (90th percentile) in the Kundelungu, which implies a 90 % probability of measuring a concentration ≤ 2 ppm in this lithostratigraphic unit (Figure 13). The 95 % CI of the 90th percentile is 2–2 ppm. In the Holocene alluvium, the PGB value of Be lies between 1 and 2 ppm (CI: 1–2 ppm). In the Grand Conglomérat, 1–2 ppm (CI: 1–2 ppm). Lower Kundelungu shows 1–2 ppm (CI: 2–3 ppm). The Katangian displays 1–2 ppm (CI: 2–3 ppm), and the Cenozoic cover 1–2 ppm (CI: 1–2 ppm). Mwashya & Roan is characterized by 1–3 ppm (CI: 2–3 ppm). In subsoil (25–50 cm), the PGB value of Be remains stable or shift slightly: Kundelungu 1–2 ppm (CI: 2–3 ppm); Holocene alluvium 1–2 ppm

(CI: 2–3 ppm); Grand Conglomérat 1–2 ppm (CI: 2–3 ppm); Lower Kundelungu 2–4 ppm (CI: 2–4 ppm); Katangian 2–2 ppm (CI: 2–3 ppm); Mwashya & Roan 1–3 ppm (CI: 2–3 ppm); and Cenozoic cover 1–3 ppm (CI: 1–3 ppm).

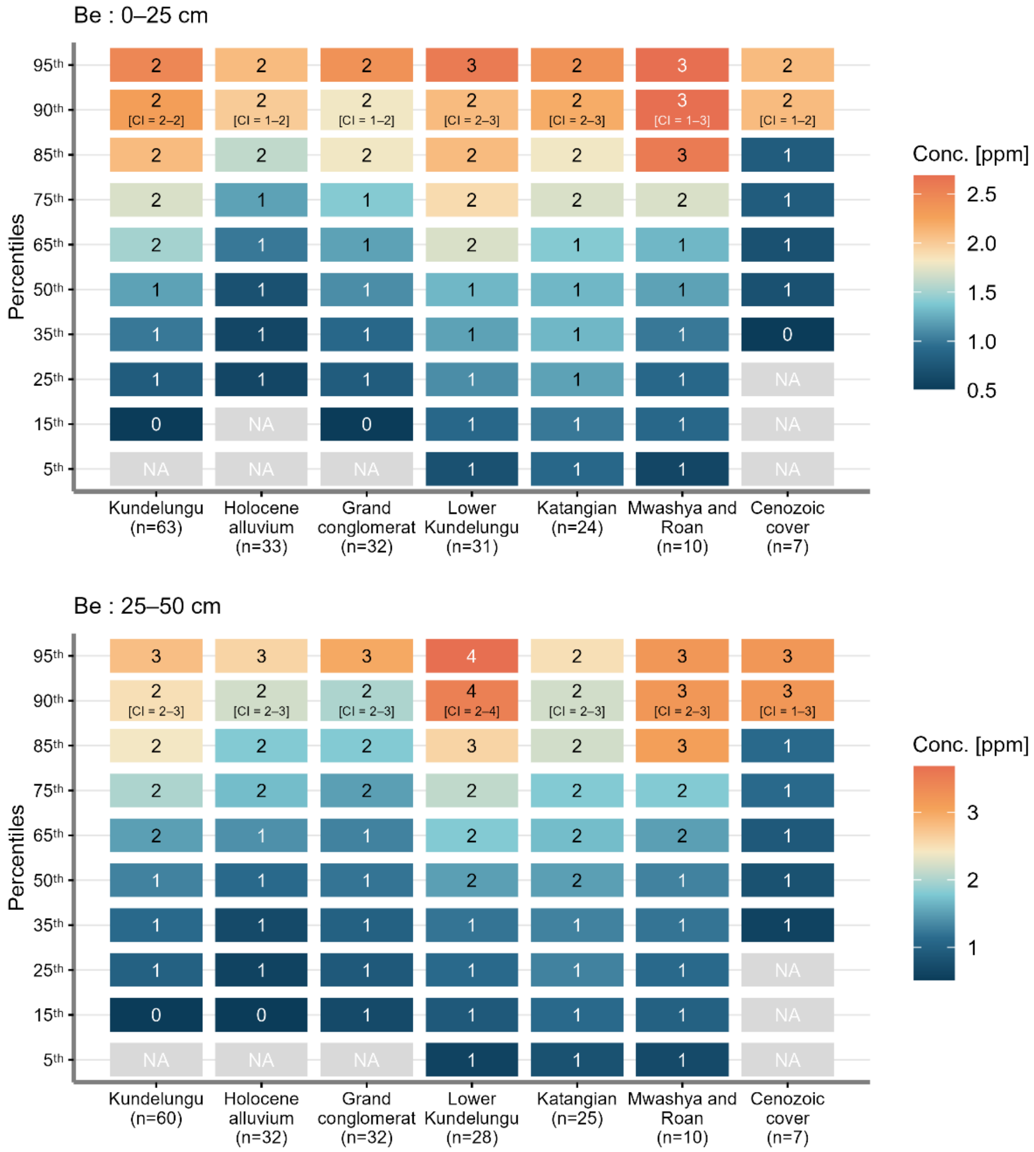

Figure 13. Pedo-geochemical background values of Be at different depths and in different lithostratigraphic units. CI: 95 % confidence interval.

4.2.4 Pedo-geochemical background of cobalt

In topsoil (0–25 cm), the PGB value of Co ranges between 11 ppm (50th percentile) and 34 ppm (90th percentile) in the Kundelungu, which implies a 90 % probability of measuring a concentration ≤ 34 ppm in this lithostratigraphic unit (Figure 14). The 95 % CI of the 90th percentile is 20–48 ppm. In the Holocene alluvium, the PGB value of Co lies between 7 and 26 ppm (CI: 12–35 ppm). In the Grand Conglomérat, the PGB value ranges from 7 to 18 ppm (CI: 12–25 ppm). Lower Kundelungu shows 13–27 ppm (CI: 19–32 ppm). The Katangian displays 12–27 ppm (CI: 23–40 ppm), Mwashya & Roan 6–23 ppm (CI: 9–27 ppm), and the Cenozoic cover 5–9 ppm (CI: 5–12 ppm). In subsoil (25–

50 cm), the PGB value of Co generally increase: Kundelungu 13–37 ppm (CI: 21–67 ppm); Holocene alluvium 10–26 ppm (CI: 17–55 ppm); Grand Conglomérat 9–28 ppm (CI: 17–31 ppm); Lower Kundelungu 16–41 ppm (CI: 21–72 ppm); Katangian 18–29 ppm (CI: 24–34 ppm); Mwashya & Roan 11–26 ppm (CI: 12–40 ppm); and Cenozoic cover 4–22 ppm (CI: 4–37 ppm).

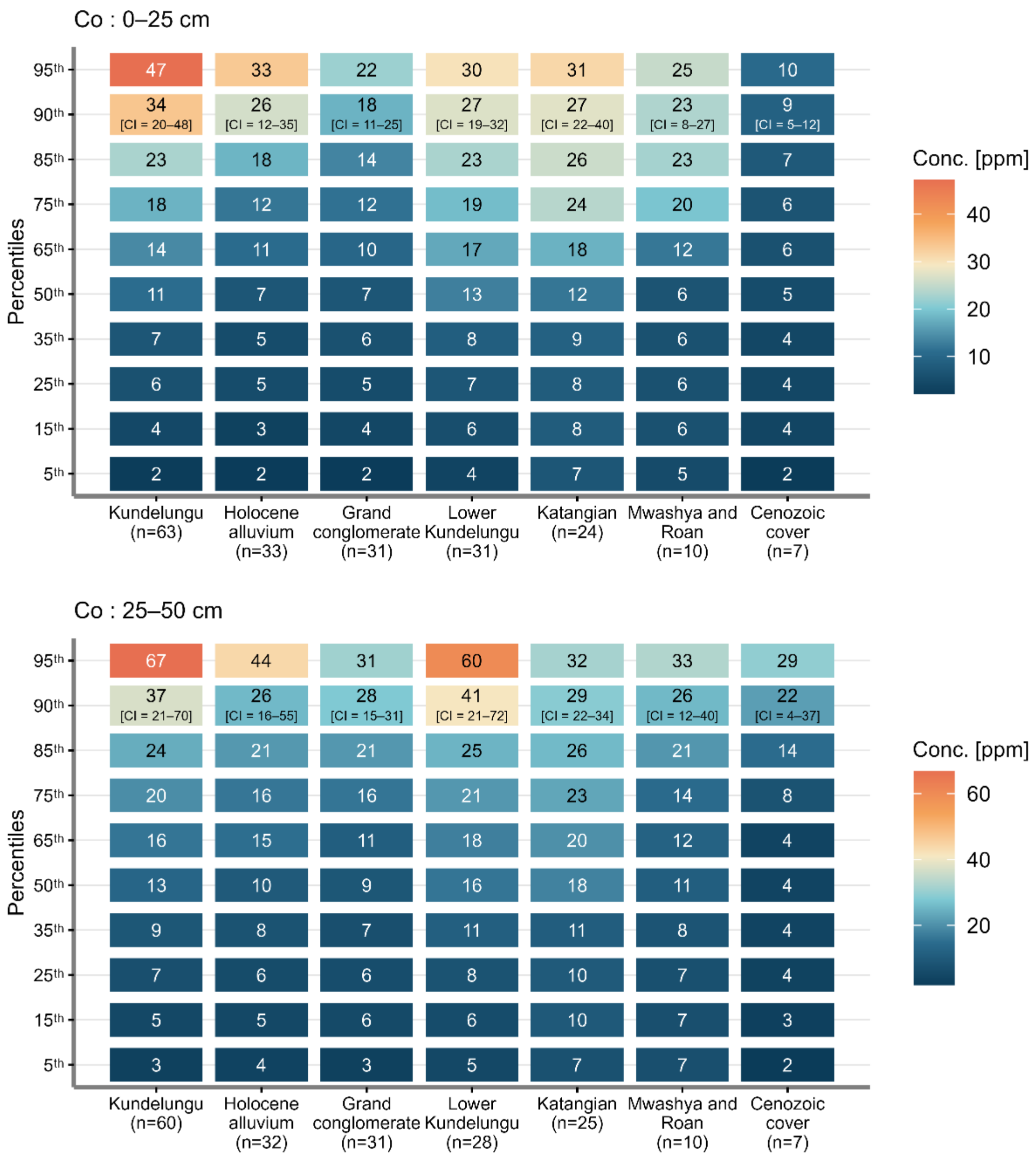

Figure 14. Pedo-geochemical background values of Co at different depths and in different lithostratigraphic units. CI: 95 % confidence interval.

4.2.5 Pedo-geochemical background of chromium

In topsoil (0–25 cm), the PGB value of Cr ranges between 304 ppm (50th percentile) and 472 ppm (90th percentile) in the Kundelungu, which implies a 90 % probability of measuring a concentration ≤ 472 ppm in this lithostratigraphic unit (Figure 15). The 95 % CI of the 90th percentile is 415–569 ppm. In the Holocene alluvium, the PGB value of Cr lies between 364 and 531 ppm (CI: 443–592 ppm). In the Grand Conglomérat, it ranges from 275 to 410 ppm (CI: 367–523 ppm). Lower Kundelungu shows 261–423 ppm (CI: 388–508 ppm). The Katangian displays 261–383 ppm (CI: 326–

452 ppm), Mwashya & Roan 314–358 ppm (CI: 322–395 ppm), and the Cenozoic cover 561–734 ppm (CI: 561–761 ppm). In subsoil (25–50 cm), the PGB value of Cr generally decrease: Kundelungu 140–325 ppm (CI: 280–505 ppm); Holocene alluvium 188–354 ppm (CI: 326–388 ppm); Grand Conglomérat 138–322 ppm (CI: 278–458 ppm); Lower Kundelungu 149–294 ppm (CI: 197–320 ppm); Katangian 215–349 ppm (CI: 274–395 ppm); Mwashya & Roan 186–246 ppm (CI: 192–268 ppm); and Cenozoic cover 545–575 ppm (CI: 513–577 ppm).

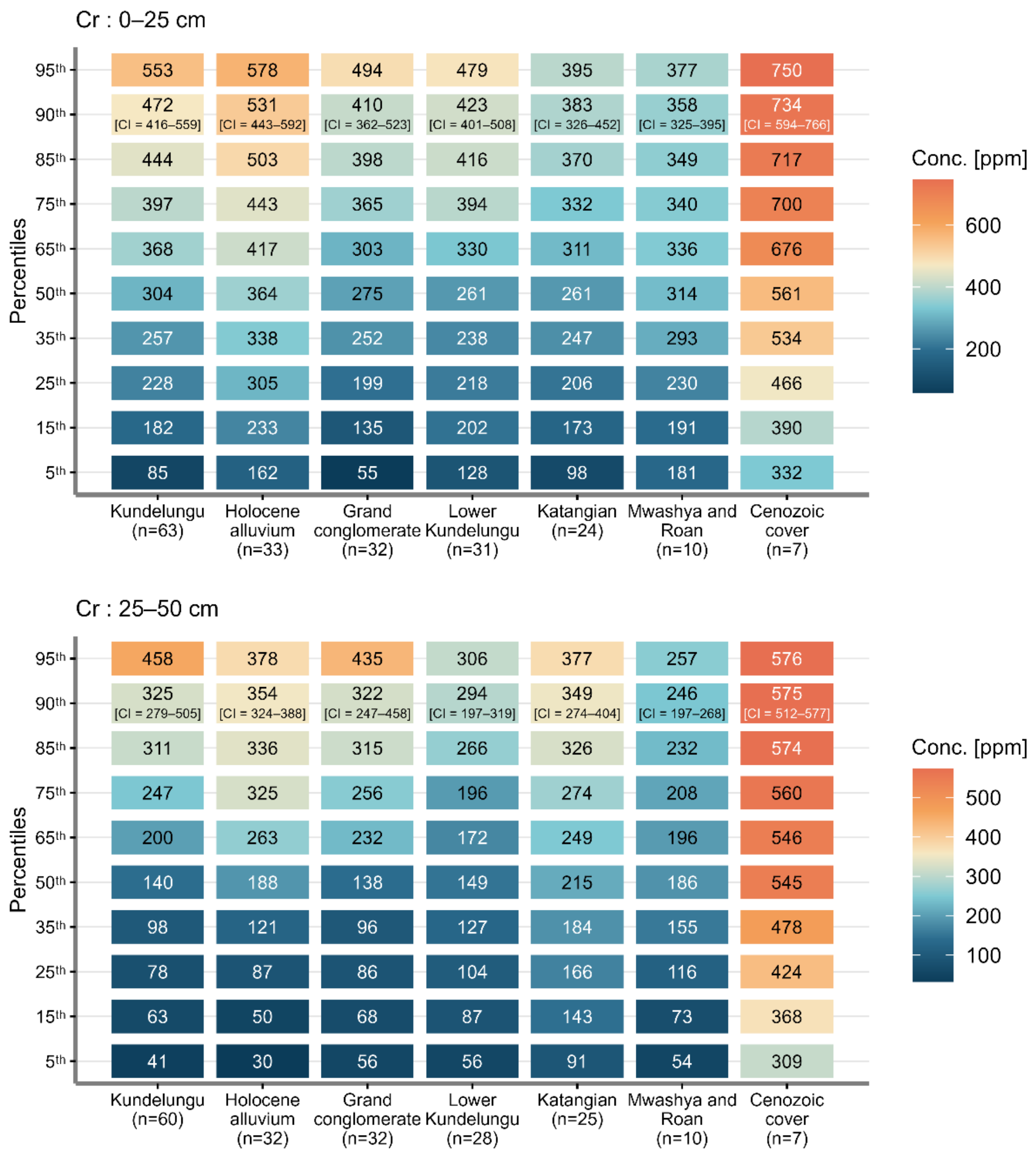

Figure 15. Pedo-geochemical background values of Cr at different depths and in different lithostratigraphic units. CI: 95 % confidence interval.

4.2.6 Pedo-geochemical background of copper

In topsoil (0–25 cm), the PGB value of Cu ranges between 31 ppm (50th percentile) and 114 ppm (90th percentile) in the Kundelungu, which implies a 90 % probability of measuring a concentration ≤ 114 ppm in this lithostratigraphic unit (Figure 16). The 95 % CI of the 90th percentile is 72–157 ppm. In the Holocene alluvium, the PGB value of Cu lies between 28 and 62 ppm (CI: 49–72 ppm).

In the Grand Conglomérat, it ranges from 36 to 81 ppm (CI: 60–123 ppm). Lower Kundelungu shows 48–88 ppm (CI: 67–125 ppm). The Katangian displays 61–101 ppm (CI: 83–142 ppm), Mwashya & Roan 24–87 ppm (CI: 31–90 ppm), and the Cenozoic cover 35–49 ppm (CI: 35–59 ppm). In subsoil (25–50 cm), the PGB value of Cu increases in most units: Kundelungu 31–134 ppm (CI: 62–173 ppm); Holocene alluvium 33–74 ppm (CI: 62–100 ppm); Grand Conglomérat 39–98 ppm (CI: 60–107 ppm); Lower Kundelungu 46–90 ppm (CI: 55–199 ppm); Katangian 61–110 ppm (CI: 83–134 ppm); Mwashya & Roan 26–94 ppm (CI: 35–116 ppm); and Cenozoic cover 28–61 ppm (CI: 36–80 ppm).

