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Reconnaissance Geochemical Survey in the Tamiang Region, Aceh, Indonesia

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Abstract

The Tamiang region in Aceh, Indonesia, is geologically complex and underexplored, with limited baseline geochemical data. This study conducted a reconnaissance geochemical survey to evaluate spatial variations in metal concentrations and their geological controls. Forty stream sediment samples from various drainage systems across the region were analyzed for 22 elements (Al, As, Ba, Ca, Co, Cr, Cu, Fe, K, La, Li, Mn, Na, Ni, Pb, Sc, Sr, Ti, V, Y, Zn, Zr) using ICP-OES. Nineteen elements exhibited anomalous concentrations, with Cu, Ca, Li, and Na showing particularly high anomalies, whereas Al, Sc, and Y remained within background levels. Based on their geochemical behaviour, the elements can be grouped into major lithogenic elements such as Al, Fe, Ca, K, Na, Ti, Sr, and Zr, which reflect lithology and weathering intensity, and ore-related elements including Cu, Pb, Zn, As, Co, Ni, and Cr, which may indicate localized metal enrichment. Rare earth and high field strength elements such as La, Y, Sc, Li, Zr, and Ti provide insight into source rock composition and magmatic or weathering processes, while miscellaneous elements including Mn, Ba, and Sr show mixed lithological or secondary origins. The spatial distribution of these anomalies may suggest localized metal enrichment associated with specific lithological zones. Despite the reconnaissance scale and limited sampling density, these results provide a preliminary geochemical framework for the Tamiang region, supporting future geological and geochemical investigations and contributing to a robust scientific assessment of the area.

Keywords:

econnaissance geochemistry; stream sediments; mineral prospecting; geochemical mapping; Aceh; Indonesia

1. Introduction

Base and transition metals play a crucial role in modern industries, such as automotive manufacturing, electronics, aerospace, and construction (**Cioacă et al., 2020; Eskdale et al., 2023; Yaisamut et al., 2023**). Understanding their occurrence and availability is essential for sustainable industrial development, and Indonesia, with its abundant mineral resources, contributes to the global supply of these metals (**Jamin et al., 2023; PWC, 2023; Tiess & Mujiyanto, 2011**). The country's metal mining sector has considerable geological potential; however, it also faces the challenge of ensuring that exploration and resource development are based on reliable geological and geochemical information rather than speculative assumptions (**Christie et al., 2019; Sun et al., 2024**).

Regional geochemical surveys represent a cornerstone of modern exploration geoscience, providing the baseline data necessary to delineate areas of geochemical enrichment, assess lithological variations, and guide mineral resource assessments (**Cohen & Bowell, 2013; Kyser et al., 2015; Saremi et al., 2024**). Among various reconnaissance techniques, stream-sediment geochemical analysis is one of the most widely applied methods for detecting metal anomalies in drainage catchments (**El-Makky & Sediek, 2012; Grunsky & de Caritat, 2020; Jo et al., 2024**). Stream sediments integrate detrital materials derived from the weathering of source rocks upstream, thereby reflecting the overall chemical composition of the contributing geological units (**Grunsky & de Caritat, 2020; Mira et al., 2020; Shirazi et al., 2022; Tonggiroh, 2020; Wardhani et al., 2018**). This method is particularly effective in areas where bedrock exposures are limited and geochemical data are scarce, making it a cost-effective and efficient approach for regional geochemical mapping.

In Indonesia, extensive research on mineral resources has primarily focused on regions with known mining activities and established ore deposits such as Papua, Kalimantan, and Sulawesi (**Kramadibrata, 2013**). These

