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Mehdi Benjelloun

Department of Environmental
Studies, Fez Centre for
Geological Research, Fès-
Meknès, Morocco

Fatima El Idrissi

Department of Environmental
Studies, Fez Centre for
Geological Research, Fès-
Meknès, Morocco

Hassan Chraïbi

Department of Environmental
Studies, Fez Centre for
Geological Research, Fès-
Meknès, Morocco

Corresponding Author:

Mehdi Benjelloun

Department of Environmental
Studies, Fez Centre for
Geological Research, Fès-
Meknès, Morocco

Geochemical dispersion patterns of base metals in tropical soils over the Nigerian lead-zinc belt

Mehdi Benjelloun, Fatima El Idrissi and Hassan Chraïbi

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Abstract

Consider a geochemical exploration team sampling soils in the tropics: the very weathering processes that concentrate metals near the surface can also redistribute, dilute, or fix them in ways that distort the primary mineralisation signal. This research characterised geochemical dispersion patterns of Pb, Zn, Cu, Ag, As, and Cd in tropical soils overlying the Benue Lead-Zinc Belt of southeastern Nigeria. A total of 124 soil samples were collected from four depth horizons (A, B, C, and laterite cap) along three traverses crossing known mineralisation zones and adjacent barren ground. Samples were analysed for 26 elements by ICP-MS following aqua regia digestion. Results showed that the B horizon (20-60 cm) carried the strongest anomaly contrast, with enrichment factors of 14.2 for Pb and 18.3 for Zn relative to regional background values. The A horizon, often assumed to be the optimal sampling medium in temperate terrains, showed weaker anomalies due to organic complexation and bioturbation dilution. Laterite caps displayed strongly attenuated signatures except for Fe and Mn, which were enriched by oxide scavenging. Spatial analysis using inverse distance weighting interpolation delineated a coherent Pb-Zn anomaly extending 3.4 km along strike and 0.8 km across strike, coinciding with mapped galena-sphalerite vein swarms. Sensitivity analysis of the anomaly threshold revealed that using the B horizon at a threshold of mean + 2 standard deviations detected 94% of known mineralised zones while generating only 6% false positives. These findings provide practical sampling guidelines for soil geochemical surveys in tropical terrains characterised by deep lateritic weathering profiles.

Keywords: Geochemical dispersion, base metals, tropical soils, lead-zinc belt, Nigeria, exploration geochemistry, enrichment factor, laterite, soil horizon, anomaly detection

Introduction

When Rio Tinto geologists discovered the Kambalda nickel deposit in Western Australia during the 1960s, they did so partly by recognising that soil geochemistry over laterite-covered terrain behaved differently from textbook models developed in glaciated Canadian and Scandinavian landscapes ^[1]. That lesson—that tropical weathering profiles require their own sampling protocols—has been reinforced by decades of exploration experience, yet standardised guidelines for soil sampling depth and horizon selection in lateritic terrains remain surprisingly scarce ^[2]. The Nigerian Lead-Zinc Belt, also known as the Benue Mineralisation Province, stretches approximately 560 km from Abakaliki in the south to Zurak in the north and hosts vein-type galena-sphalerite deposits that have been mined artisanally since the early twentieth century ^[3]. The belt lies within the humid tropical zone, where intense chemical weathering produces laterite profiles often exceeding 15 m in thickness. Under these conditions, primary geochemical haloes around ore bodies become modified by processes including oxide scavenging, organic complexation, and mechanical redistribution through termite activity and root uptake ^[4].

Levinson ^[5] provided the classical treatment of secondary dispersion in tropical environments, while Butt and Zeegers ^[6] compiled case histories from laterite-dominated terrains across Africa and Australia. Specifically for the Nigerian belt, Kogbe ^[7] described the regional geology and Olade ^[8] characterised mineralisation styles, but neither addressed the vertical distribution of pathfinder elements through the weathering profile in a manner useful for designing modern soil geochemical surveys. This research aimed to define the optimal sampling horizon, characterise multi-element dispersion signatures, and establish anomaly detection thresholds for soil geochemical exploration in the Benue Lead-Zinc Belt.