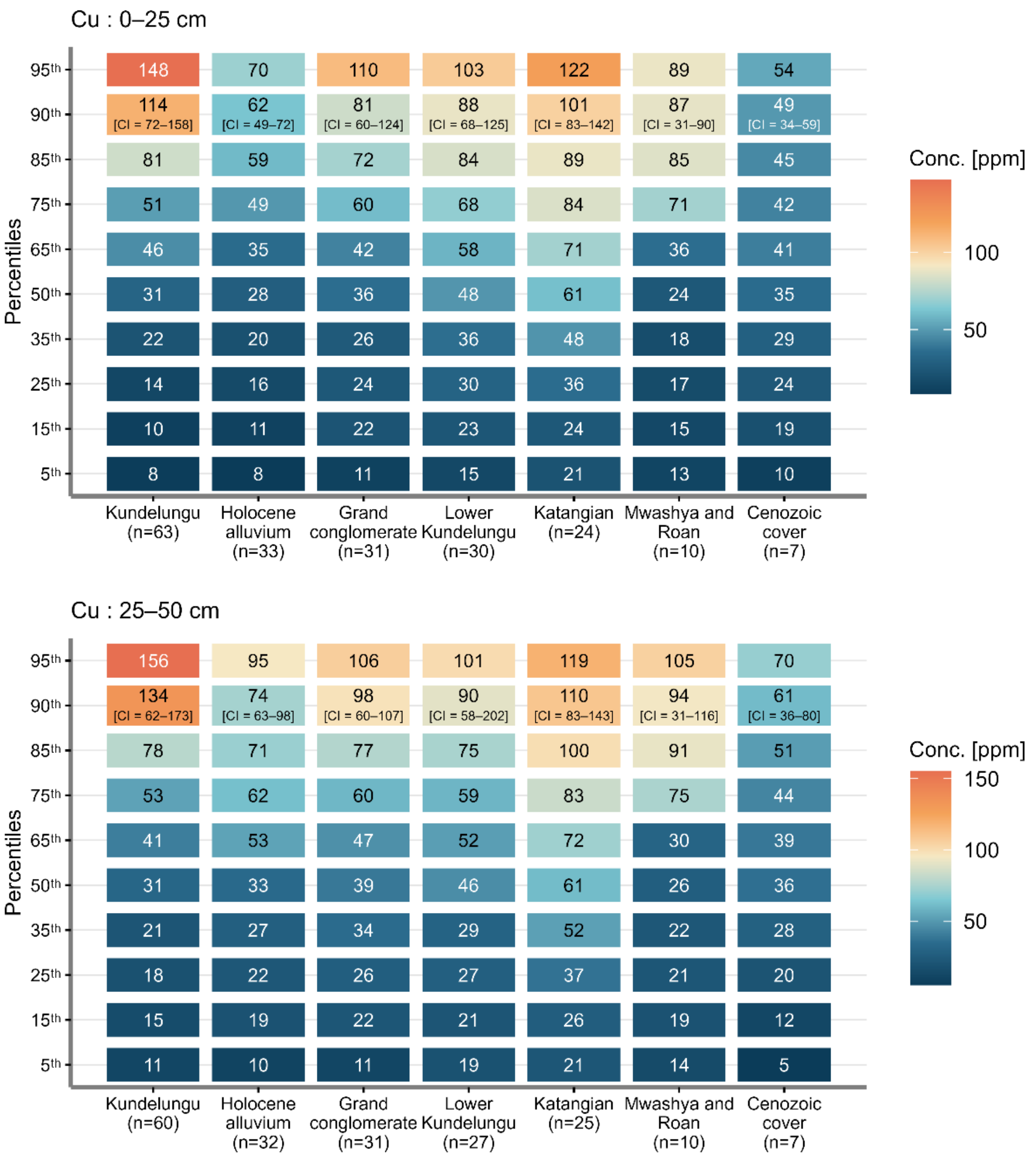

Figure 16. Pedo-geochemical background values of Cu at different depths and in different lithostratigraphic units. CI: 95 % confidence interval.

4.2.7 Pedo-geochemical background of manganese

In topsoil (0–25 cm), the PGB value of Mn ranges between 226 ppm (50th percentile) and 869 ppm (90th percentile) in the Kundelungu, which implies a 90 % probability of measuring a concentration

≤ 869 ppm in this lithostratigraphic unit (Figure 17). The 95 % CI of the 90th percentile is 568–1,020 ppm. In the Holocene alluvium, the PGB value of Mn lies between 137 and 556 ppm (CI: 443–711 ppm). In the Grand Conglomérat, 149–356 ppm (CI: 259–418 ppm). Lower Kundelungu shows 219–654 ppm (CI: 420–1,615 ppm). The Katangian displays 238–510 ppm (CI: 317–586 ppm), Mwashya & Roan 196–806 ppm (CI: 228–1,075 ppm), and the Cenozoic cover 95–123 ppm (CI: 100–141 ppm). In subsoil (25–50 cm), Mn behavior is contrasting between units: Kundelungu 216–940 ppm (CI: 469–1,250 ppm); Holocene alluvium 166–613 ppm (CI: 370–1,020 ppm); Grand Conglomérat 170–394 ppm (CI: 327–1,290 ppm); Lower Kundelungu 188–616 ppm (CI: 347–1,291 ppm); Katangian 220–452 ppm (CI: 371–505 ppm); Mwashya & Roan 215–450 ppm (CI: 238–1,485 ppm); and Cenozoic cover 117–225 ppm (CI: 117–254 ppm).

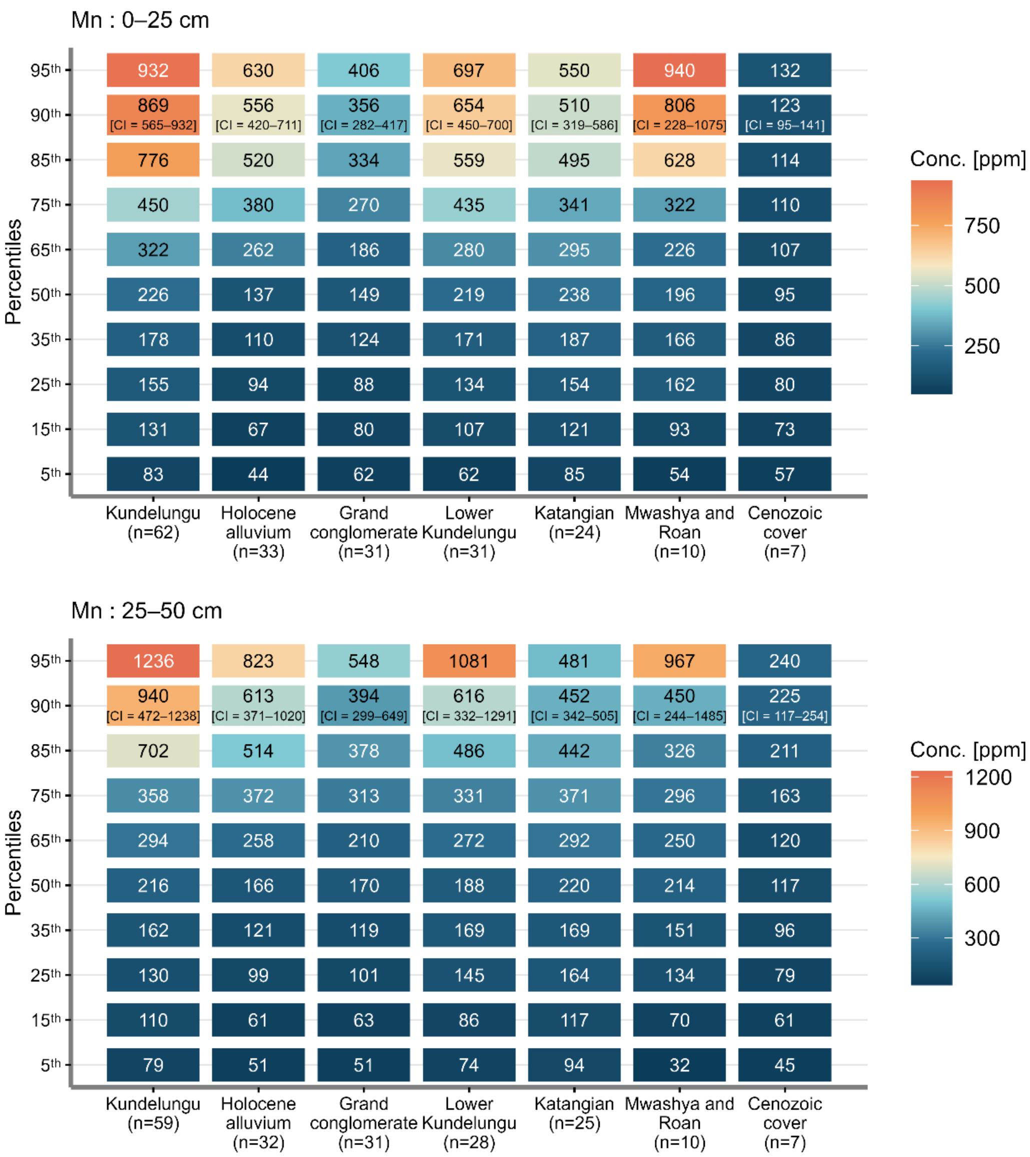

Figure 17. Pedo-geochemical background values of Mn at different depths and in different lithostratigraphic units. CI: 95 % confidence interval.

4.2.8 Pedo-geochemical background of molybdenum

In topsoil (0–25 cm), the PGB value of Mo ranges between 1 ppm (50th percentile) and 3 ppm (90th percentile) in the Kundelungu, which implies a 90 % probability of measuring a concentration ≤ 3 ppm in this lithostratigraphic unit (Figure 18). The 95 % CI of the 90th percentile is 3–4 ppm. In the Holocene alluvium, the PGB value of Mo lies between 1 and 2 ppm (CI: 2–3 ppm). In the Grand Conglomérat, 1–4 ppm (CI: 2–4 ppm). Lower Kundelungu shows 2–4 ppm (CI: 2–5 ppm). The Katangian displays 4–6 ppm (CI: 5–9 ppm), Mwashya & Roan 2–3 ppm (CI: 2–3 ppm), and the Cenozoic cover 1–4 ppm (CI: 1–5 ppm). In subsoil (25–50 cm), Mo values increase or widen slightly: Kundelungu 2–5 ppm (CI: 4–6 ppm); Holocene alluvium 2–5 ppm (CI: 3–5 ppm); Grand Conglomérat 2–5 ppm (CI: 4–6 ppm); Lower Kundelungu 2–5 ppm (CI: 4–5 ppm); Katangian 4–6 ppm (CI: 5–10 ppm); Mwashya & Roan 3–4 ppm (CI: 3–6 ppm); and Cenozoic cover 2–5 ppm (CI: 2–7 ppm).

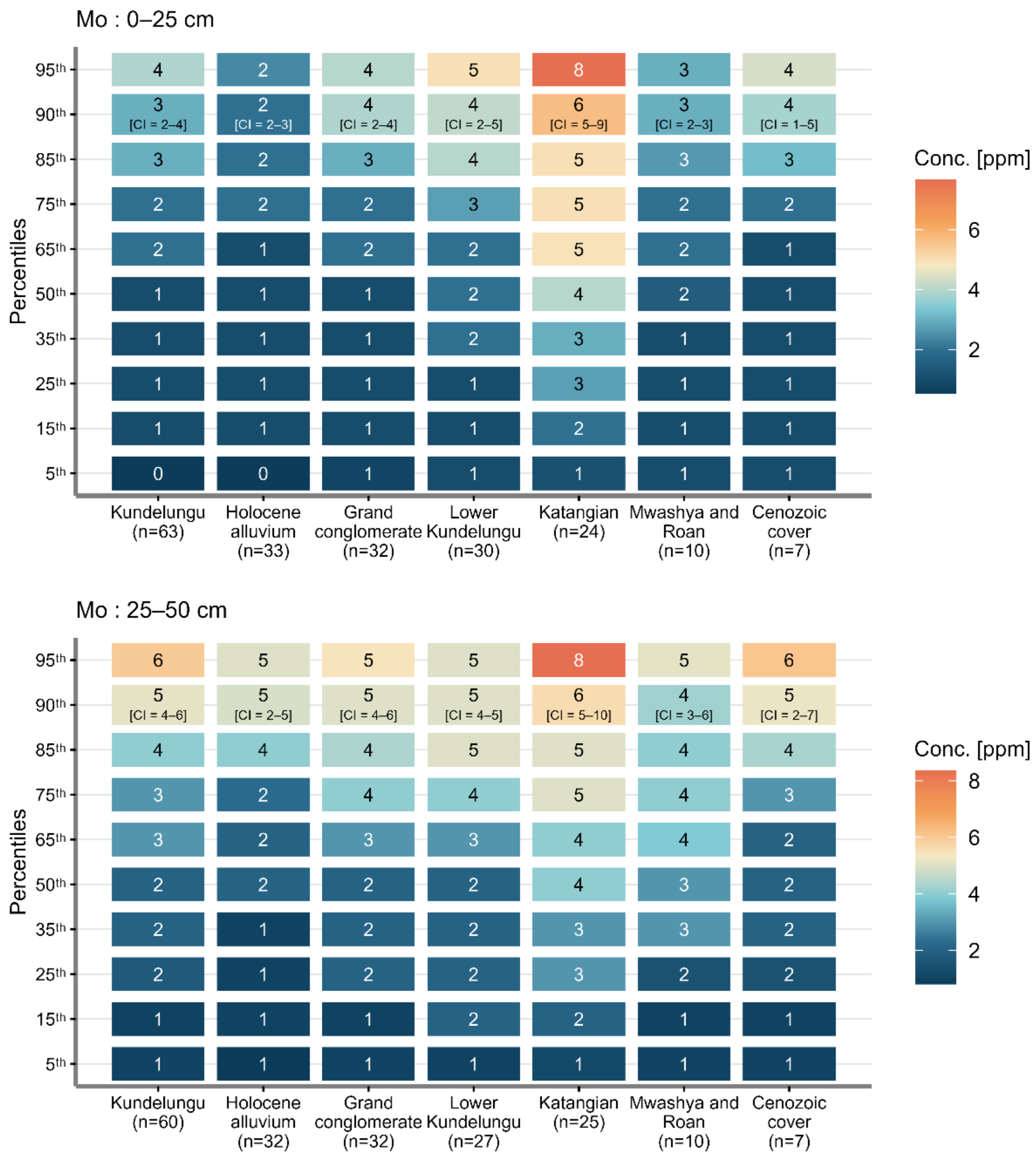

Figure 18. Pedo-geochemical background values of Mo at different depths and in different lithostratigraphic units. CI: 95 % confidence interval.

4.2.9 Pedo-geochemical background of nickel

In topsoil (0–25 cm), the PGB value of Ni ranges between 23 ppm (50th percentile) and 42 ppm (90th percentile) in the Kundelungu, which implies a 90 % probability of measuring a concentration ≤ 42 ppm in this lithostratigraphic unit (Figure 19). The 95 % CI of the 90th percentile is 35–52 ppm. In the Holocene alluvium, the PGB value of Ni lies between 17 and 34 ppm (CI: 26–36 ppm). In the Grand Conglomérat, 24–40 ppm (CI: 34–51 ppm). Lower Kundelungu shows 33–60 ppm (CI: 44–87 ppm). The Katangian displays 45–79 ppm (CI: 52–92 ppm), Mwashya & Roan 26–42 ppm (CI: 30–80 ppm), and the Cenozoic cover 15–19 ppm (CI: 15–19 ppm). In subsoil (25–50 cm), Ni values increase slightly in several units: Kundelungu 24–42 ppm (CI: 39–60 ppm); Holocene alluvium 22–40 ppm (CI: 33–47 ppm); Grand Conglomérat 28–40 ppm (CI: 38–62 ppm); Lower Kundelungu 40–63 ppm (CI: 48–85 ppm); Katangian 48–78 ppm (CI: 58–94 ppm); Mwashya & Roan 30–48 ppm (CI: 31–89 ppm); and Cenozoic cover 15–23 ppm (CI: 15–24 ppm).

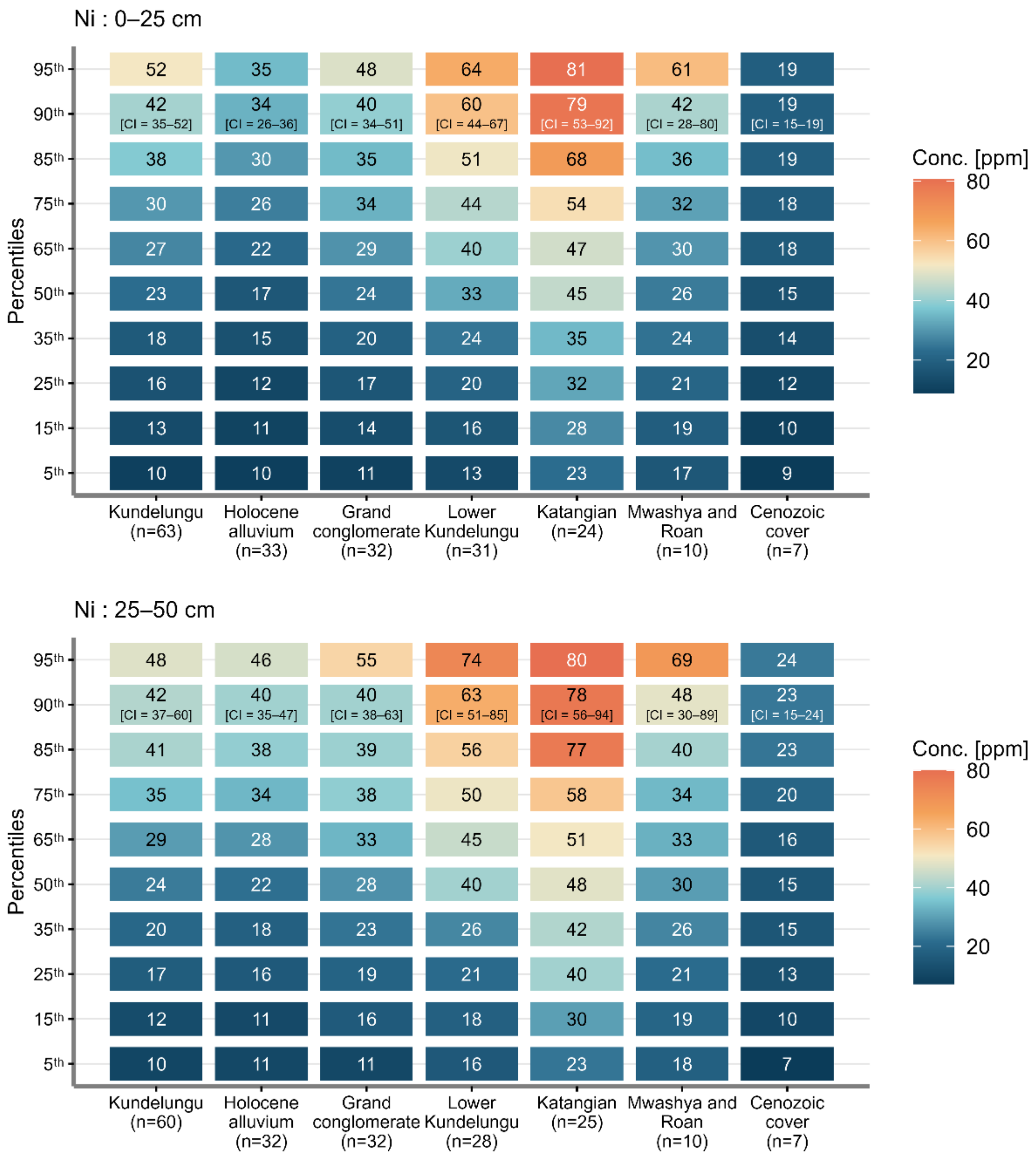

Figure 19. Pedo-geochemical background values of Ni at different depths and in different lithostratigraphic units. CI: 95 % confidence interval.