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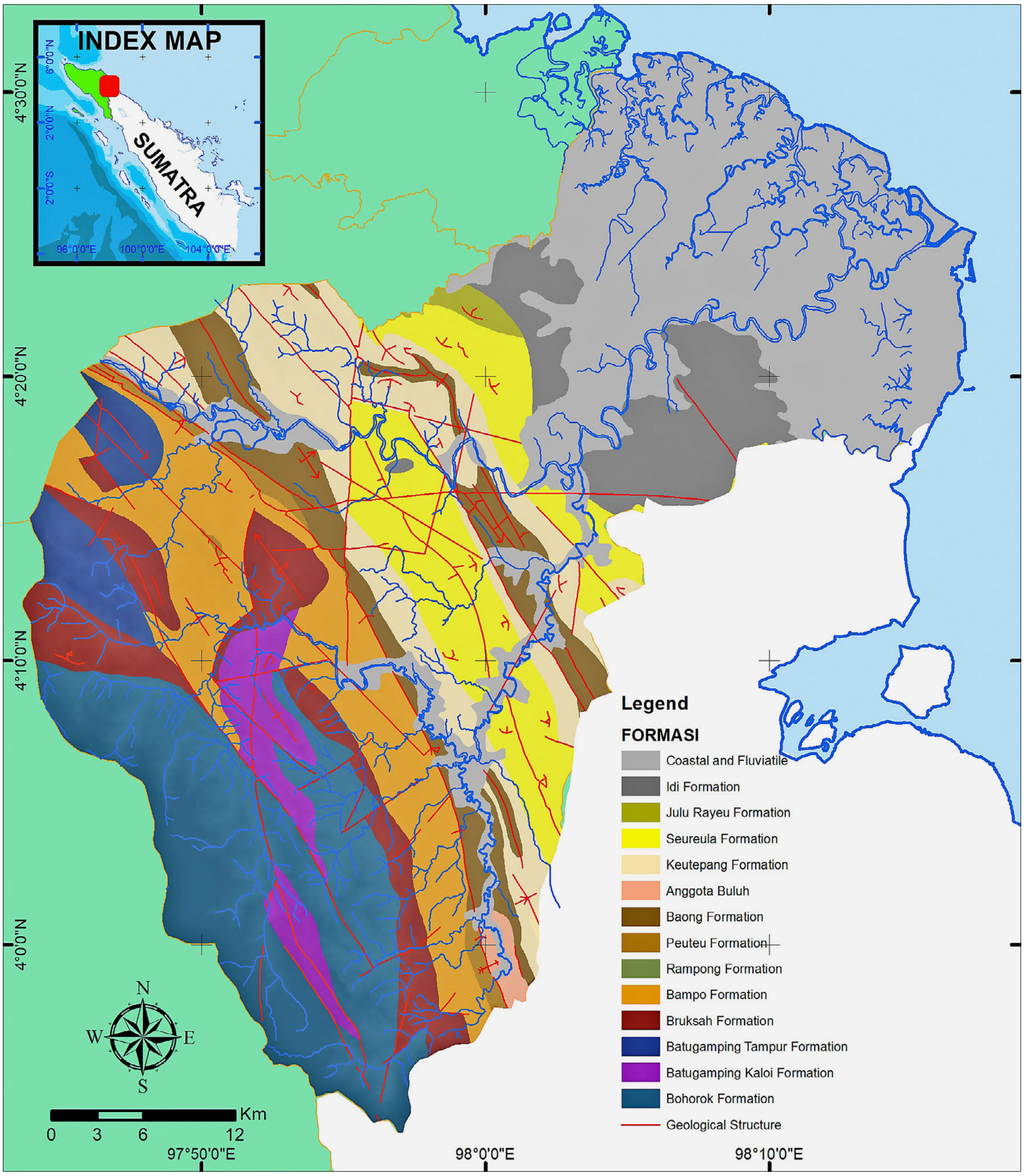

Figure 1: Regional geological map of the Tamiang, Aceh Province. Modified and redrawn from (**Cameron et al., 2007**)

areas have been studied in detail due to their economic significance and the availability of geological data. Conversely, Aceh Province particularly the Tamiang region has received relatively little attention, despite its complex geological framework and potential for diverse mineralization styles. The limited availability of geochemical baseline data from this region represents a major gap in the current understanding of Sumatra's metallogenic and lithogeochemical evolution. Geologically, the Tamiang region lies in the eastern part of Aceh, within the influence of the Sumatra Fault Zone, one of the most active tectonic features in Southeast Asia (**Barber et al., 2005; Cameron et al., 2007**). The area comprises pre-Paleogene metamorphic basement rocks, Paleogene intrusive bodies, and younger volcanic sequences. These lithologies are known to be associated with magmatic–hydrothermal processes that can lead to metal enrichment in various parts of Sumatra (**Aida et al., 2025**). Although preliminary geological mapping indicates favorable structural and lithological conditions for mineralization, there have been no systematic geochemical surveys to characterize the background element concentrations or to delineate metal distribution patterns in this region. The absence of such data limits both academic understanding and the future application of geoscientific information for resource evaluation. The stream-sediment geochemical approach provides a suitable framework for establishing a regional geochemical baseline in such underexplored areas. Through systematic sampling and multielement analysis, spatial variations in element concentrations can be evaluated in relation to underlying lithology, geomorphology, and drainage patterns. These relationships can be visualized using geospatial mapping techniques, allowing for a comprehensive interpretation of the regional geochemical framework (**Grunsky & de Caritat, 2020**).