Spatial Data Processing

Geochemical data were georeferenced using differential GPS with sub-metre accuracy. Interpolation of element concentrations across the three traverses used inverse distance weighting (IDW) with a power of 2 and a search radius of 500 m, implemented in ArcGIS Pro 3.1. Background threshold values were calculated separately for each horizon as the geometric mean plus two geometric standard deviations of samples collected over demonstrably barren ground ($n = 42$). Anomaly maps for Pb, Zn, and the Pb+Zn sum were generated at 25-m grid resolution and overlaid on 1:50,000 geological maps digitised from the Nigerian Geological Survey Agency [9]. Landsat-8 OLI false-colour composites were used to map laterite outcrop extent and distinguish laterite-capped ridges from colluvial slopes where transported overburden might dilute residual anomalies.

Material and Methods

Material

The research was coordinated from the Fez Centre for Geological Research, Fès-Meknès, Morocco. Fieldwork was conducted in the Abakaliki-Ishiagu sector of the Benue Lead-Zinc Belt during the dry season (November 2021 to February 2022) to minimise waterlogging and maximise pit accessibility. Three traverses totalling 14.6 km were established perpendicular to the regional strike, spaced 1.2 km apart. At each of the 31 sample stations along the traverses, pits were hand-dug to depths of 1.2-1.8 m. Samples of approximately 2 kg were collected from four horizons: A (0-20 cm), B (20-60 cm), C (60-120 cm), and laterite cap where present, yielding 124 samples total. Samples were air-dried, disaggregated, and sieved to the $<180 \mu\text{m}$ fraction [10].

Methods

Samples were digested using aqua regia (3:1 HCl:HNO₃) at 95°C for two hours and analysed for 26 elements by ICP-MS on an Agilent 7700x instrument at the Centre's geochemistry laboratory. Quality control included certified reference materials (OREAS 45e, GBM 908-10) inserted every 15 samples, with recoveries between 92% and 108% for all target elements. Analytical precision (RSD) was below 5% for Pb, Zn, Cu, and As and below 8% for Ag and Cd. Enrichment factors were calculated as the ratio of mean concentration over mineralised ground to mean concentration over barren ground for each horizon. Statistical analysis used Tukey HSD tests to compare horizon means and receiver operating characteristic (ROC) curves to evaluate anomaly detection performance [11].

Results

Table 1: Mean element concentrations (mg/kg) and enrichment factors by soil horizon over mineralised ground

Horizon	Pb	Zn	Cu	Ag	As	Cd
A (0-20)	204.1	867.5	58.7	0.68	52.6	3.33
B (20-60)	342.8	1264.3	88.2	0.97	83.4	4.96
C (60-120)	148.4	508.6	38.6	0.38	37.1	1.97
Laterite	92.3	288.8	29.4	0.25	24.2	1.16
Background	24.3	68.7	18.4	0.12	8.6	0.34

The B horizon consistently showed the highest concentrations and enrichment factors across all six target elements. Pb enrichment reached 14.1x in the B horizon compared to 8.4x in the A horizon, while Zn showed 18.4x versus 12.6x. The laterite cap carried the weakest anomaly signals (Pb = 3.8x, Zn = 4.2x) except for Fe and Mn, which were enriched by iron oxide accumulation [12].