4.2.10 Pedo-geochemical background of lead

In topsoil (0–25 cm), the PGB value of Pb ranges between 11 ppm (50th percentile) and 20 ppm (90th percentile) in the Kundelungu, which implies a 90 % probability of measuring a concentration ≤ 20 ppm in this lithostratigraphic unit (Figure 20). The 95 % CI of the 90th percentile is 17–23 ppm. In the Holocene alluvium, the PGB value of Pb lies between 8 and 16 ppm (CI: 13–20 ppm). In the Grand Conglomérat, 8–18 ppm (CI: 12–20 ppm). Lower Kundelungu shows 8–21 ppm (CI: 14–30 ppm). The Katangian displays 7–17 ppm (CI: 12–32 ppm), Mwashya & Roan 8–16 ppm (CI: 9–23 ppm), and the Cenozoic cover 7–21 ppm (CI: 7–23 ppm). In subsoil (25–50 cm), Pb values evolve in a contrasting way: Kundelungu 10–21 ppm (CI: 18–25 ppm); Holocene alluvium 10–22 ppm (CI: 16–28 ppm); Grand Conglomérat 9–19 ppm (CI: 16–24 ppm); Lower Kundelungu 10–23 ppm (CI: 15–37 ppm); Katangian 5–15 ppm (CI: 11–34 ppm); Mwashya & Roan 9–17 ppm (CI: 11–20 ppm); and Cenozoic cover 11–29 ppm (CI: 9–36 ppm).

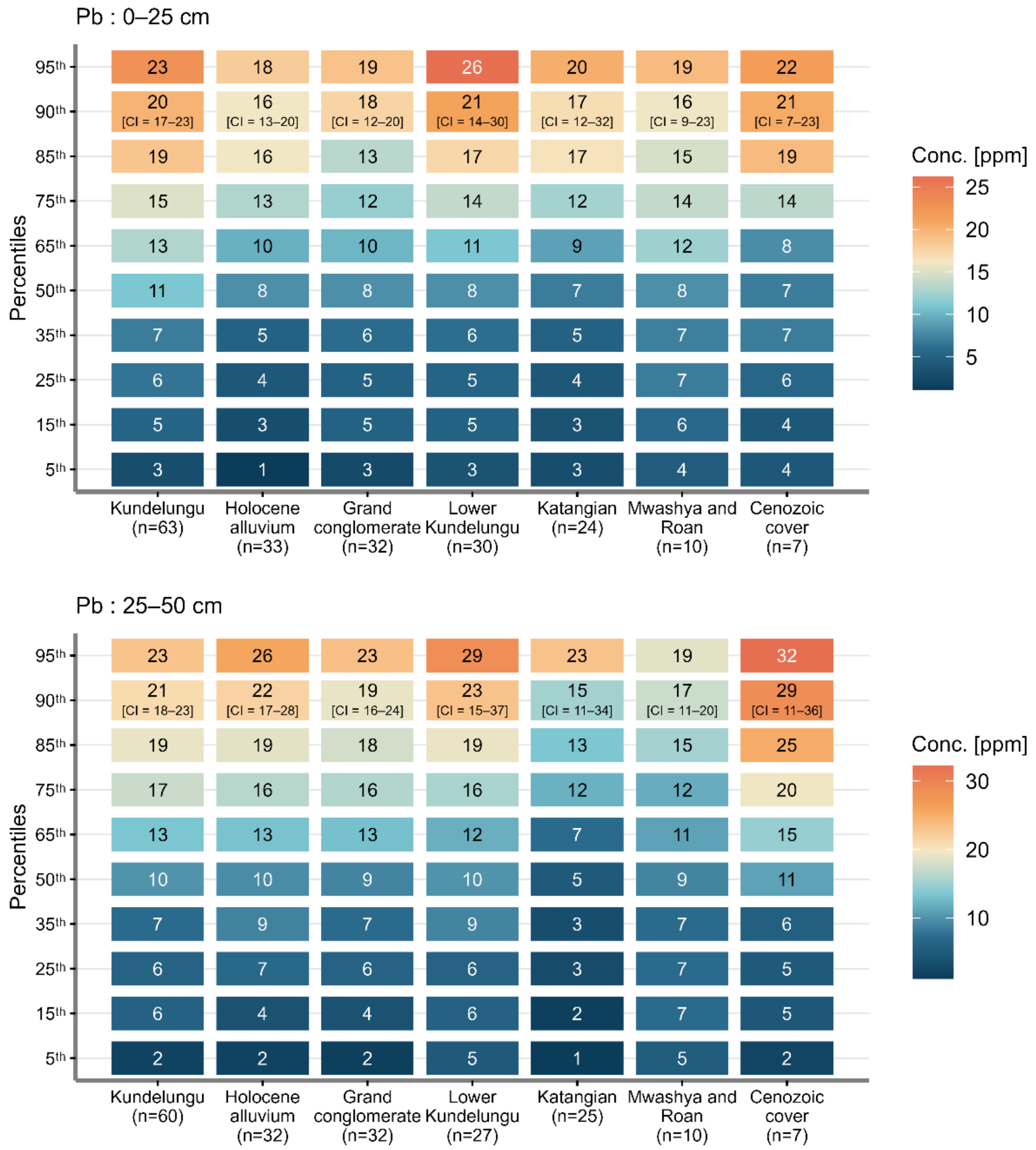

Figure 20. Pedo-geochemical background values of Pb at different depths and in different lithostratigraphic units. CI: 95 % confidence interval.

4.2.11 Pedo-geochemical background of strontium

In topsoil (0–25 cm), the PGB value of Sr ranges between 13 ppm (50th percentile) and 29 ppm (90th percentile) in the Kundelungu, which implies a 90 % probability of measuring a concentration ≤ 29 ppm in this lithostratigraphic unit (Figure 21). The 95 % CI of the 90th percentile is 22–34 ppm. In the Holocene alluvium, the PGB value of Sr lies between 9 and 35 ppm (CI: 16–40 ppm). In the Grand Conglomérat, 11–21 ppm (CI: 14–45 ppm). Lower Kundelungu shows 13–27 ppm (CI: 17–45 ppm). The Katangian displays 11–19 ppm (CI: 15–24 ppm), Mwashya & Roan 14–24 ppm (CI: 18–47 ppm), and the Cenozoic cover 9–20 ppm (CI: 9–31 ppm). In subsoil (25–50 cm), Sr values tend to narrow and shift downwards: Kundelungu 10–25 ppm (CI: 20–29 ppm); Holocene alluvium 9–26 ppm (CI: 14–37 ppm); Grand Conglomérat 10–22 ppm (CI: 12–38 ppm); Lower Kundelungu 10–24 ppm (CI: 17–32 ppm); Katangian 11–19 ppm (CI: 13–23 ppm); Mwashya & Roan 10–22 ppm (CI: 13–27 ppm); and Cenozoic cover 9–15 ppm (CI: 9–16 ppm).

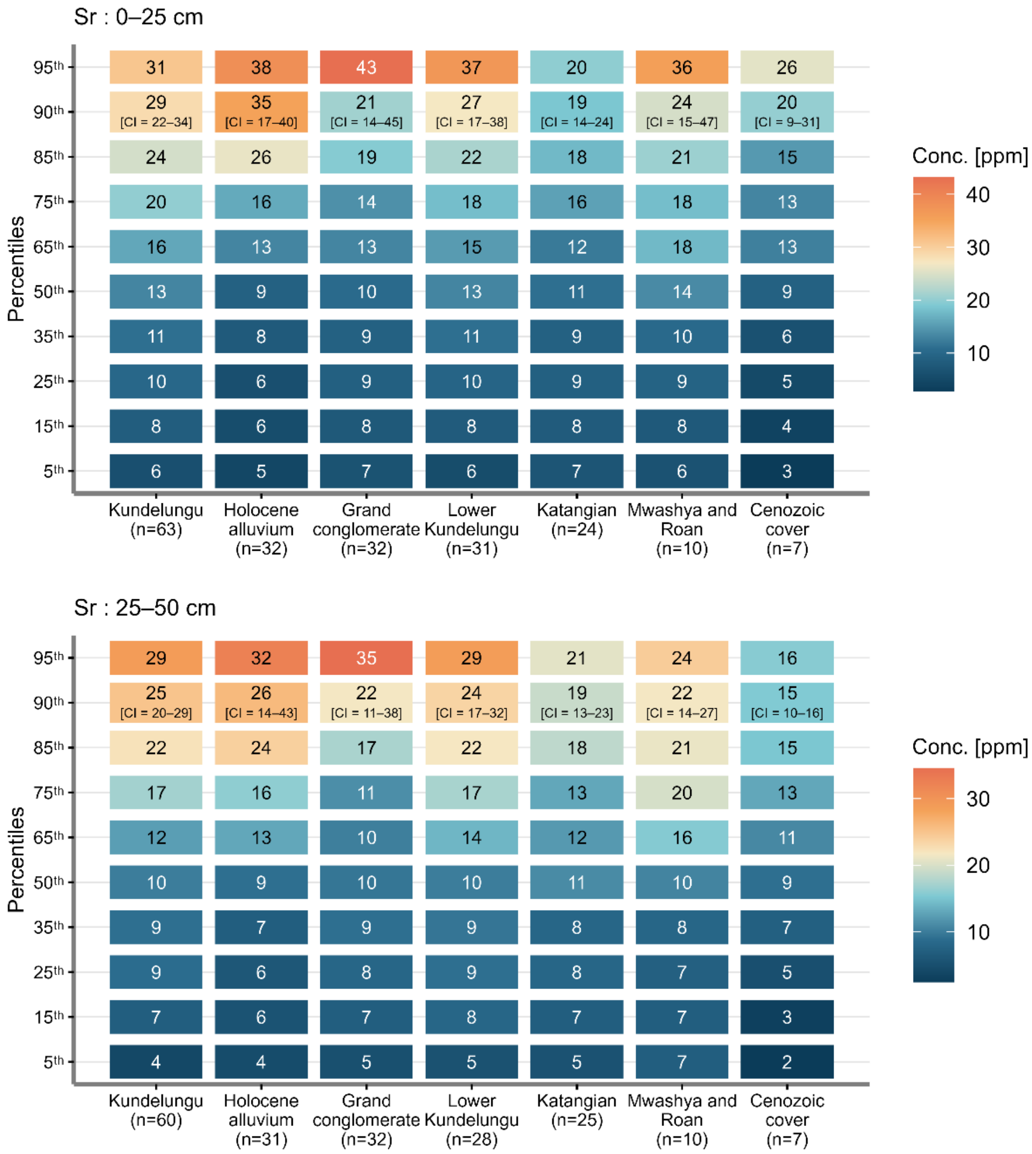

Figure 21. Pedo-geochemical background values of Sr at different depths and in different lithostratigraphic units. CI: 95 % confidence interval.

4.2.12 Pedo-geochemical background of vanadium

In topsoil (0–25 cm), the PGB value of V ranges between 120 ppm (50th percentile) and 189 ppm (90th percentile) in the Kundelungu, which implies a 90 % probability of measuring a concentration ≤ 189 ppm in this lithostratigraphic unit (Figure 22). The 95 % CI of the 90th percentile is 164–232 ppm. In the Holocene alluvium, the PGB value of V lies between 76 and 182 ppm (CI: 125–211 ppm). In the Grand Conglomérat, 119–213 ppm (CI: 154–289 ppm). Lower Kundelungu shows 173–262 ppm (CI: 231–269 ppm). The Katangian displays 244–372 ppm (CI: 283–390 ppm), Mwashya & Roan 134–236 ppm (CI: 146–348 ppm), and the Cenozoic cover 124–292 ppm (CI: 135–345 ppm). In subsoil (25–50 cm), V values increase in all units: Kundelungu 148–256 ppm (CI: 203–276 ppm);

Holocene alluvium 122–218 ppm (CI: 179–297 ppm); Grand Conglomérat 155–244 ppm (CI: 194–311 ppm); Lower Kundelungu 200–260 ppm (CI: 238–269 ppm); Katangian 280–382 ppm (CI: 322–401 ppm); Mwashya & Roan 162–307 ppm (CI: 200–388 ppm); and Cenozoic cover 204–415 ppm (CI: 233–488 ppm).

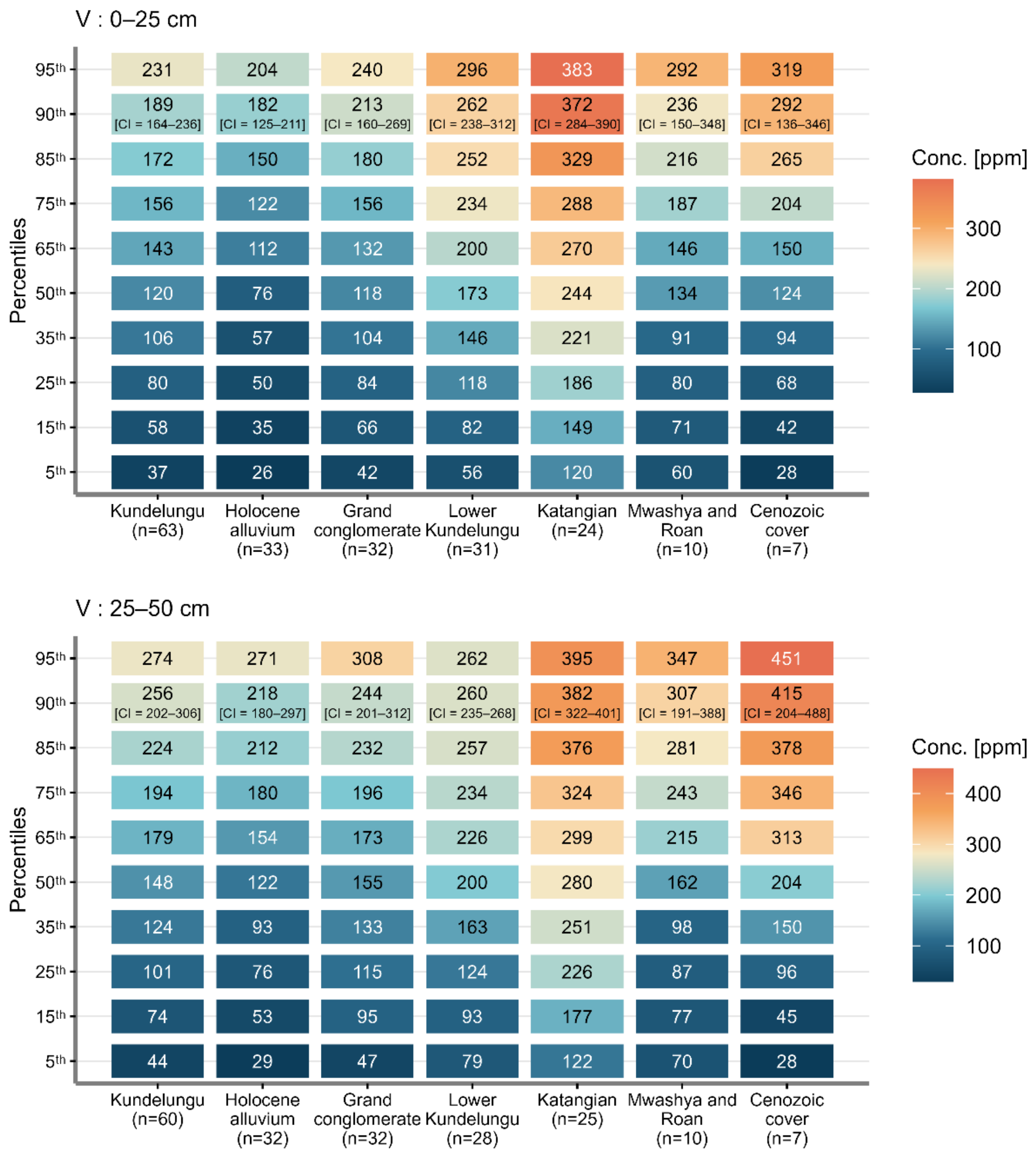

Figure 22. Pedo-geochemical background values of V at different depths and in different lithostratigraphic units. CI: 95 % confidence interval.

4.2.13 Pedo-geochemical background of zinc

In topsoil (0–25 cm), the PGB value of Zn ranges between 30 ppm (50th percentile) and 63 ppm (90th percentile) in the Kundelungu, which implies a 90 % probability of measuring a concentration ≤ 63 ppm in this lithostratigraphic unit (Figure 23). The 95 % CI of the 90th percentile is 47–72 ppm. In the Holocene alluvium, the PGB value of Zn lies between 19 and 38 ppm (CI: 29–69 ppm). In the Grand Conglomérat, 27–55 ppm (CI: 34–69 ppm); Lower Kundelungu shows 36–64 ppm (CI: 51–87 ppm); the Katangian displays 29–61 ppm (CI: 52–73 ppm); Mwashya & Roan 25–64 ppm (CI: 28–64 ppm); and the Cenozoic cover 15–19 ppm (CI: 15–22 ppm). In subsoil (25–50 cm), Zn values show a general upward trend: Kundelungu 29–65 ppm (CI: 44–86 ppm); Holocene alluvium 22–49 ppm (CI: 30–95 ppm); Grand Conglomérat 25–48 ppm (CI: 38–67 ppm); Lower Kundelungu 34–85 ppm (CI: 55–105 ppm); Katangian 31–66 ppm (CI: 55–73 ppm); Mwashya & Roan 24–68 ppm (CI: 32–79 ppm); and Cenozoic cover 13–20 ppm (CI: 15–25 ppm).

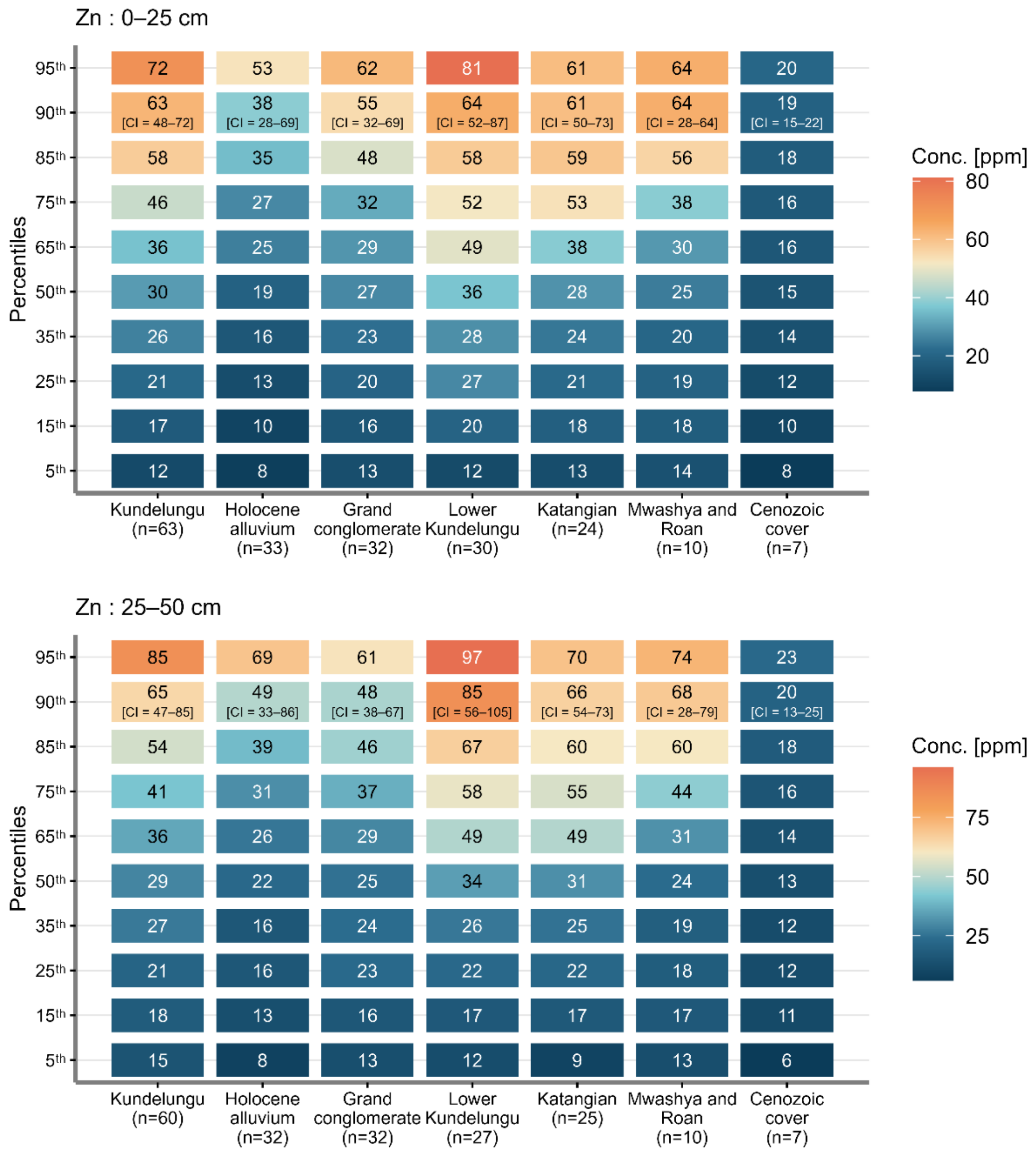

Figure 23. Pedo-geochemical background values of Zn at different depths and in different lithostratigraphic units. CI: 95 % confidence interval.