The Tamiang region, located along the Sumatra Fault Zone, has not been systematically studied for its geochemical characteristics. The absence of baseline geochemical data hampers regional geological correlations and the identification of areas with geochemical anomalies indicative of mineralization. To address this knowledge gap, the present study conducted a reconnaissance-level stream-sediment geochemical survey in the Tamiang region, Aceh, Indonesia. The primary objective of this study is to establish baseline geochemical data for base and transition metals within the region's drainage systems. The dataset was used to evaluate spatial variations in element concentrations and to interpret their relationship with the regional geological framework. This approach contributes new information to Indonesia's regional geochemical database and enhances understanding of the lithogeochemical characteristics of eastern Aceh. The findings are expected to support future geological and mineral resource assessments and provide a foundation for subsequent geoscientific investigations in the Tamiang region, Aceh, Indonesia.

2. Geological Setting

The study area is located in the Tamiang region, Aceh Province, which lies within the northern part of the Sumatra Basin. The regional geology comprises a variety of sedimentary, volcanic, and intrusive rock units, with ages ranging from the pre-Paleogene to the Quaternary. The main lithological units include the Coastal and Fluviatile deposits (Qh) consisting of gravel, sand, and clay; the Idi Formation (Qpi) with semi-consolidated gravels, sands, and clays containing vein quartz, arenites, and rhyolites; the Julu Rayeu Formation (QTjr) with rhythmic sandstone, lignitic clay, and mudstone; and the Seureula Formation (Tps) with alternating sandstone and mudstone (see **Figure 1**).

Other significant formations are the Keutapang Formation (Tuk) comprised of sandstone, carbonaceous mudstone, and minor conglomerate; the Buluh Member (Tmbb) dominated by calcareous sandstone; the Baong Formation (Tmb) with calcareous mudstone, sandstone, and glauconitic sandstone; and the Peutu Formation (Tmp) consisting of calcareous and carbonaceous mudstones and fine sandstone. The Rampang Formation (Tlr) consists of euxinic mudstone, siltstone, and volcaniclastic sandstone, indicating deposition in anoxic marine conditions. The Bampo Formation (Tlb) is comprised of black pyritic mudstone, sandstone, and laminated siltstone. The Bruksah Formation (Tob) includes calcareous and micaceous conglomerates with thin coal beds, deposited in fluvio-deltaic environments. The Tampur Limestone (Totl) is made up of reefal limestone and dolomite with chert nodules. The Kaloi Limestone (MPkl) consists of massive limestone associated with Triassic shale, limestone, and sandstone. The Bohorok Formation (Pub) includes undated conglomerate, minor quartzite, slate, and metamorphic limestone (**Cameron et al., 2007**). This geological diversity contributes to the genesis of metal enrichments through weathering, erosion, and fluvial transport processes that mobilize metallic elements from bedrock to stream sediments.

3. Materials and Methods

3.1. Materials

This study was conducted in the Tamiang region of Aceh, Indonesia, an area known for its promising geological potential for mineral exploration. A total of 40 sampling points were selected along the Tamiang River and its main tributaries, including the Simpang Kanan, Simpang Kiri, Tamiang, and Tenggulun rivers (see **Figure 2**). Sampling locations were systematically chosen from the river mouths upstream toward the headwaters to capture a representative distribution of sediment along the drainage network.

Stream sediments represent the eroded material transported from the surrounding bedrock and reflect the characteristics of the local drainage system, making them suitable for geochemical studies. A total of 40 samples, each weighing 1 kg, were collected from 40 locations across the Tamiang rivers. Sampling was conducted along riverbanks using two distinct approaches tailored to depositional conditions. In downstream locations, particularly near river mouths with vegetated sediment surfaces (e.g. grasses), the vegetated surface was first removed, and then samples were taken from 5 to 10 cm below, to avoid organic contamination and ensure collection of true stream sediment (**Aida et al., 2025**). In upstream areas where active fluvial deposits had minimal organic cover, samples were collected directly from the sediment surface.

The collected samples were air-dried, homogenized, and sieved. The fraction passing through an 80-mesh sieve (0.177 mm), comprising silt, clay, and the finer portion of fine sand, was selected for geochemical analysis (**Shirazi et al., 2022**). This fraction excludes coarser sand and gravel, representing the mobile geochemical component relevant to mineral detection. Each sieved sample was placed into polyethylene bags and subsequently sent to the laboratory for analysis. The laboratory used for this analysis was PT Intertek Utama Services, located at Jl. Raya Bogor KM. 28, Jakarta Timur 13710, Indonesia.