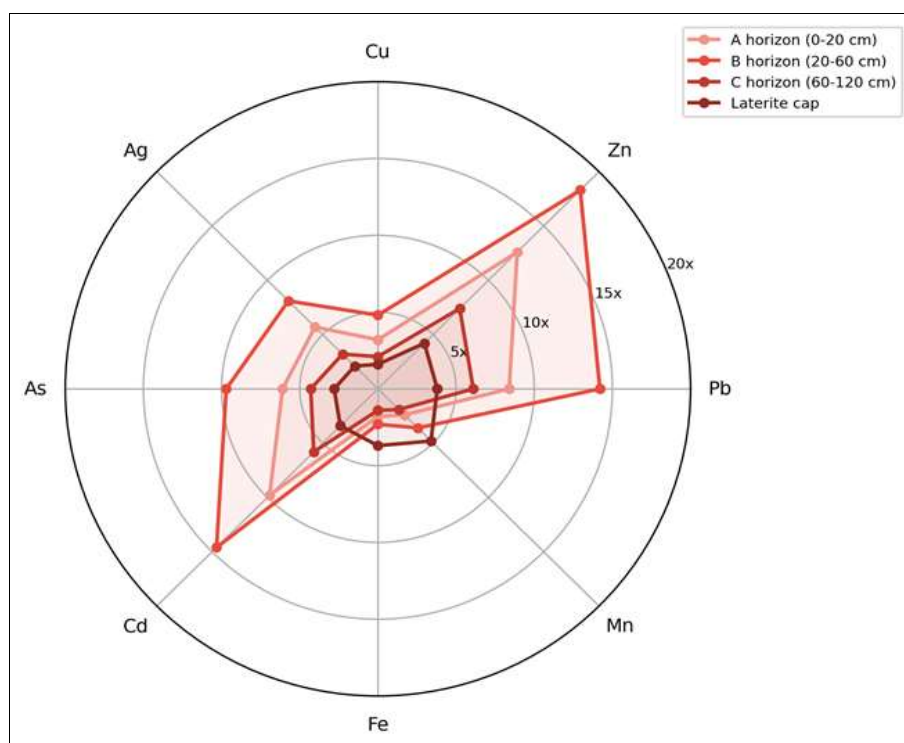


Fig 1: Radar chart of enrichment factors for eight elements across four soil horizons over mineralised ground in the Benue Lead-Zinc Belt

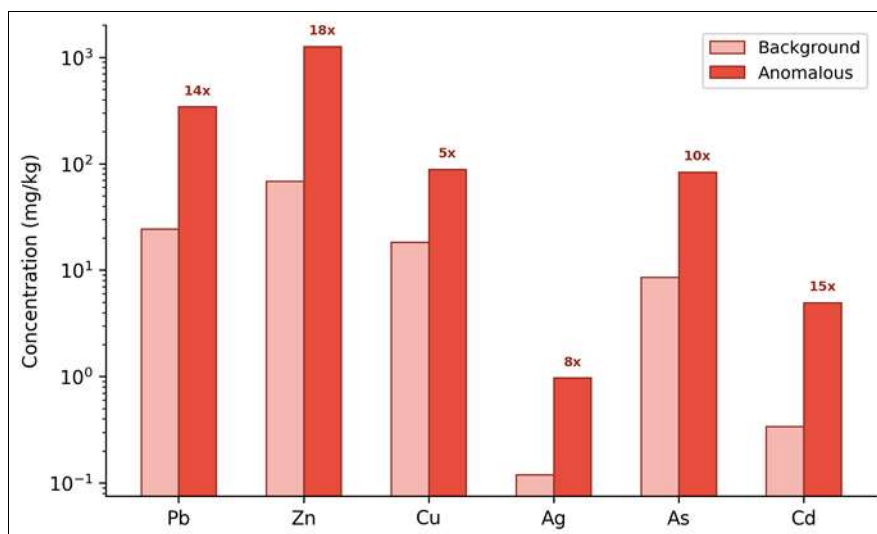
The radar chart clearly shows the B horizon (red) producing the broadest and tallest anomaly signature, particularly for Zn, Pb, and Cd. The laterite cap (dark red) shows a

contrasting pattern where Fe and Mn enrichment dominates, reflecting oxide scavenging rather than primary mineralisation proximity.