4.3 Spatial distribution of selected trace metals

The mapped values result from intra–lithostratigraphic-unit transferability (projection of measured P90 values to sectors of the same unit). Outside directly sampled areas, these values remain indicative and must be verified locally before any operational decision. This methodological caveat applies to all trace metals presented in the study. In the main text, we describe in detail the spatial distribution maps of Cu, Co, Pb and Zn. The spatial distribution maps of the other trace metals analyzed are presented in Annex 6.

4.3.1 Arsenic

In topsoil (0–25 cm), the vast majority of lithostratigraphic units show an upper limit of the PGB value (P90) between 25 and 35 ppm. In subsoil (25–50 cm), P90 values increase markedly and most of the territory shifts beyond 40 ppm, with a more homogeneous distribution (Figure 24).

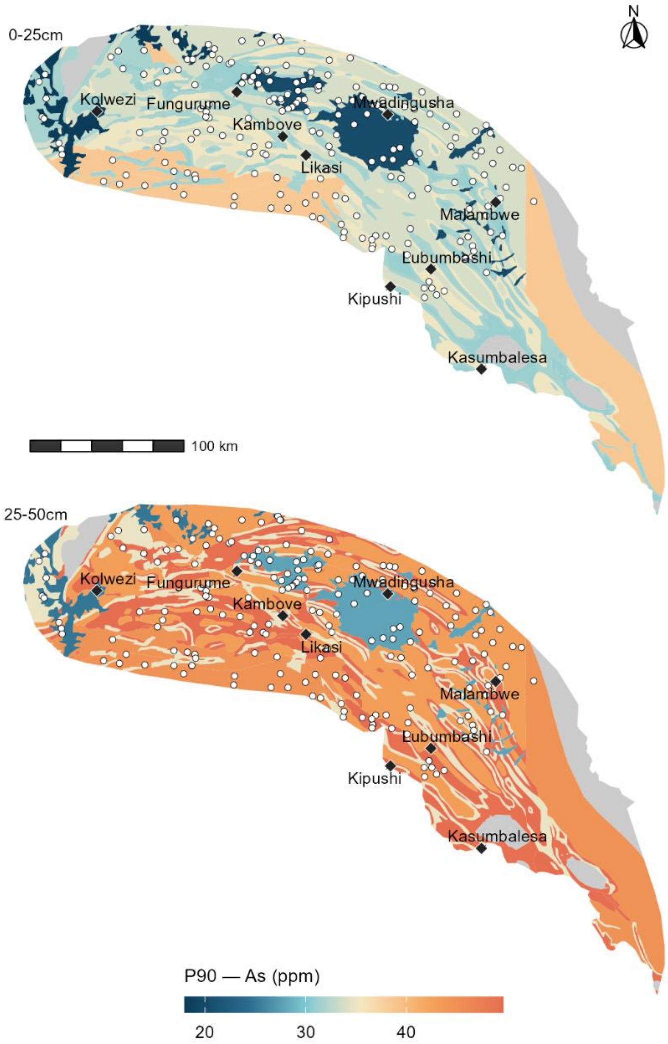

Figure 24. Spatial distribution of pedo-geochemical background (P90) values of As along the KCB. The grey area indicates lithostratigraphic units that were not sampled. The values shown in the unsampled area are indicative only.

4.3.2 Cobalt

In topsoil (0–25 cm), the vast majority of lithostratigraphic units show PGB values (P90) for Co between 20 and 30 ppm (Figure 28). In subsoil (25–50 cm), P90 values increase markedly: most units shift to a higher class, with values generally between 37 and 40 ppm, while the spatial structure remains broadly similar between the two horizons (Figure 25).

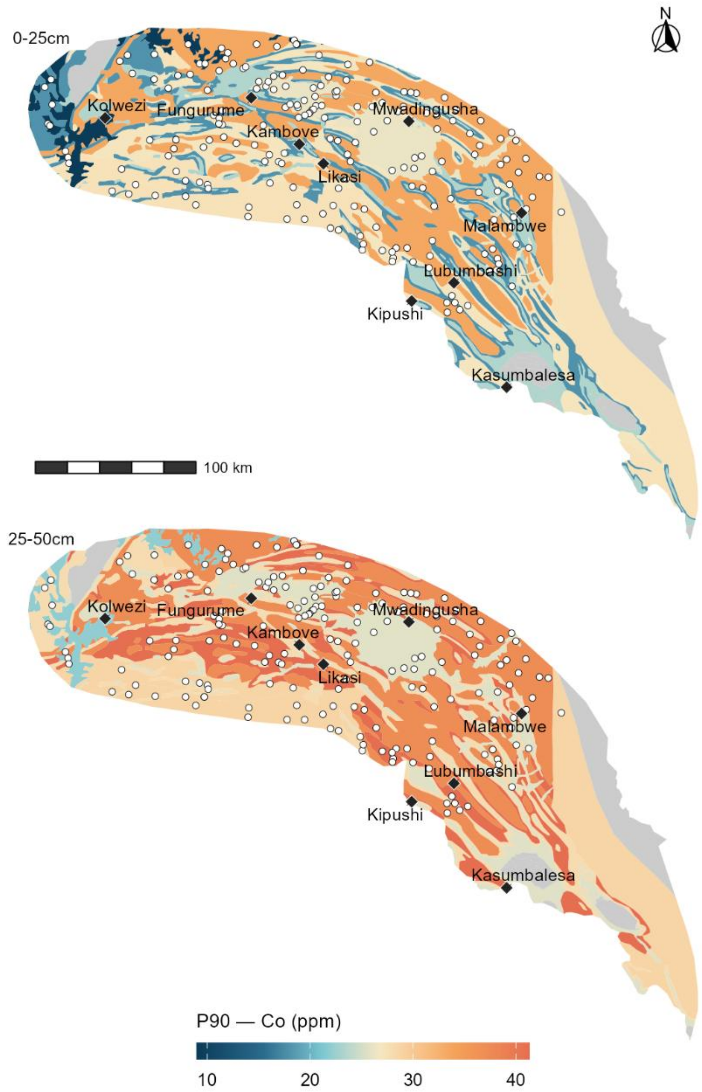

Figure 25. Spatial distribution of pedo-geochemical background (P90) values of Co along the KCB. The grey area indicates lithostratigraphic units that were not sampled. The values shown in the unsampled area are indicative only.

4.3.3 Copper

In topsoil (0–25 cm), the vast majority of lithostratigraphic units show an upper limit of the PGB value (P90) for Cu between 75 and 115 ppm. In subsoil (25–50 cm), P90 values increase markedly and most of the territory shifts beyond 120 ppm. The spatial distribution forms a wide band of high values following the Lubumbashi–Likasi–Kambove–Fungurume–Kolwezi axis, while the north, west and south-west of Kolwezi stand out with relatively lower P90 values, especially in the surface horizon (Figure 26).

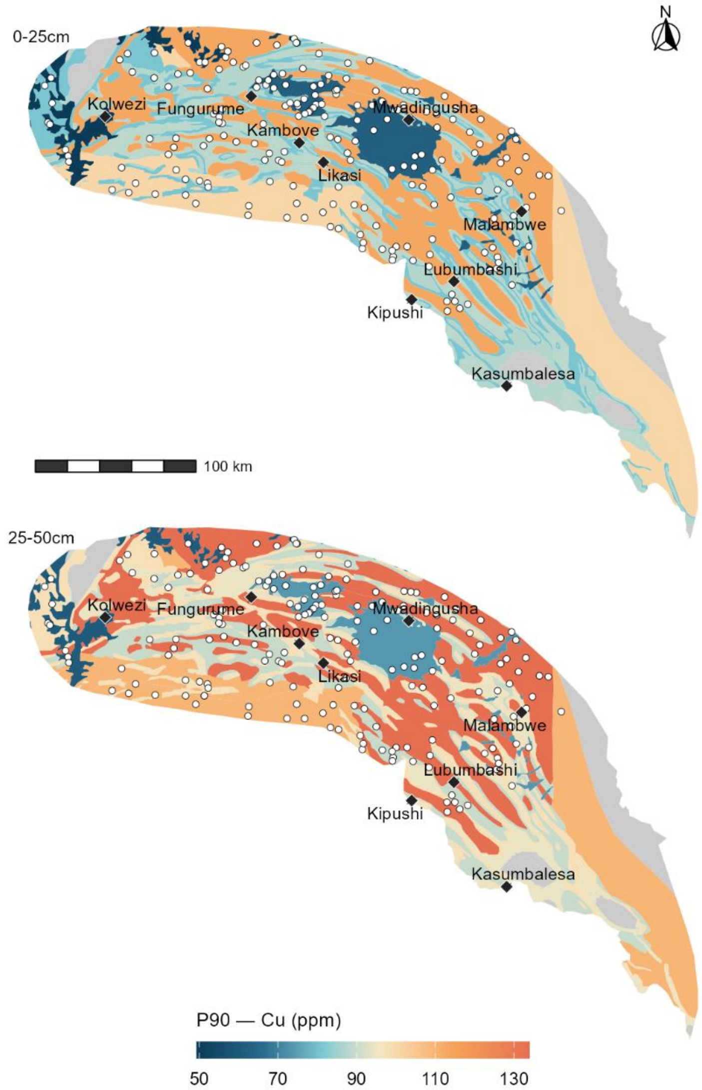

Figure 26. Spatial distribution of pedo-geochemical background (P90) values of Cu along the KCB. The grey area indicates lithostratigraphic units that were not sampled. The values shown in the unsampled area are indicative only.

4.3.4 Lead

In topsoil (0–25 cm), the vast majority of lithostratigraphic units show PGB values (P90) for Pb below 20 ppm, indicating a generally low background and moderate contrast at the scale of the KCB (Figure 27). No continuous belt of high contents appears: higher P90 values remain localized and are concentrated mainly to the north, south and west of Kolwezi, where they are more pronounced in subsoil (25–50 cm).

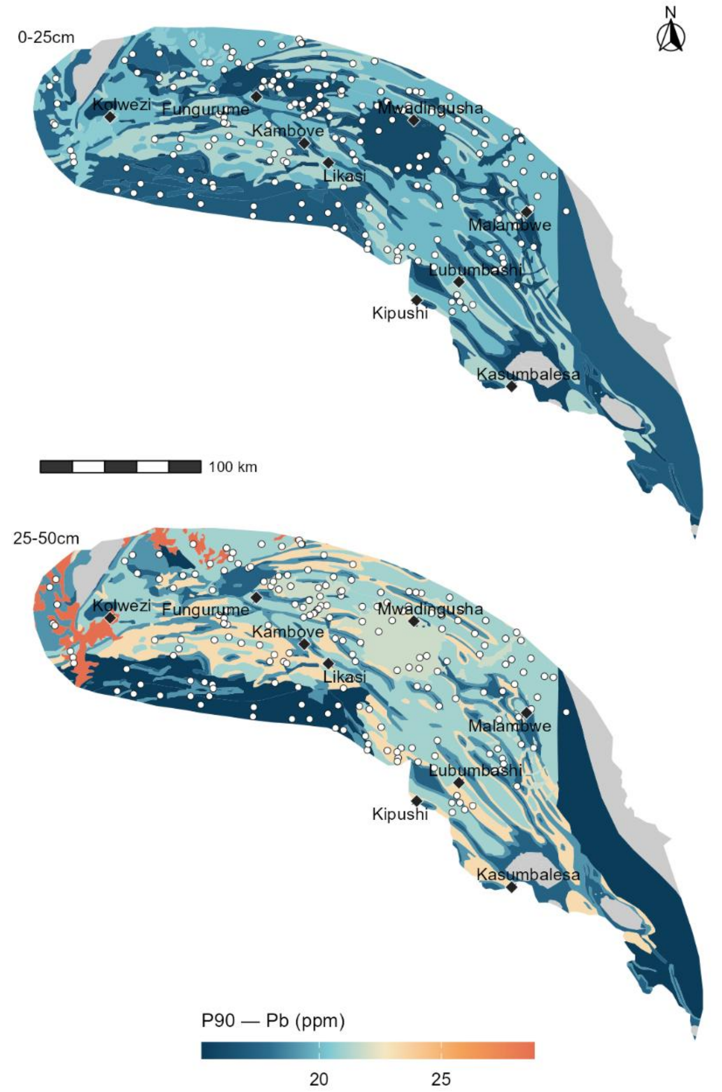

Figure 27. Spatial distribution of pedo-geochemical background (P90) values of Pb along the KCB. The grey area indicates lithostratigraphic units that were not sampled. The values shown in the unsampled area are indicative only.

4.4 Limits and uncertainties of the results

4.4.1 Intra–lithostratigraphic-unit heterogeneity

Estimating PGB values by lithostratigraphic unit implicitly assumes that each unit is a relatively homogeneous geological entity. In the KCB, this assumption is only partially valid. A single unit may include several rock facies with distinct mineralogical and geochemical signatures. The national lithostratigraphic map used for stratification is relatively coarse. PGB values derived at this scale may therefore mask local lithogeochemical contrasts. For example, the Mines Subgroup of the Roan—the main copper-bearing sequence in the region—includes alternating dolomites, dolomitic shales, siltstones and sandstones, sometimes with interbedded evaporites (Batumike et al., 2007; Cailteux et al., 2007). At finer scale, some of these sub-units could naturally exhibit PGB values substantially higher than the average values derived for the aggregated unit.

4.4.2 Limits of sampling and spatial transferability

In this study, some lithostratigraphic units with limited spatial extent (notably the Kibaran and pre-Kibaran) were not sampled. No PGB values are therefore available for these units. This is an explicit limitation and a gap to be addressed in future sampling campaigns.

Most lithostratigraphic units have sample sizes considered acceptable (25–62 samples), but Mwashya & Roan and the Cenozoic cover have only 10 and 7 samples, respectively. Sample size directly affects the reliability of PGB values, especially for high percentiles such as P90. Small sample numbers increase estimation variance, make percentiles more sensitive to extreme values and widen uncertainty intervals. PGB estimates for these two units must therefore be regarded as indicative only.

The choropleth maps produced (Figures 24–27) assign each lithostratigraphic unit an upper PGB limit (90th percentile) and project these values over all outcrops of the same unit, including unsampled areas. This extrapolation assumes geochemical continuity within each unit, an assumption that is only partly valid and subject to several sources of uncertainty. As a result, transferring trace-metal values from sampled units to similar unsampled sectors must be treated as strictly indicative. Extrapolated values in unsampled areas must not be interpreted as measurements, but as spatial approximations that help visualize regional trends. They are not a sufficient basis for site-specific environmental, industrial or regulatory decisions, for which targeted sampling remains necessary.

4.4.3 Spatial limits of application

The PGB values presented in this report apply only to the KCB and, more precisely, to the areas actually sampled. They cannot be directly transferred to other regions of the DRC or to areas that may show similar lithostratigraphic units, such as the Zambian Copperbelt.

In the absence of local data, these PGB values can be used as an exploratory frame of reference, for example to situate point measurements, support initial screening or inform dialogue among stakeholders. In such cases, the ranges between the 50th and 90th percentile, together with the 95 % CI of the 90th percentile, provide an order-of-magnitude context, but have no normative or regulatory status. They must not be used as the sole basis for operational or environmental decision-making.

5. Potential practical applications

5.1 Application in the industrial mining sector

The PGB values proposed here, defined by lithostratigraphic unit and by soil horizon (topsoil and subsoil), provide an operational framework for distinguishing natural variability from industrial inputs in the KCB. They describe the distribution of concentrations observed at sites that are not affected by identifiable point sources, and do not represent a single "clean" threshold. They must not be confused with health-based guideline values or regulatory thresholds (Reimann & Garrett, 2005).

In Environmental and Social Impact Assessments (ESIAs), the primary role of PGB values is to characterize baseline conditions. Soil-sampling campaigns should be designed and interpreted at the scale of the lithostratigraphic units present on site, and at depths relevant to exposure pathways and land use. When interpreting results, concentrations should ideally be compared with the P50–P90 range of the corresponding unit (together with the 95 % CI of P90), to position measured values relative to local natural variability and identify potential exceedances (Díez et al., 2009; Dung et al., 2013).

For screening and day-to-day soil management, any single result above P90 should be treated as an early warning signal rather than definitive evidence of contamination. Follow-up should include checking data and metadata (location, depth, land use) and, where necessary, targeted resampling and more detailed spatial analysis (Jiang et al., 2020). During operations, PGB values should be used to guide monitoring of soil chemistry around industrial facilities, waste-rock dumps, tailings storage facilities (TSFs) and other potential sources of contamination. Monitoring should be organized by lithostratigraphic unit, with a frequency proportional to risk, and applying a consistent methodology. When trace-metal concentrations remain stable within the P50–P90 range (including the 95 % CI of P90) and within the range of initial local baseline values, existing practices can generally be maintained. When exceedances recur, causal analysis is required to distinguish natural variability from inputs related to mining activities.