Figure 2: The research location

3.2. Laboratory Methods

The metal content of stream sediments was analyzed using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) (**Liu, 2023; Luis Manrique Carreño, 2022; Zhang et al., 2024**). ICP-OES was selected for stream sediment analysis as its detection limits were suitable for the expected concentrations of target metals, while practical considerations such as local availability, cost-effectiveness, and operational simplicity further supported its use (**Aida et al., 2025; Göçmengil et al., 2022; Zhang et al., 2024**). Instrumental parameters, calibration standards, and quality control procedures followed standard laboratory protocols. Detection limits for each element were monitored, and replicate analyses were performed to ensure data precision and reliability.

A total of 22 elements were measured, including Al, As, Ba, Ca, Co, Cr, Cu, Fe, K, La, Li, Mn, Na, Ni, Pb, Sc, Sr, Ti, V, Y, and Zr. For the purpose of data interpretation, these elements were grouped based on their geochemical and genetic significance: major and lithogenic elements (Al, Fe, Ca, K, Na, Ti, Sr, Zr), indicating lithology, mineral composition, and weathering intensity; ore-related (chalcophile) elements (Cu, Pb, Zn, As, Co, Ni, Cr), assessing possible mineralization or hydrothermal influence; REE and HFSE (La, Y, Sc, Li, Zr, Ti), reflecting source rock composition and magmatic or weathering processes; and miscellaneous or ambiguous elements (Mn, Ba, Sr, V), which may have mixed lithological or secondary origins.

Elements such as Sb, Mo, and W were also analyzed; however, their concentrations were predominantly below the instrument detection limits (Sb $<$ 5 ppm, Mo $<$ 1 ppm, W $<$ 10 ppm) and were therefore excluded from further interpretation. All elemental data, including average concentrations, standard deviations, background levels, and anomalies, are presented in **Table 1** and further discussed in the Results section.

Table 1: Elemental concentrations in the stream sediment of the Tamiang Aceh, Indonesia

Elements	Units	Mean	Min.	Max.	Site (Max)	Standard deviation	Background	Threshold	Anomaly Location
Al	%	3.20	2.02	4.48	TM02	0.67	3.86	4.53	-
As	ppm	16	6	38	TM37	9.00	25	34	TM33, TM34, TM37, TM 38
Ba	ppm	343	207	673	TM38	121.11	464	585	TM01, TM11, TM38
Ca	%	0.20	0.04	3.58	TM22	1.05	1.25	2.30	TM20, TM21, TM22, TM23, TM32
Co	ppm	11	6	17	TM38	2.94	14	17	TM01, TM37, TM38
Cr	ppm	41	18	82	TM02	14.47	55	69	TM02, TM03
Cu	ppm	13	3	89	TM37	16.37	29	46	TM37, TM38
Fe	%	3.27	1.5	7.82	TM03	1.39	4.66	6.06	TM02, TM03, TM37
K	%	2.01	1.39	3.07	TM01	0.43	2.44	2.88	TM01, TM17
La	ppm	25	11	44	TM05	6.41	31	37	TM05
Li	ppm	24	16	42	TM02	6.09	30	36	TM02, TM03
Mn	ppm	454	160	1350	TM30	273.72	728	1001	TM28, TM30, TM32, TM37, TM38
Na	%	0.36	0.09	0.93	TM17	0.27	0.63	0.90	TM17, TM18
Ni	ppm	23	10	44	TM03	6.56	29	36	TM03
Pb	ppm	23	9	83	TM30	16.87	39	56	TM28, TM30, TM32, TM 37, TM38
Sc	ppm	6	2	9	TM21	1.67	8	9	-
Sr	ppm	56	12	144	TM22	37.60	94	131	TM21, TM22, TM32
Ti	%	0.19	0.1	0.28	TM02	0.04	0.23	0.27	TM02
V	Ppm	53.00	22	101	TM02	18.40	71	90	TM02, TM03
Y	ppm	8.00	3	13	TM02	2.59	11	13	-
Zn	ppm	70	36	152	TM38	27.77	97	125	TM02, TM03, TM30, TM31, TM33, TM37, TM38
Zr	ppm	23	10	43	TM03	8.44	31	40	TM02, TM03

3.3. Data processing and analysis

The laboratory analysis results were subjected to statistical analysis to determine mean, standard deviation, detection limit, and metal distribution, as shown in the histogram curves (**Yaisamut et al., 2023**). Geographic Information System (GIS, ArcGIS) was used to map the spatial distribution of metals in stream sediments from the Tamiang region, Aceh, with concentrations represented as points and color gradients indicating low-to-high values (**Smith et al., 2019; Sun et al., 2019**). Anomaly analysis was conducted to identify unusual metal concentrations potentially related to mineralization or other geological processes. Anomalies were defined as values significantly deviating from the background, calculated using background value = median + standard deviation and threshold = median + 2 × standard deviation (**Manrique, 2022; Yaisamut et al., 2023**), with values exceeding the threshold considered anomalous and further analyzed to assess their spatial patterns.