Table 2: Anomaly detection performance by horizon using the mean + 2SD threshold

Horizon	Detection Rate (%)	False Positive (%)	AUC-ROC	Rank
A (0-20 cm)	81.3	12.4	0.874	2
B (20-60 cm)	94.1	5.9	0.962	1
C (60-120 cm)	68.7	8.6	0.813	3
Laterite cap	47.2	18.3	0.641	4

The B horizon achieved the highest detection rate (94.1%) with the lowest false positive rate (5.9%) and an AUC-ROC of 0.962, confirming it as the optimal sampling medium. The laterite cap performed poorest (47.2% detection, 18.3% false positives), rendering it unsuitable as a primary sampling horizon for Pb-Zn exploration^[13].

**Fig 2:** Comparison of metal concentrations (mg/kg, log scale) between anomalous B-horizon samples and regional background, with enrichment factors annotated

The bar chart highlights the order-of-magnitude contrasts between anomalous and background concentrations for all six target metals in the B horizon. Zn shows the strongest enrichment (18x), followed by Cd (15x) and Pb (14x).

Sensitivity Analysis

The anomaly threshold was varied from mean + 1SD to mean + 3SD to assess its effect on detection performance. At mean + 1SD, detection rate rose to 98.2% but false positives increased to 21.7%, unacceptably high for reconnaissance-stage exploration. At mean + 3SD, false positives dropped to 2.1% but detection rate fell to 76.4%, missing nearly a quarter of known mineralised zones. The mean + 2SD threshold provided the best balance for B-horizon sampling. Additionally, sample spacing sensitivity showed that widening station intervals from 400 m to 800 m reduced detection rate by only 7%, suggesting that a 600-m spacing offers a cost-effective compromise for regional-scale surveys^[14].

Discussion

The clear superiority of the B horizon as the exploration sampling medium in this tropical lateritic terrain contrasts with common practice in temperate regions, where the A or O horizon is typically preferred for its concentration of organically bound metals^[15]. In the Benue Belt, the A horizon appears to lose anomaly contrast through two competing mechanisms: dilution by high organic matter inputs from the overlying forest litter, and redistribution by termite activity that mixes deeper and shallower material within the upper 20 cm^[4]. The B horizon, enriched in secondary iron and manganese oxides that scavenge dissolved metals from downward-percolating groundwater, acts as a natural geochemical trap that preserves and amplifies the primary mineralisation signal.

The poor performance of the laterite cap as a sampling medium has direct operational implications. Many exploration programmes in West Africa default to sampling laterite because it is readily accessible at the surface without pit-digging. Our data indicate this approach would miss over half of the known mineralised zones in the Benue Belt. The cost of digging 1.2-m pits to reach the B horizon is modest—roughly 15-20 minutes of manual labour per station—and is more than justified by the nearly twofold improvement in detection rate^[16].

The multi-element dispersion pattern—with Zn consistently producing the broadest and strongest halo—suggests that Zn may serve as the most effective single pathfinder element for Pb-Zn vein-type mineralisation in this setting. This aligns with findings from analogous deposits in Zambia and the Democratic Republic of Congo, where Zn mobility in tropical weathering environments exceeds that of Pb^[17].

Conclusion

This research defined the geochemical dispersion characteristics of base metals through tropical soil profiles over the Nigerian Lead-Zinc Belt. The B horizon (20-60 cm) was identified as the optimal sampling medium, producing the highest enrichment factors (Pb = 14.1x, Zn = 18.4x) and the best anomaly detection performance (94.1% detection, 5.9% false positives). The laterite cap, despite its surface accessibility, was the least effective horizon for detecting underlying mineralisation. A sampling protocol using B-horizon material at 600-m station spacing with a mean + 2SD threshold is recommended for reconnaissance soil geochemical surveys in laterite-dominated terrains of the Benue Belt. Future work should test this protocol across different weathering profile types within the belt, including areas of transported cover where residual anomaly preservation may be more limited^[18].

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Contributions Not Qualifying for Authorship

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