In geochemical exploration, using P90 (and its 95 % CI) as a reference helps to reduce false positives in units that are intrinsically enriched. Reliability can be further improved by combining this reference with graphical tools (Q–Q plots, box plots) and, where necessary, fractal approaches to separate background and anomalous populations (Cheng et al., 1994; Hawkes & Webb, 1962). For rehabilitation, closure and post-closure, PGB values can be used to define realistic performance criteria. Targets should be set by lithostratigraphic unit and by horizon, for example aiming for concentrations ≤ local P90 in the relevant surface horizons.

5.2 Application in the artisanal and small-scale mining sector

In the artisanal and small-scale mining (ASM) sector, PGB values can be used voluntarily as a tool to assess initial soil conditions in Artisanal Exploitation Zones (ZEAs) and associated sites (crushing/washing areas, waste-rock and tailings storage areas). The recommended approach is to interpret soil analyses by lithostratigraphic unit and soil horizon (topsoil / subsoil) as defined in this study. Individual measurements should be interpreted in relation to percentiles as described in Section 5.1. This is not a legal requirement of the Mining Code, but a methodological support consistent with good environmental practice and with the use of PGB values as contextual references in environmental risk assessment (Díez et al., 2009; Dung et al., 2013; Stelljes & Wood, 2003).

In a participatory monitoring context, cooperatives and, where appropriate, NGOs and local communities could, under the guidance of a technically competent institution (e.g. a university, accredited laboratory or consulting firm), establish networks of control points around ZEAs and related sites to track changes in trace-metal concentrations over time. In this framework, the main reference for monitoring should not be the regional PGB value, but a local baseline (measurements taken at the start of operations or before any significant activity) at the same points and using the same protocol. The PGB values for the KCB can then be used as contextual information to position this local baseline within regional natural variability, but they must not replace it (Díez et al., 2009; Dung et al., 2013). Any deterioration in soil chemical properties would be detected through a significant and repeated increase in concentrations relative to the local baseline, rather than from direct comparison with regional PGB values, which may in some cases be naturally higher than initial on-site concentrations.

5.3 Application by decision-makers

From a regulatory perspective, environmental quality management in the DRC is primarily governed by Framework Law No. 11/009 of 9 July 2011 on the fundamental principles of environmental protection. This law mandates the Ministry of Environment and Sustainable Development (MEDD), through the Congolese Environment Agency (ACE), to assess and approve ESIAs and monitor their implementation. In the mining sector, these provisions are complemented by the Mining Code (Law No. 007/2002, amended by Law No. 18/001 of 9 March 2018) and the Mining Regulations (Decree of 8 June 2018), which regulate ESIAs and Environmental and Social Management Plans (ESMPs) for mining projects under the joint supervision of the DPEM (Ministry of Mines) and ACE.

Within this institutional framework, PGB values can, on the one hand, provide MEDD and ACE with a practical basis for reviewing ESIAs and ESMPs for mining and industrial projects in the KCB, helping to distinguish soil trace-metal levels that remain within the PGB range described here from those suggesting additional anthropogenic inputs. On the other hand, PGB values can support the Ministry of Mines (DPEM) in interpreting environmental monitoring results for soil chemistry, improving identification of trace-metal concentrations of anthropogenic origin.

Similar approaches, where PGB values are explicitly used to differentiate natural levels from contamination, have already been implemented in several countries, for example in assessments of urban soils in Karachi (Pakistan) and mining valleys in China (Karim et al., 2015; Z. Li et al., 2019).

In the longer term, these PGB values could inform the development of soil-specific regulatory thresholds for the KCB in implementing texts (Mining Regulations, ministerial orders, technical guidelines), in line with the environmental framework law and national pollution-control strategies. In several jurisdictions, PGB values have been used for this purpose to derive regulatory "quality" or "target" values—as in the Netherlands, where maximum allowable concentrations were set taking natural background into account, or in the State of São Paulo (Brazil), where reference quality values for Cd in soil were established (Crommentuijn et al., 2000; De Oliveira et al., 2014; Mello et al., 2020).

5.4 Application in scientific research

Although the PGB values produced for the KCB do not in themselves constitute a tool for analyzing the physiological or toxicological responses of organisms, they provide a coherent reference framework for research (Díez et al., 2009; Dung et al., 2013; Stelljes & Wood, 2003). In particular, they can: (i) provide a geochemical baseline for selecting reference and enriched sites in ecotoxicological or phytoremediation studies; (ii) be used as a contextual explanatory variable in multivariate analyses combining soil composition, additional contamination and biological responses; and (iii) serve as a starting point for combining, in future work, information on total concentrations, speciation, bioavailability and biological effects, as has been done in various studies using PGB values to assess contamination and ecological risk in agricultural, urban or mining soils (Jiang et al., 2020; Karim et al., 2015; Z. Li et al., 2019; Tian et al., 2017). Their main contribution is to place biological observations within a better constrained geochemical landscape, avoiding interpreting as "anomalies" situations that actually reflect naturally elevated backgrounds, and vice versa.

5.5 Guidelines for using pedo-geochemical background values

5.5.1 Define the context and objectives

Before applying PGB values, users must clarify the intended context: environmental monitoring, impact assessment, scientific research or community support. It is also necessary to determine whether the objective is an initial assessment (baseline) or a compliance check (evolution of concentrations over time). This step includes delimiting the study area, identifying the lithostratigraphic units present and characterizing land uses (agricultural, industrial, natural).

5.5.2 Select the appropriate reference value

The user should first identify the lithostratigraphic unit corresponding to the site, then select the P50–P90 reference range (with the 95 % CI for P90) that characterizes the natural variability of that unit.

5.5.3 Design and implement the sampling plan

Soil sampling must be representative of internal variability within the study area. Obvious point sources (dumps, effluents, busy roads, buildings) should be avoided so as not to bias comparisons. Sampling depth must match the available PGB horizons (topsoil and/or subsoil). Each point should be georeferenced and described (soil type, texture, drainage, vegetation cover). Composite samples must be collected and analyzed for the same trace metals and using analytical protocols that are compatible with those used to establish the reference dataset.

5.5.4 Interpret results against the pedo-geochemical background values

Measured concentrations are compared with the P50–P90 range (with the 95 % CI on P90) of the reference. If the values fall within this range, they are interpreted as reflecting normal variability. If they exceed P90, this is an early warning signal that justifies data verification and possibly targeted resampling.

It is important to note that the PGB values presented in this study were established using four-acid digestion (HF–HNO_3–$HClO_4$ + HCl) followed by ICP-OES measurement (Figure 28). This method is used to measure the near-total content of trace metals, including the fraction trapped in silicates (U.S. EPA, 1996). In many field contexts, available analyses may instead be X-ray fluorescence (XRF) or aqua regia extraction. Aqua regia mainly targets oxidizable and carbonate phases and organic matter, without dissolving silicates, whereas XRF provides an apparent elemental estimate that is sensitive to grain size, moisture and mineralogy. Their results are therefore not directly comparable with a reference based on the four-acid method (ADEME, 2018; ISO 19258, 2018).

To make effective use of the reference established in this study when only XRF or aqua regia data are available, it is essential to state clearly in any report the method and fraction analyzed, and then to interpret results primarily in terms of relative trends (between sites, over time, between horizons) rather than absolute values. When one wishes to position results relative to the P50–P90 range (with the 95 % CI on P90), this range can be considered as a conservative upper bound for elements that are generally well extracted by aqua regia (e.g. Cu, Zn, Pb, Mn). In contrast, for elements that are largely hosted in silicates (e.g. Cr, Ni, V, sometimes Co), caution is required: in the absence of a local conversion factor, a direct comparison would be misleading. The most robust approach is, whenever possible, to analyze a small subset of samples in parallel by XRF or aqua regia and by the four-acid method, in order to establish empirical, element-specific conversion relationships.

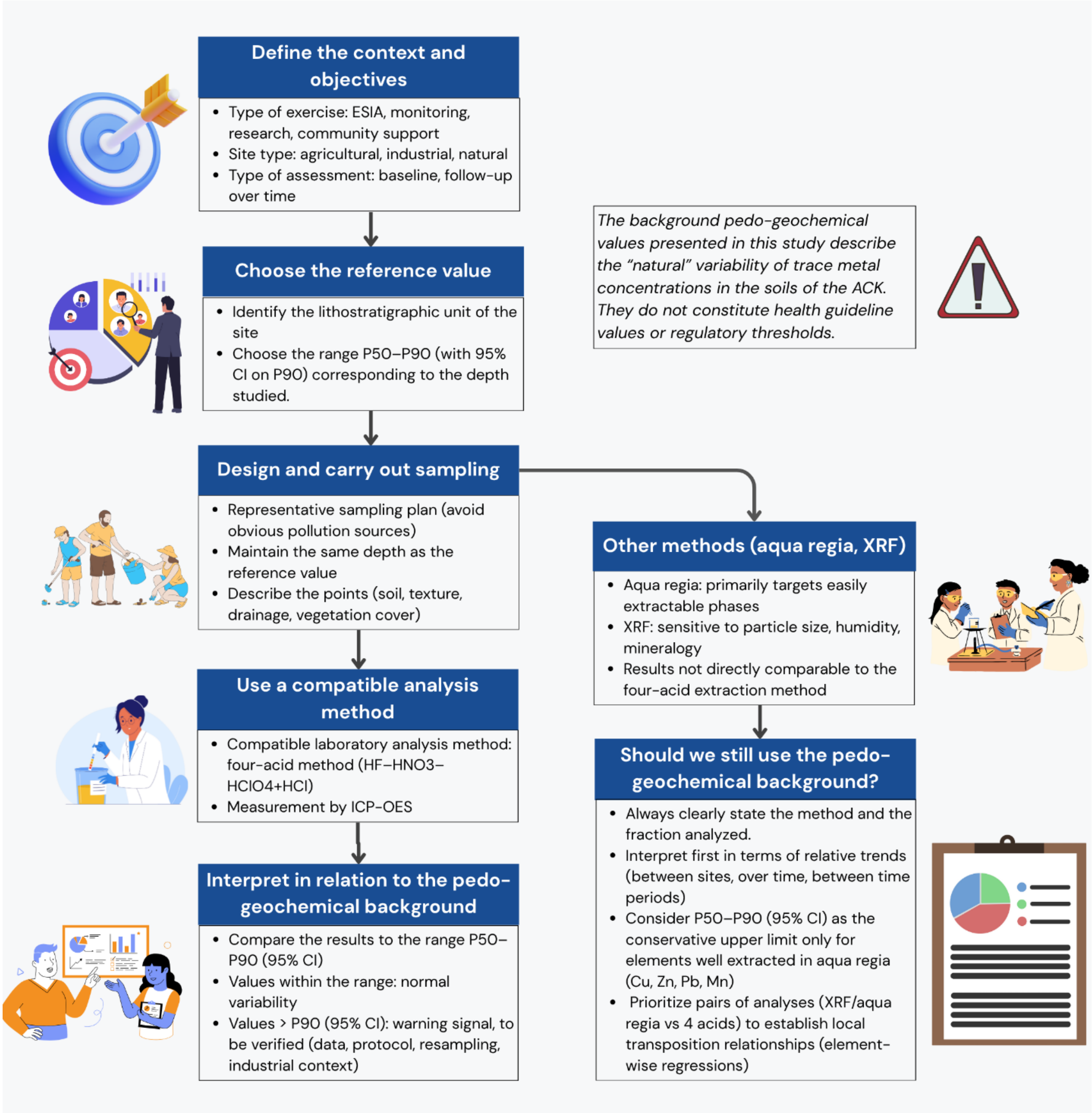

Figure 28. Schematic summary of recommended practices for using pedo-geochemical background values.

6. Conclusions and perspectives

6.1 Main contributions of the study

This study provides the Katangan Copperbelt (KCB) with a practical pedo-geochemical reference framework. Using a representative sampling design and a harmonized protocol, we characterized two soil horizons (topsoil and subsoil) and defined, for each lithostratigraphic unit, PGB values expressed as 50th percentile (median) and 90th percentile, with 95 % confidence intervals, in a format directly usable by decision-makers and practitioners.

Conceptually, the study clarifies key definitions—distinguishing clearly between geochemical background and pedo-geochemical background, and between "background value" and "background concentration"—to reduce common ambiguities. Another major contribution lies in the description and classification of soils across the KCB. By organizing soils into a coherent typology, the study highlights the region's pedological diversity and provides a common basis for future modeling and interpretation of PGB values.

Finally, this work is accompanied by an interactive map (https://doi.org/10.17632/ds3582v368.1) that brings together all results. Users can select the trace metal of interest (e.g. Cu, Co) and the soil horizon (topsoil: 0–25 cm; subsoil: 25–50 cm), access summary statistics (50th and 90th percentiles, mean, standard deviation, coefficient of variation) and display spatial distribution maps for the KCB. The interface allows users to query a point by GPS coordinates and view the PGB values and other statistics of the lithostratigraphic unit in which that point lies. It also supports map export for direct inclusion in reports. Available in French, English and German, this interactive map improves accessibility and uptake by stakeholders.

6.2 Recommendations

Building on this study, several priority directions emerge:

- Fill gaps in lithostratigraphic coverage by sampling units not yet documented (Kibaran and pre-Kibaran) and increasing sampling density in less well-represented units (Mwashya, Roan, Cenozoic cover), in order to narrow uncertainty around P90 and refine maps.
- Conduct finer-scale studies in selected parts of the KCB, focusing on lithologically more homogeneous zones and higher sampling density. Such local work would help identify subsets that are naturally more enriched in trace metals and define PGB values that may be higher than the regional trends currently observed along the KCB.
- Generate paired measurements using four-acid digestion, aqua regia and XRF to develop local, element-specific conversion models, facilitating use of the reference dataset in contexts where XRF or aqua regia are the main analytical methods.
- Extend the approach geographically, first to the portion of the KCB not yet covered (between Sakania and Lubumbashi) and, more broadly, progressively to the national scale.

Priority areas would include not only zones of intense mining activity but also other industrial areas and major transport corridors (for example along the future Lobito railway and other key routes), in order to document reference conditions before traffic and industrial pressure increase.

- Create a working group or expert network dedicated to background values, bringing together institutions from the DRC and, where appropriate, neighboring countries facing similar mining and industrial challenges (e.g. Zambia). This network would aim to share experience on methods for determining background values, their applications, and best practices for communicating them to decision-makers and operators.
- Initiate a formal regulatory process in the DRC, led by the competent national authorities (e.g. MEDD/ACE and the Ministry of Mines/DPEM), to integrate PGB values into the regulatory framework. This could include establishing a national expert group tasked with issuing technical opinions and proposing regulatory thresholds for soil chemistry (reference values, guideline values, alert values) to be incorporated into legal instruments such as the Mining Regulations.

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8. Annexes

8.1 Annex 1 : Sampling point description form

KILIMANJARO GENERAL SERVICES Sarl
Your Sustainability Partner

FICHE DESCRIPTIVE

Code de l'échantillon :

I. Informations de base

1. Date : ……………………………………………………………………………………………………

2. Chercheurs ………………………………………………………………………………………………

3. Axes (village/ville) ………………………………………………………………………………………

4. Photo de la parcelle a été prise : ☐ Oui ☐ Non

5. S'agit-il du point initialement prévu ou un point initialement prévu ? ☐ Initialement prévu ☐ Alternatif

Si alternatif, raisons de changement du point :

………

………

II. Informations sur la parcelle d'échantillonnage

1. Coordonnées GPS et altitude : …………………………………………………………………………

2. Pente (%) : ………………………………………………………………………………………………

3. Position topographique : ☐ Plateau ☐ Pente ☐ Bas-fond (Vallée)

4. Type d'utilisation de terre : ……………………………………………………………………………

5. Pour champs agricoles (paysans uniquement) : Utilisation d'engrais minéraux et ou pesticides ☐ Oui ☐ Non ; Utilisation d'amendement organique : ☐ Oui ☐ Non ; Champs planté au moment de l'échantillonnage ☐ Oui ☐ Non ; Culture mise en place…………………………………………………

6. Signes d'anthropisation visibles ☐ Oui ☐ Non. Si oui, lesquels :

………

………

7. Présence d'affleurement rocher : ☐ Oui ☐ Non

8. Signes d'érosion : ☐ Oui ☐ Non

9. Autres commentaires (caractéristiques supplémentaires visibles dans la parcelle d'échantillonnage) :

....

....

....

....

....

....

III. Informations sur les points d'échantillonnage

1. Profondeurs échantillonnées : ☐ 0-25 cm ☐ 25-50 cm ☐ Autre (commentez) :

....

....

2. Nombre des sous-échantillons : ☐ Quatre ☐ Autre (commentez) :

....

....

3. Couleur de l'échantillon : ....

4. Texture du sol : ....

5. Odeur de sol (Présence d'odeurs éventuelles qui pourraient indiquer une contamination) :

....

....

6. Condition d'humidité : ....

....

....

8.2 Annex 2: Quality assurance and quality control (QA/QC)

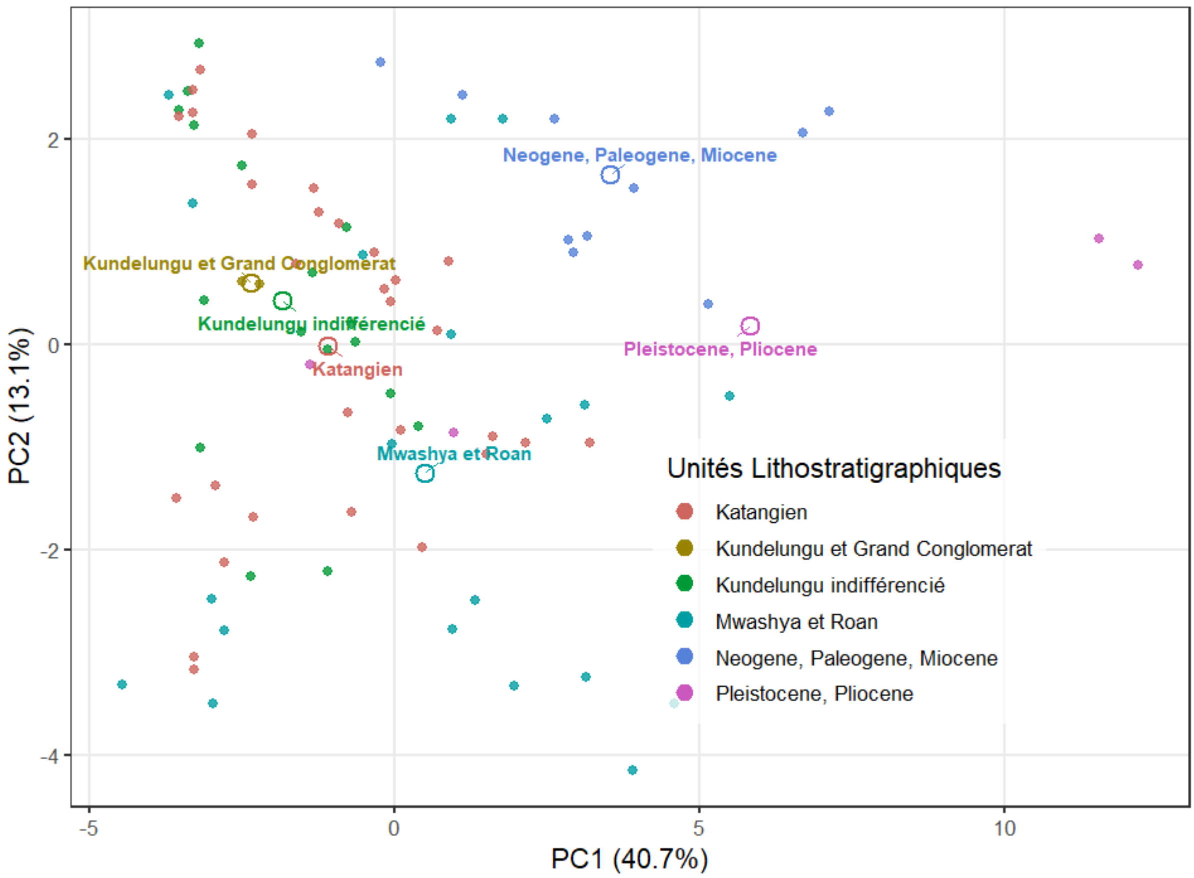
From field to laboratory, all soil samples were individually labelled (unique code, date, depth, GPS coordinates), recorded on field forms and in the database. Sampling equipment (augers, trays, knives) was systematically cleaned between sites or between horizons to minimize the risk of cross-contamination. Samples were pre-treated in accordance with ISO 11464 (air-drying at ≤ 40 °C, sieving to 2 mm, homogenization by quartering) before shipment and/or analysis.