Graphical presentations focused on elements showing distinct spatial anomalies, as these are most likely to reflect geological controls such as lithological variations, structural features, or hydrothermal alteration. The concentrations of Cu, Zn, Pb, and Co in Tenggulun; Ca and Sr in Tamiang Hulu; La and Li in Sekerak and Bandar Pusaka; and Na and K in Rantau and Seruway were highlighted due to their geochemical significance and correspondence with regional lithologies or weathering processes (**Freitas et al., 2024; Müller et al., 2025; Reinhardt et al., 2018; Xu et al., 2025; Zhao et al., 2025**).

4. Results and Discussion

4.1. Elemental concentrations in the stream sediment

Table 1 summarizes the concentrations of the analyzed elements. To clarify spatial variations and maintain consistency with the subsequent geochemical interpretation, the elements were grouped into four geochemical categories: (1) major and lithogenic elements (Al, Fe, Ca, K, Na, Ti, Sr, Zr), (2) ore-related (chalcophile) elements (Cu, Pb, Zn, As, Co, Ni, Cr), (3) REE and HFSE elements (La, Y, Sc, Li, Zr, Ti), and (4) miscellaneous elements (Mn, Ba, Sr, V). This grouping provides a framework for interpreting spatial geochemical patterns in relation to lithological controls, weathering in-

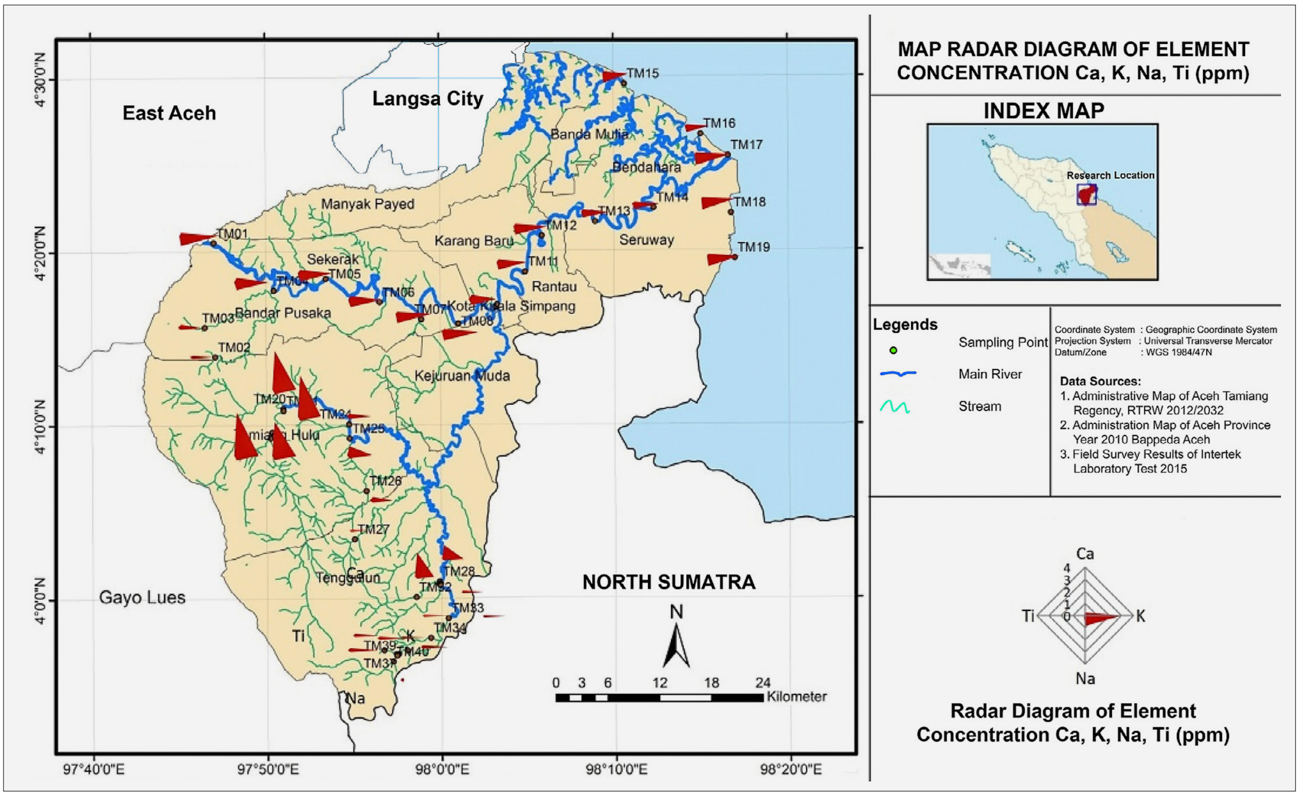

Figure 3: Spatial distribution of metal elements Ca, K, Na, and Ti in the Tamiang region, Aceh, Indonesia

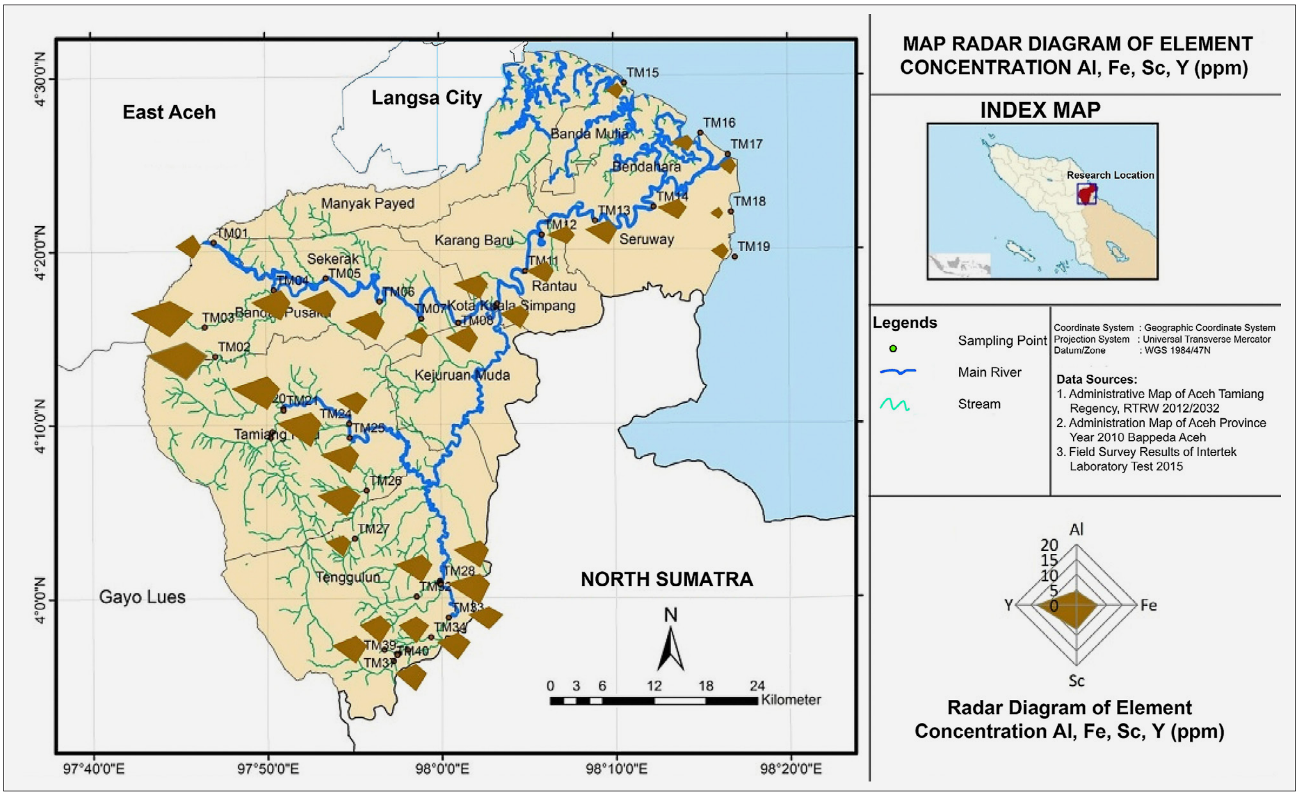

Figure 4: Distribution map of metal elements (Al, Fe, Sc, Y) in Tamiang, Aceh, Indonesia

tensity, and potential mineralization within the Tamiang region. The distinction between background and threshold values for each element provides a useful basis for identifying geochemical variability and delineating potential anomaly zones within the Tamiang region, Aceh, Indonesia.