For the trace metals analyzed at the COAL laboratory, quality control followed the ALS protocol (formerly Australian Laboratory Services) for ICP-OES methods: each analytical batch includes blanks, certified reference materials (CRMs) and duplicates, inserted according to the rack format (40 positions), routinely with two standards, one duplicate and one blank per sequence of approximately 40 samples. Sample-preparation performance (crushing, homogenization) is also monitored through particle-size specifications (for example > 70 % < 2 mm after crushing and > 85 % < 75 µm after milling), whose results are regularly compiled and reviewed during quality meetings. CRM and duplicate results are used to check accuracy and repeatability; any drift leads to instrument recalibration and, if necessary, re-analysis of a batch of samples.

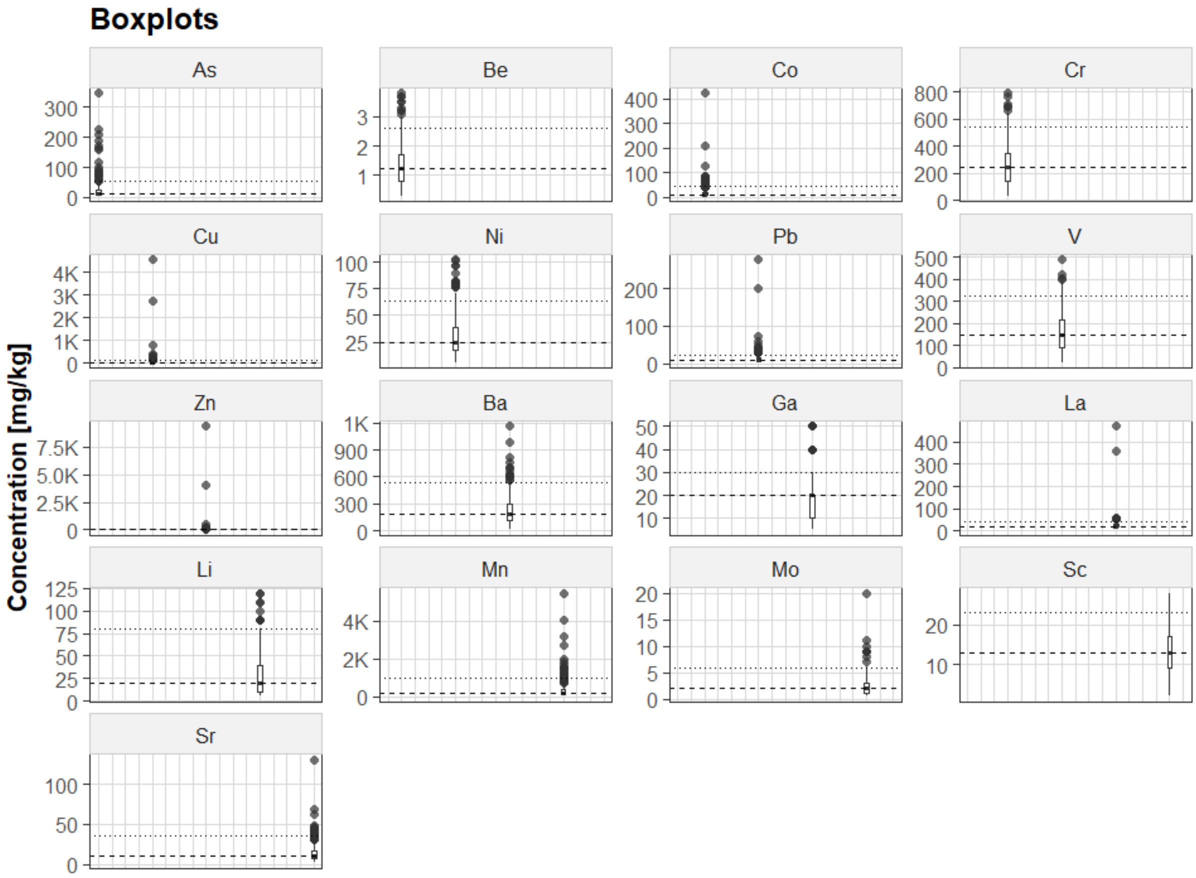
In addition to these internal laboratory controls, a blind-duplicate strategy was implemented at project level. A carefully homogenized soil sample was used as a control sample and inserted blindly into the batches sent to COAL, with one duplicate approximately every 25 samples. The results obtained for these duplicates were compared with those of the corresponding samples by calculating the relative error (or relative difference), with an acceptance threshold set at 15 % per element.

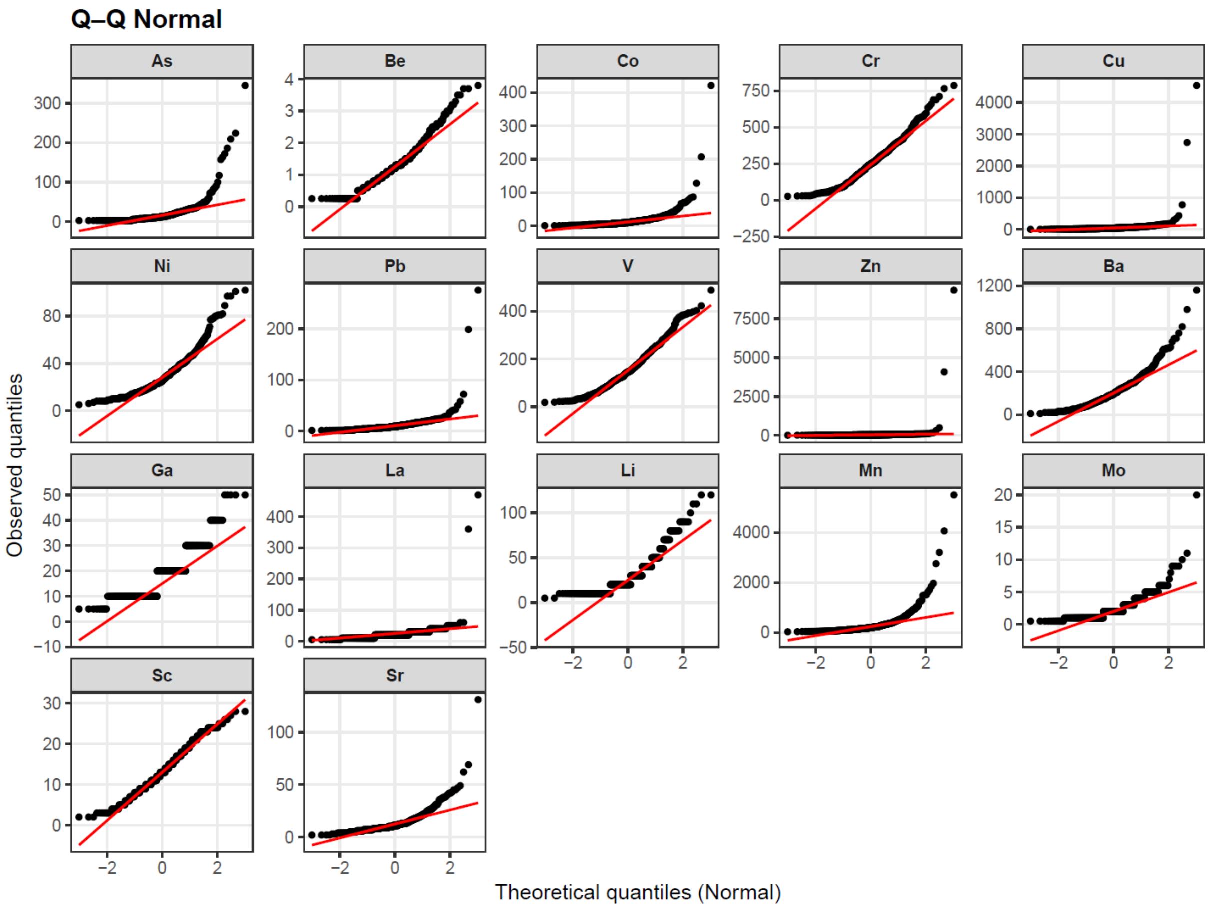
For the physico-chemical analyzes carried out at LAP-UNILU, a formal QA/QC procedure was implemented for the batch of soil-profile samples. It provides in particular for: 5 % reagent blanks to monitor cross-contamination, 10 % laboratory duplicates to assess repeatability, and 5 % certified reference materials (for pH) covering the range of measured values. Target criteria for relative differences are ≤ 0.05 pH unit, ≤ 10 % for CEC and ≤ 15 % for particle-size fractions, with adjustment and/or re-analysis of samples in the event of exceedance. The pH meter is calibrated daily with several buffers (≈ pH 4, 7 and 9–10), and each block of around 25 samples includes one blank and two CRMs (acidic and alkaline pH).

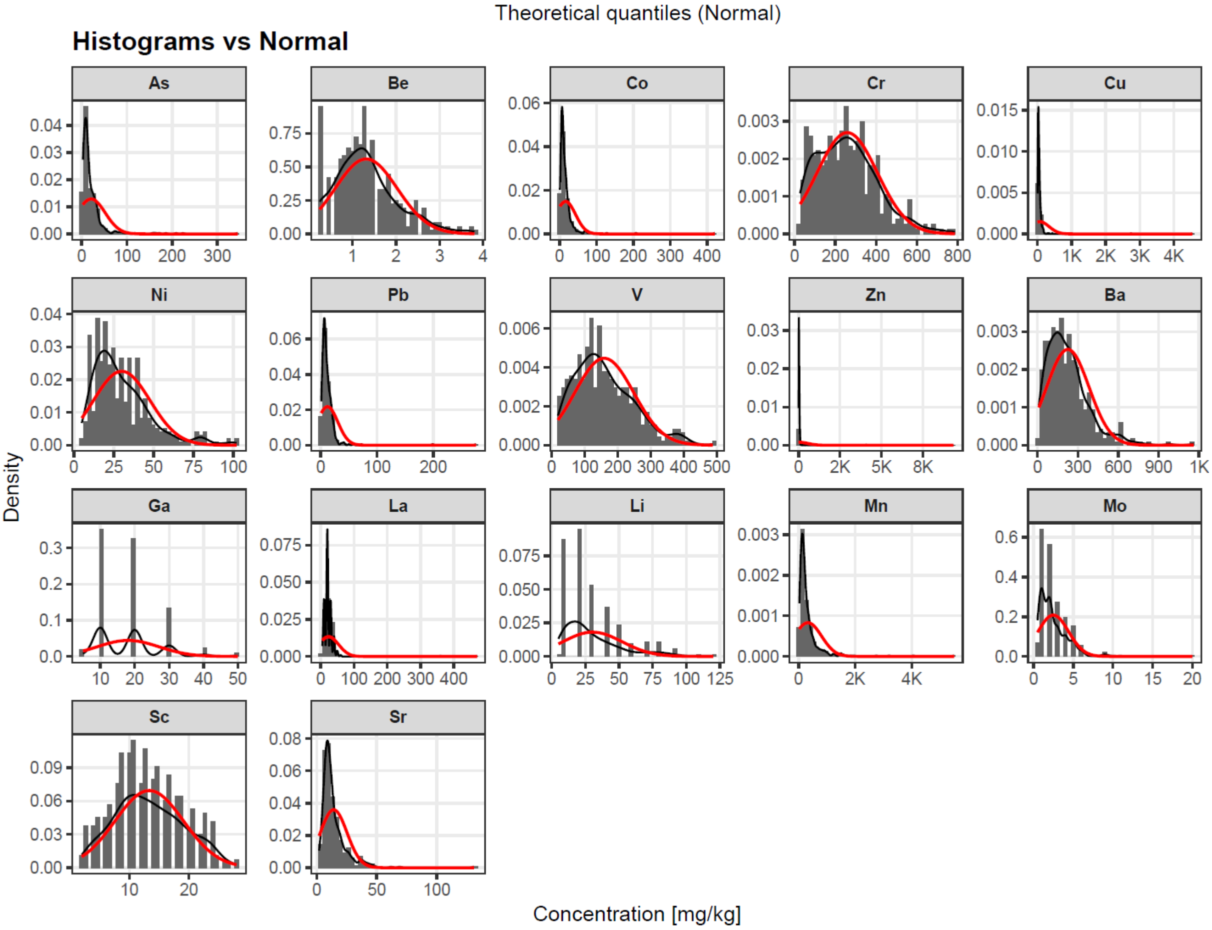
8.3 Annex 3: Principal component analysis showing chemical similarities and differences between geological formations with fewer than 20 samples



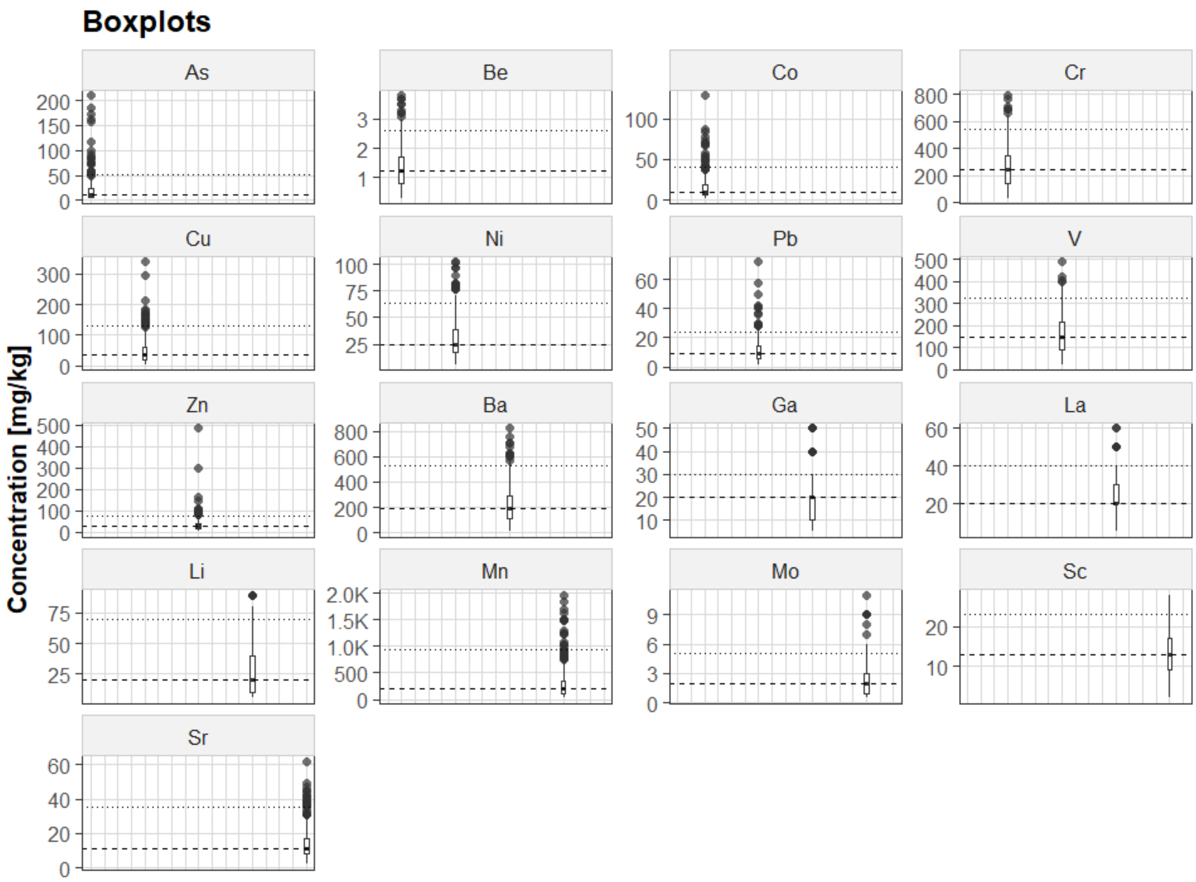
8.4 Annex 4: Distribution shapes of trace-metal concentrations in soil before exclusion of geochemical anomalies