Major and lithogenic elements such as aluminum (Al), iron (Fe), calcium (Ca), potassium (K), sodium (Na), titanium (Ti), strontium (Sr), and zirconium (Zr) exhibit relatively consistent concentrations across most sampling sites. Aluminum did not exceed the threshold value at any location. Elevated Fe values at TM02, TM03, and TM37 correspond to lithologies enriched in iron oxides and heavy minerals (Tonggiroh, 2020). Calcium and sodium show minor anomalies at TM20–TM23, TM32, and TM17–TM18, respectively, consistent with variations in carbonate and feldspathic lithologies rather than distinct mineralization processes (**Cameron et al., 2007**). Sodium shows background and threshold values both below 1%, with TM17 and TM18 exceeding this limit, likely derived from feldspathic or clay-bearing sediments. Potassium anomalies occur at TM01 and TM17, exceeding its background value of 2% and threshold of 3%. Titanium exhibits an anomaly at TM02, with a background of 0.23% and a threshold of 0.27%. The presence of Ti may be associated with heavy minerals such as ilmenite or titanite (**Ghadimi et al., 2016**). Strontium shows anomalies at TM21, TM22, and TM32, with a background of 94 ppm and a threshold of 131 ppm. These Sr enrichments could indicate localized concentrations related to carbonate-rich lithologies or fluid-induced mobilization (**Li et al., 2020; Smith et al., 2009**). Zirconium anomalies at TM02 and TM03, with a background of 31 ppm and a threshold of 40 ppm, potentially indicate detrital zircon grains or resistant lithological units (**Ali et al., 2022**).

Ore-related (chalcophile) elements, including copper (Cu), lead (Pb), zinc (Zn), arsenic (As), cobalt (Co), nickel (Ni), and chromium (Cr), display more pronounced spatial variability. Arsenic (As), with a background value of 25 ppm and a threshold of 34 ppm, exceeded the threshold at TM33, TM34, TM37, and TM38, suggesting localized As enrichment possibly associated with sulfide-bearing lithologies (**El-Makky & Sediek, 2012**). Cobalt (Co) anomalies occur at TM01, TM37, and TM38 (above 17 ppm), while chromium (Cr) enrichment at TM02–TM03 (above 69 ppm) indicates possible derivation from mafic or ultramafic rocks (**Maier et al., 2016**). Copper (Cu) concentrations surpass the threshold of 46 ppm at TM37–TM38, and lead (Pb) anomalies are recorded at TM28, TM30, TM32, TM37, and TM38, with a background of 39 ppm and a threshold of 56 ppm. Zinc (Zn) enrichment is widespread, occurring at TM02–TM03, TM30–TM33, and TM37–TM38, exceeding its background of 97 ppm and threshold of 125 ppm. Such Zn anomalies may be linked to sulfide mineralization or remobilization by weathering (**Ayari et al., 2022**). The co-occurrence of Cu, Zn, and Pb at multiple sites marks zones of multi-element enrichment, though their origin cannot yet be confirmed without mineralogical evidence (**Ayari et al., 2022; Saadat, 2022; Tonggiroh, 2020; Zheng et al., 2014**). The potential anthropogenic contribution of Pb is considered unlikely given the absence of supporting land-use or contamination data; thus, these variations are more plausibly natural in origin (**Ignatavičius et al., 2022; Saadat, 2022; Tan et al., 2018; Zheng et al., 2014**). Nickel (Ni) shows a background of 29 ppm and a threshold of 36 ppm, with an anomaly detected at TM03. This localized Ni enrichment may be linked to ultramafic rock fragments or hydrothermal veins (**Maier et al., 2016; Shine et al., 2022**).

REE and HFSE elements (La, Y, Sc, Li, Zr, Ti) generally occur at low to moderate levels. Lanthanum (La) exhibits a minor anomaly at TM05, reflecting possible heavy-mineral accumulation or distinct lithological provenance (**Fakolade et al., 2024**). Both yttrium (Y) and scandium (Sc) show stable concentrations throughout the study area, with background values of 11 ppm and uniform distributions, respectively. No geochemical anomalies were detected for either element, indicating stable geochemical behaviour and strong lithological control within the region (**Chassé et al., 2017; Halkoaho et al., 2020; Zhou et al., 2022**). Lithium (Li) enrichment at TM02–TM03, exceeding its 36 ppm threshold, may relate to clay-rich sediments or pegmatitic sources (**Cameron et al., 2007; Rohiman et al., 2024**). Zirconium (Zr) anomalies at TM02–TM03 are consistent with detrital zircon grains hosted in resistant lithologies (**Ali et al., 2022**).