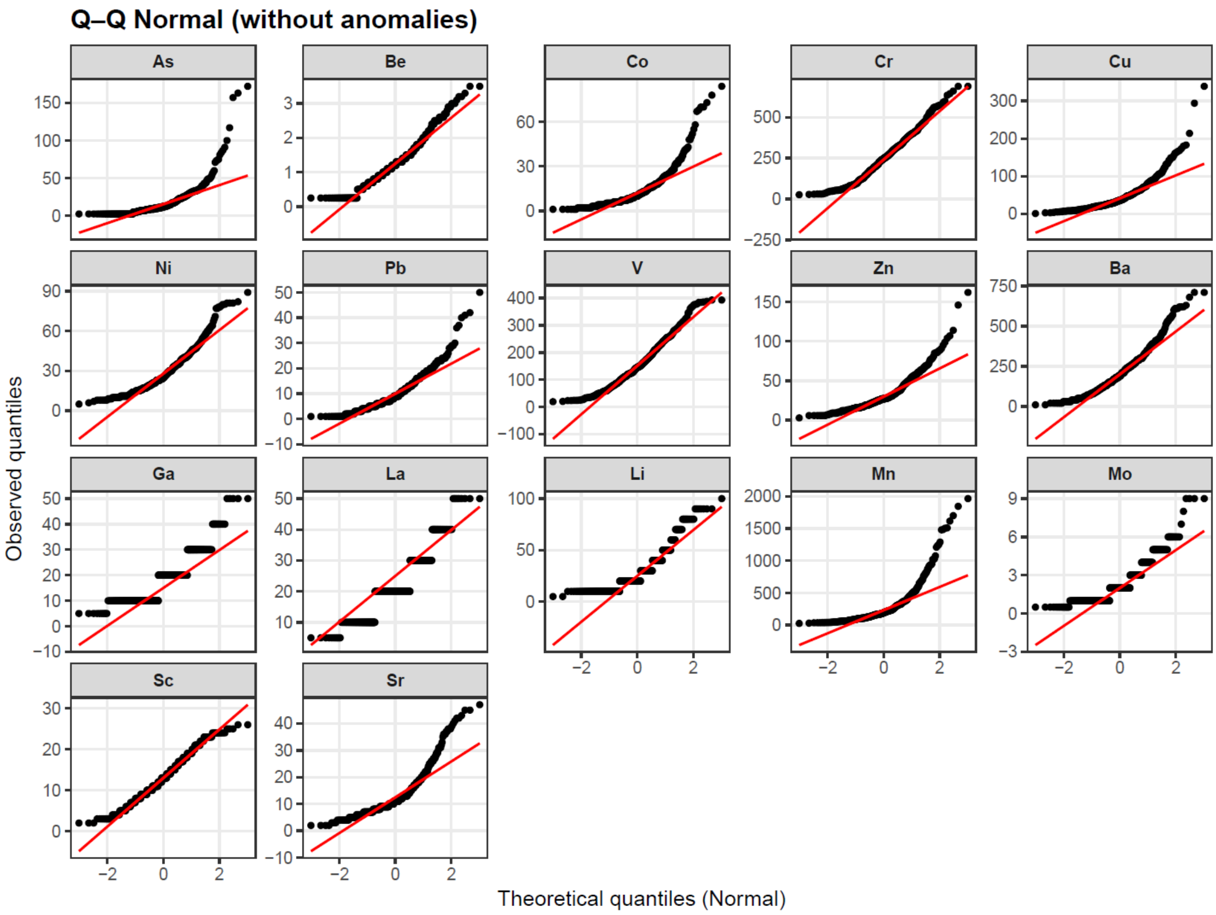


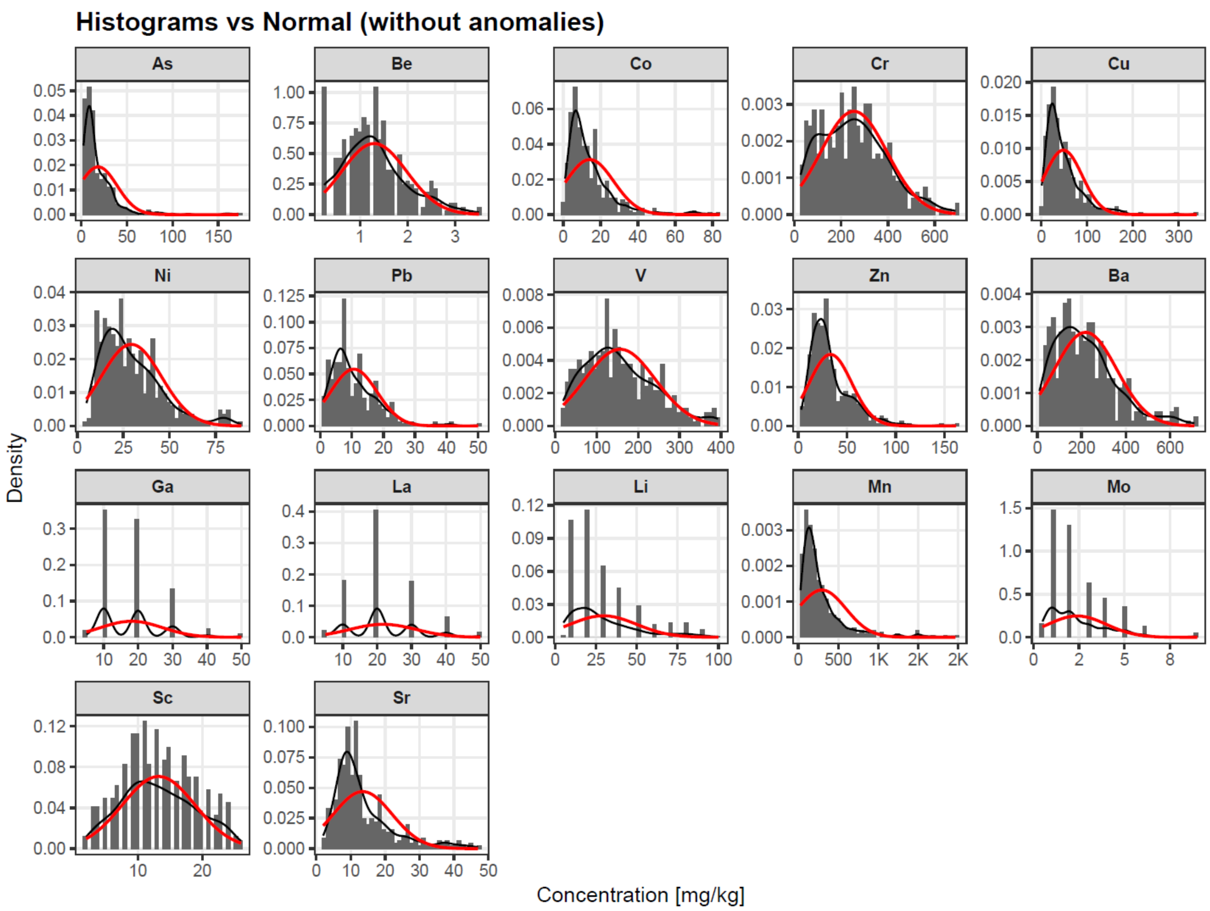

Q–Q Normal
As
Be
Co
Cr
Cu
Ni
Pb
V
Zn
Ba
Ga
La
Li
Mn
Mo
Sc
Sr
Observed quantiles
Theoretical quantiles (Normal)


Histograms vs Normal
As
Be
Co
Cr
Cu
Ni
Pb
V
Zn
Ba
Ga
La
Li
Mn
Mo
Sc
Sr
Density
Concentration [mg/kg]

8.5 Annex 5: Distribution shapes of trace-metal concentrations in soil after exclusion of geochemical anomalies

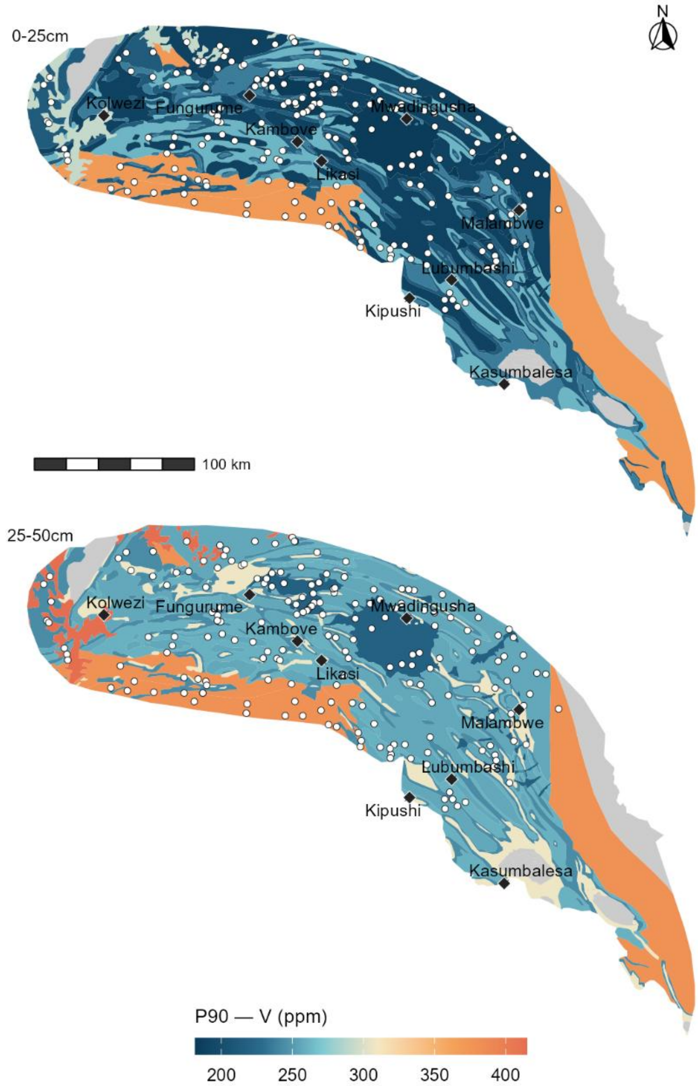


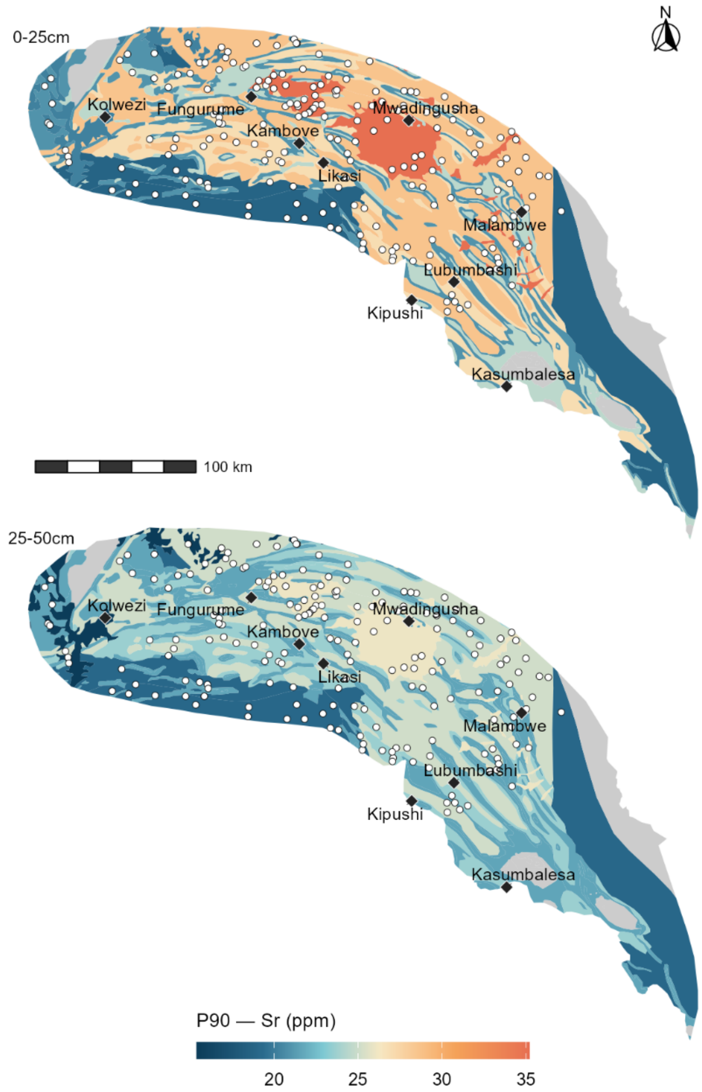

Q–Q Normal (without anomalies)
As
Be
Co
Cr
Cu
Ni
Pb
V
Zn
Ba
Ga
La
Li
Mn
Mo
Sc
Sr
Observed quantiles
Theoretical quantiles (Normal)

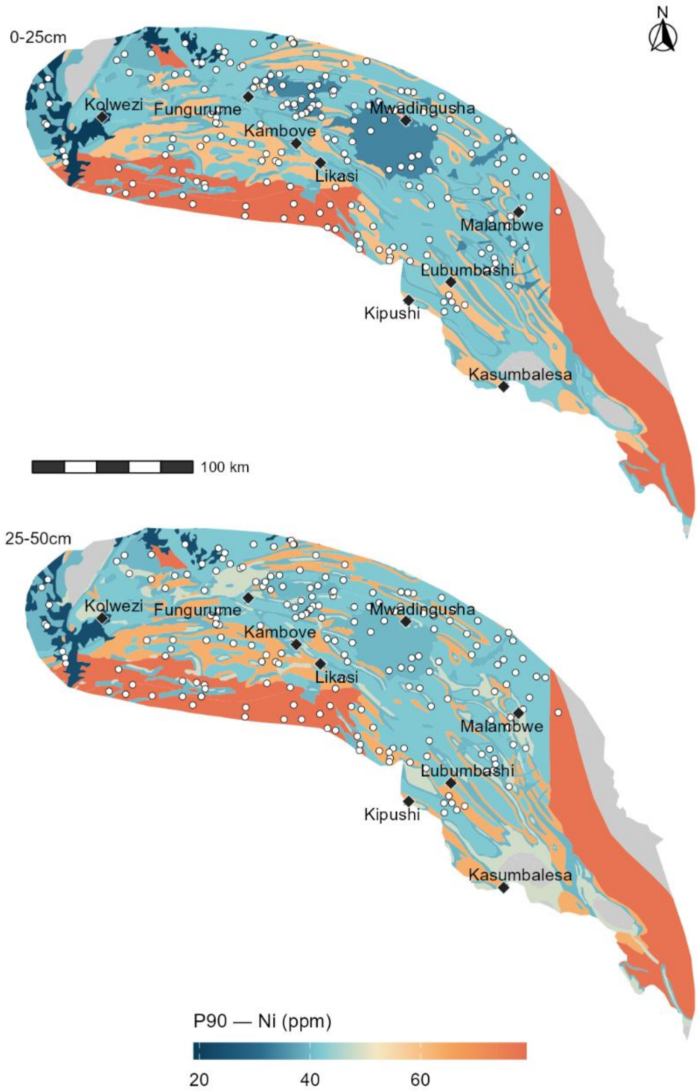

Histograms vs Normal (without anomalies)
As
Be
Co
Cr
Cu
Ni
Pb
V
Zn
Ba
Ga
La
Li
Mn
Mo
Sc
Sr
Density
Concentration [mg/kg]

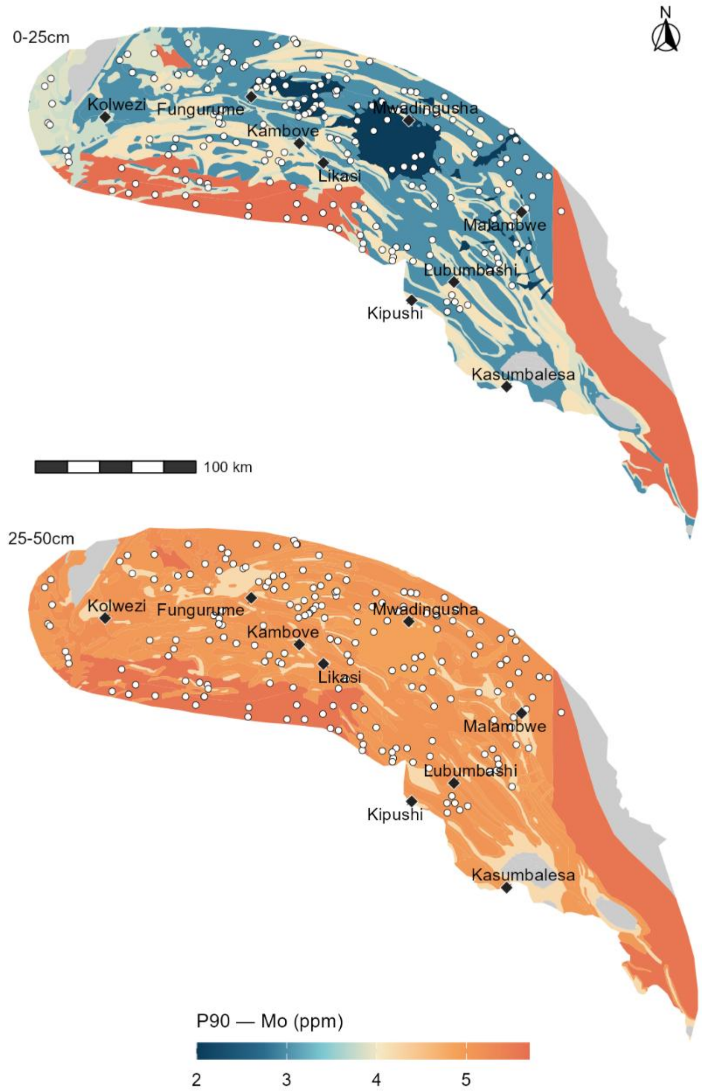
8.6 Annex 6: Spatial distribution of pedo-geochemical background values (P90) of trace metals.

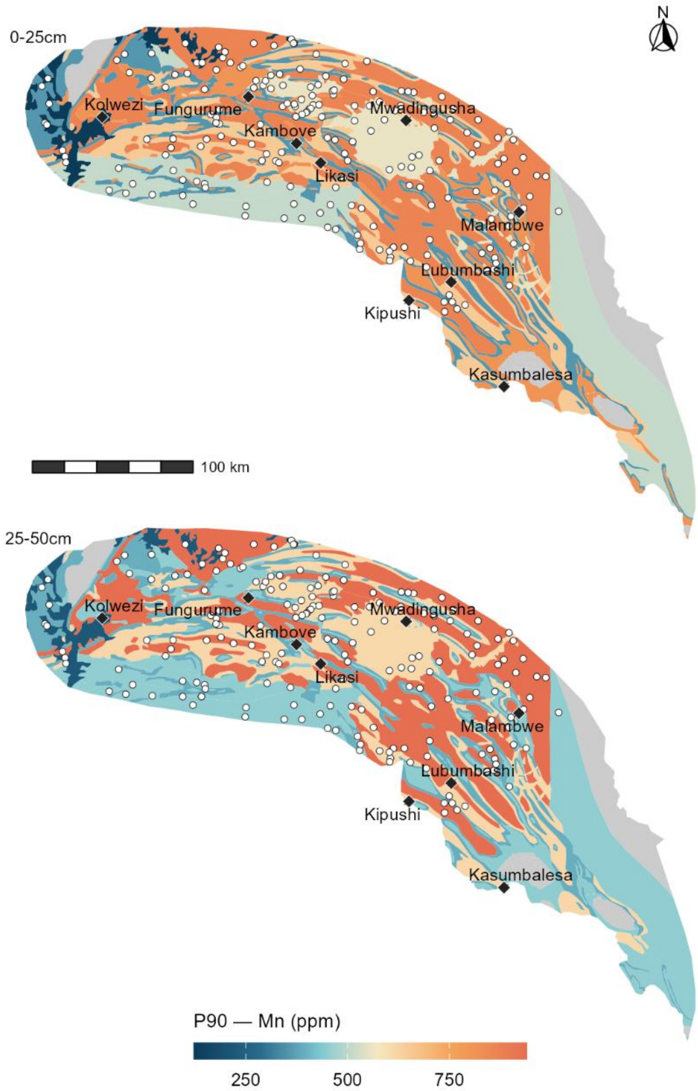
The grey area indicates lithostratigraphic units that were not sampled. The values shown in the unsampled area are indicative only.

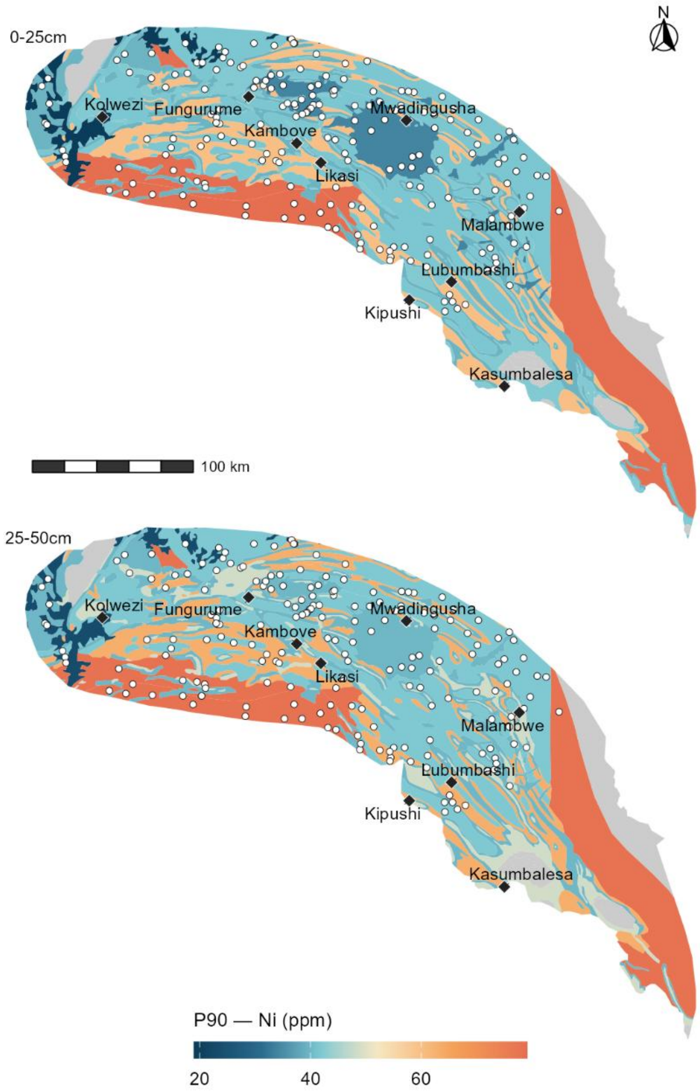


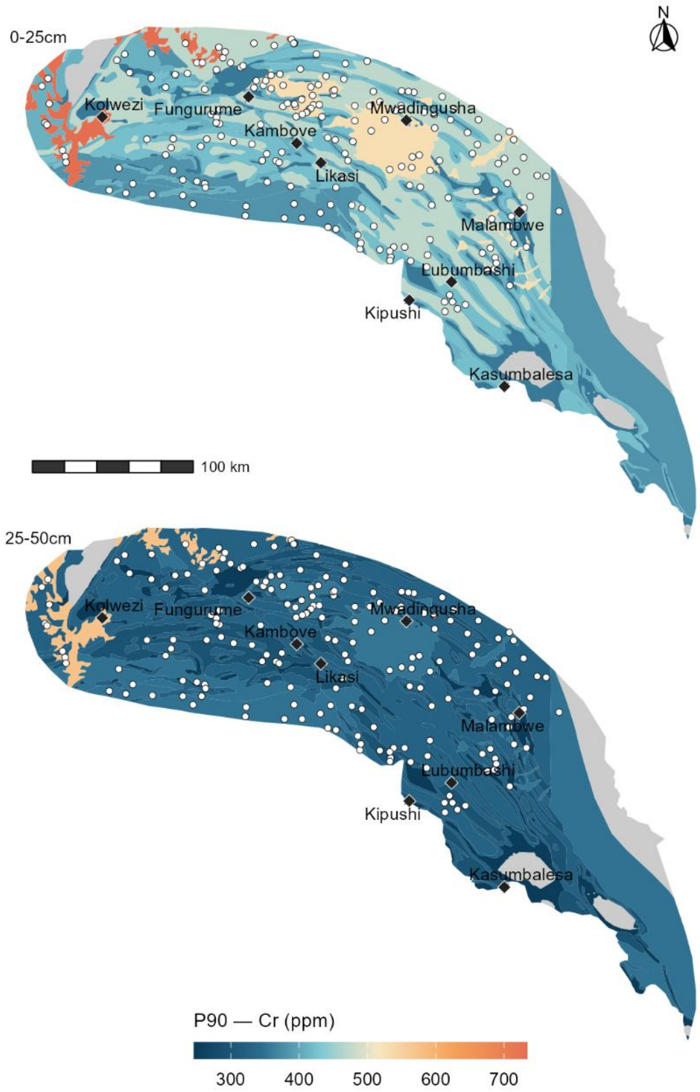

0-25cm
N
Kolwezi
Fungurume
Kambove
Likasi
Mwadingusha
Malambwe
Lubumbashi
Kipushi
Kasumbalesa
100 km
25-50cm
Kolwezi
Fungurume
Kambove
Likasi
Mwadingusha
Malambwe
Lubumbashi
Kipushi
Kasumbalesa
P90 — Sr (ppm)
20
25
30
35

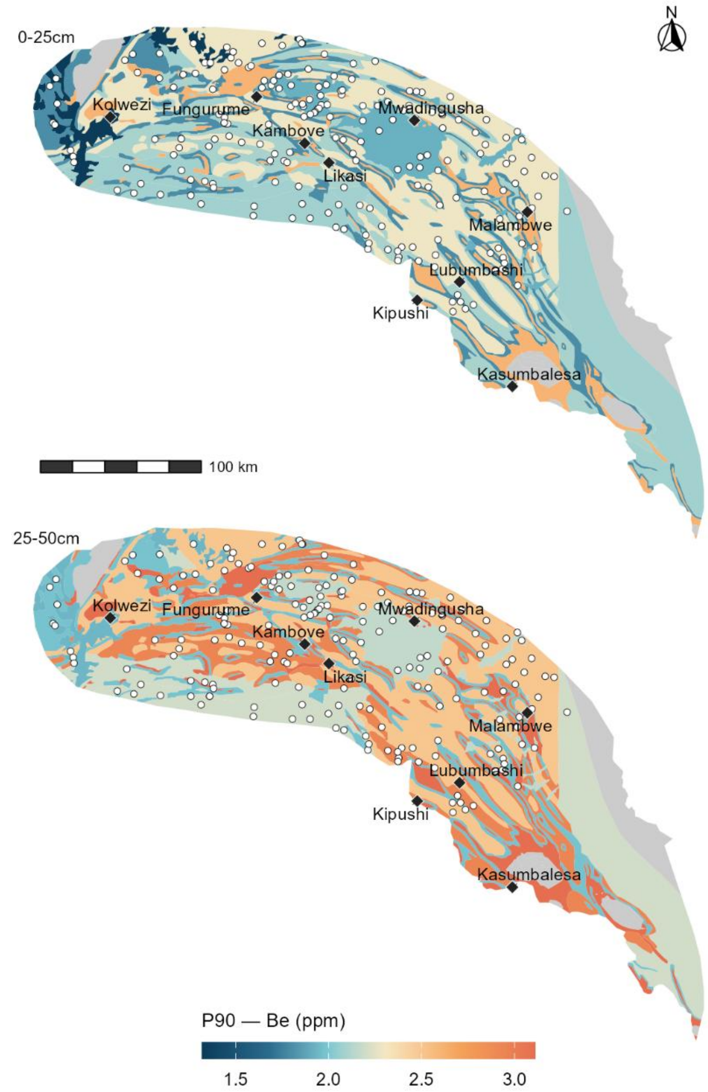

N
0-25cm
Kolwezi
Fungurume
Kambove
Mwadingusha
Likasi
Malambwe
Lubumbashi
Kipushi
Kasumbalesa
100 km
25-50cm
Kolwezi
Fungurume
Kambove
Mwadingusha
Likasi
Malambwe
Lubumbashi
Kipushi
Kasumbalesa
P90 — Ni (ppm)
20
40
60

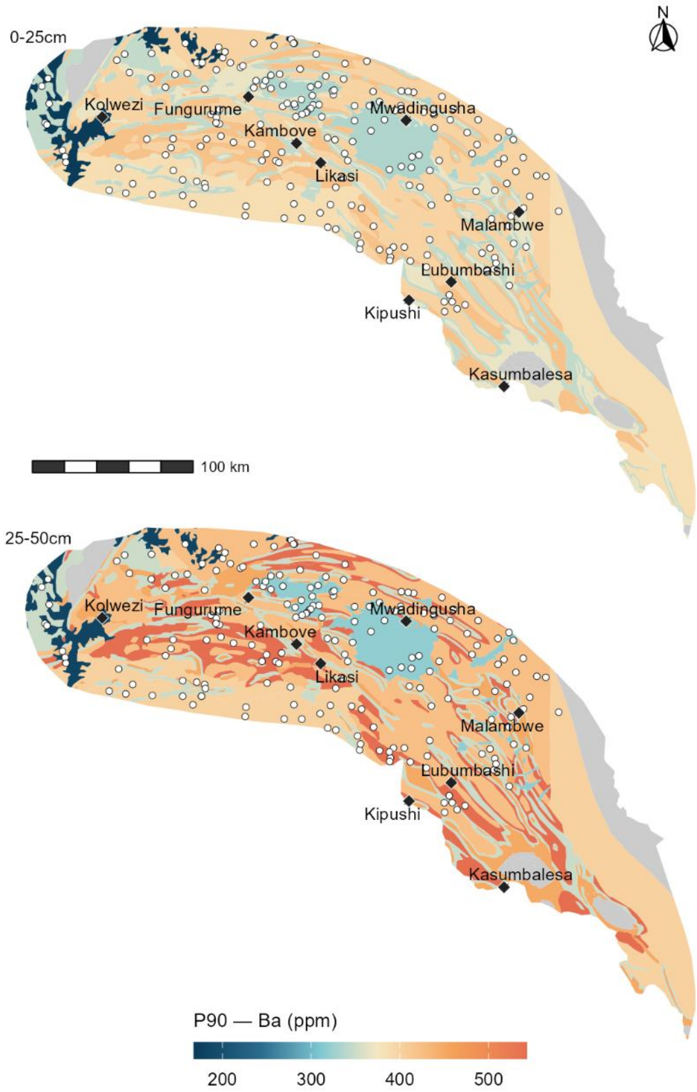

N
0-25cm
Kolwezi
Fungurume
Kambove
Mwadingusha
Likasi
Malambwe
Lubumbashi
Kipushi
Kasumbalesa
100 km
25-50cm
Kolwezi
Fungurume
Kambove
Mwadingusha
Likasi
Malambwe
Lubumbashi
Kipushi
Kasumbalesa
P90 — Mo (ppm)
2
3
4
5

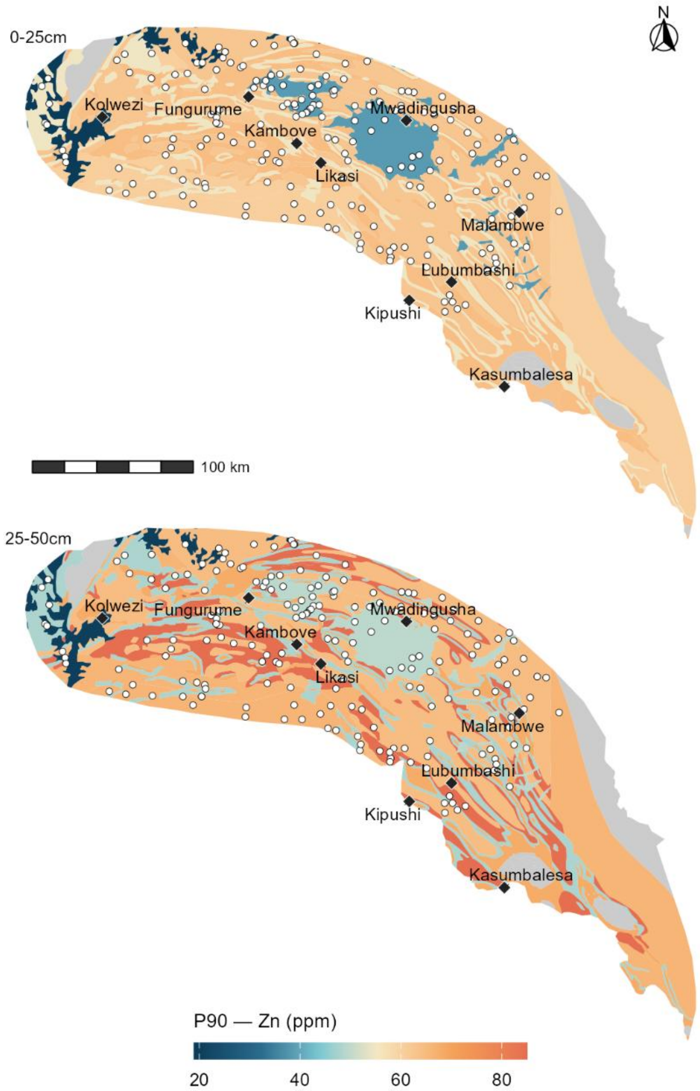

N
0-25cm
Kolwezi
Fungurume
Mwadingusha
Kambove
Likasi
Malambwe
Lubumbashi
Kipushi
Kasumbalesa
100 km
25-50cm
Kolwezi
Fungurume
Mwadingusha
Kambove
Likasi
Malambwe
Lubumbashi
Kipushi
Kasumbalesa
P90 — Mn (ppm)
250
500
750


0-25cm
N
Kolwezi
Fungurume
Kambove
Mwadingusha
Likasi
Malambwe
Lubumbashi
Kipushi
Kasumbalesa
100 km
25-50cm
Kolwezi
Fungurume
Kambove
Mwadingusha
Likasi
Malambwe
Lubumbashi
Kipushi
Kasumbalesa
P90 — Ni (ppm)
20
40
60

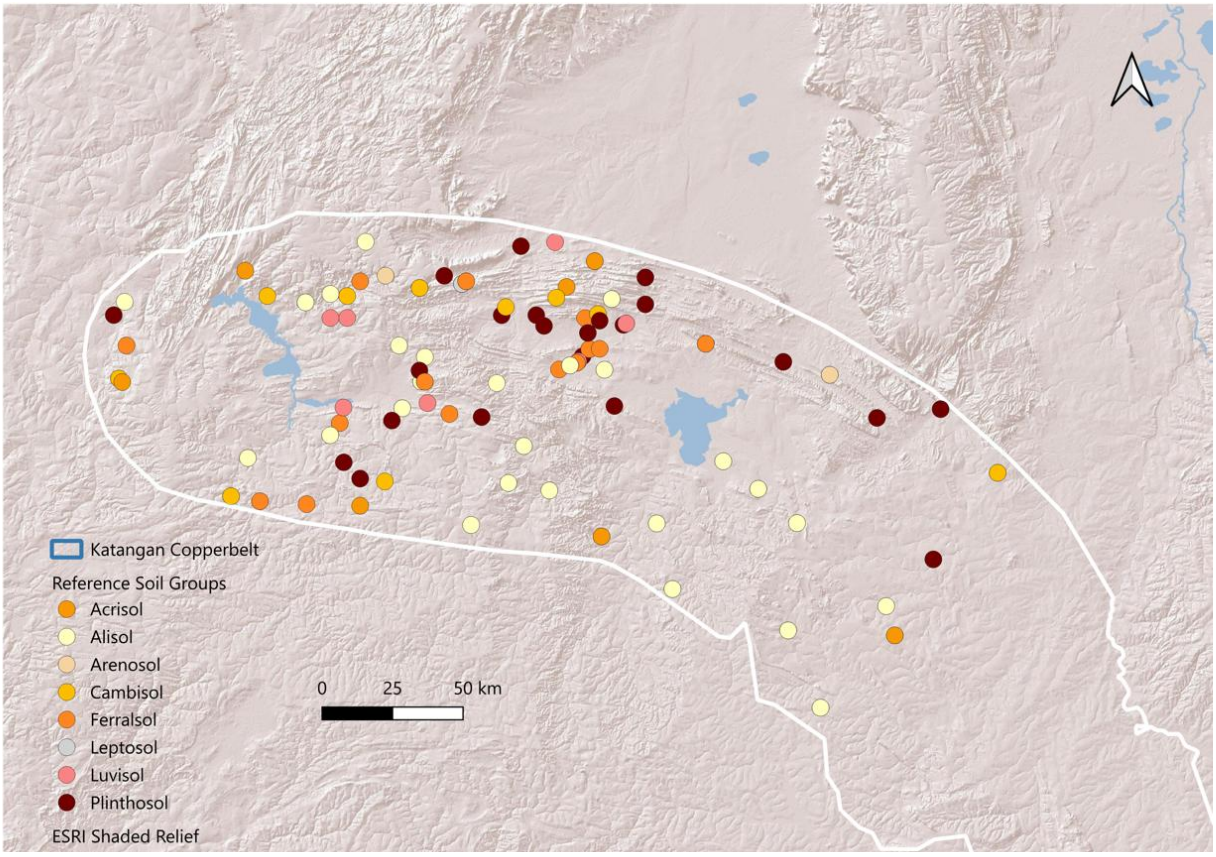

N
0-25cm
Kolwezi
Fungurume
Kambove
Likasi
Mwadingusha
Malambwe
Lubumbashi
Kipushi
Kasumbalesa
100 km
25-50cm
Kolwezi
Fungurume
Kambove
Likasi
Mwadingusha
Malambwe
Lubumbashi
Kipushi
Kasumbalesa
P90 — Cr (ppm)
300
400
500
600
700


N
0-25cm
Kolwezi
Fungurume
Kambove
Likasi
Mwadingusha
Malambwe
Lubumbashi
Kipushi
Kasumbalesa
100 km
25-50cm
Kolwezi
Fungurume
Kambove
Likasi
Mwadingusha
Malambwe
Lubumbashi
Kipushi
Kasumbalesa
P90 — Be (ppm)
1.5
2.0
2.5
3.0


0-25cm
N
Kolwezi
Fungurume
Kambove
Mwadingusha
Likasi
Malambwe
Lubumbashi
Kipushi
Kasumbalesa
100 km
25-50cm
Kolwezi
Fungurume
Kambove
Mwadingusha
Likasi
Malambwe
Lubumbashi
Kipushi
Kasumbalesa
P90 — Ba (ppm)
200
300
400
500


0-25cm
N
Kolwezi
Fungurume
Kambove
Mwadingusha
Likasi
Malambwe
Lubumbashi
Kipushi
Kasumbalesa
100 km
25-50cm
Kolwezi
Fungurume
Kambove
Mwadingusha
Likasi
Malambwe
Lubumbashi
Kipushi
Kasumbalesa
P90 — Zn (ppm)
20
40
60
80

8.7 Annex 7: Reference soil group of the study area



Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)
Stilleweg 2, 30655 Hannover, Allemagne

www.bgr.bund.de