Miscellaneous elements such as barium (Ba), manganese (Mn), strontium (Sr), and vanadium (V) reveal diverse patterns. Barium anomalies at TM01 and TM11 (exceeding 585 ppm) may be associated with barite or Ba-bearing feldspar minerals transported by fluvial processes (**Yaisamut et al., 2023**). Manganese enrichment at TM28, TM30, TM32, TM37, and TM38 could reflect secondary precipitation under variable redox conditions in sedimentary environments (**Haghighizadeh et al., 2024**). Strontium anomalies at TM21–TM22 and TM32 likely indicate local carbonate-rich lithologies or fluid-induced mobilization (**Li et al., 2020; Smith et al., 2009**). The observed patterns provide essential baseline data for subsequent spatial interpretation presented in Section 4.2, ensuring that the discussion remains grounded in observed geochemical evidence.

4.2. Map of Metal Element Distribution in Tamiang, Aceh

Building upon the geochemical classification described in Section 4.1, the spatial distribution of elements was interpreted through four geochemical groups: (1) major and lithogenic (Al, Fe, Ca, K, Na, Ti, Sr, Zr), (2) ore-related or chalcophile (Cu, Pb, Zn, As, Co, Ni, Cr), (3) REE–HFSE (La, Y, Sc, Li, Zr, Ti), and (4) miscellaneous or ambiguous elements (Mn, Ba, Sr, V). This framework facilitates the interpretation of distribution

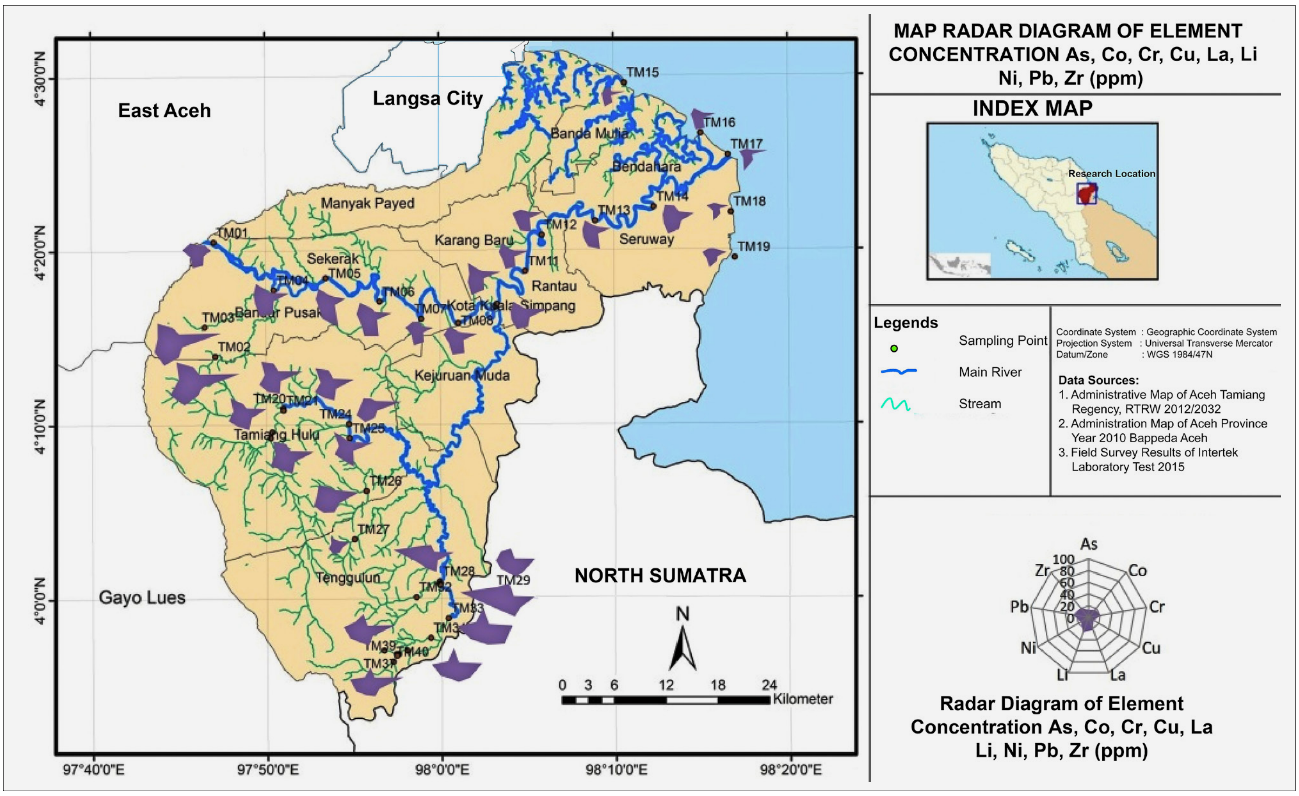

Figure 5: Distribution map of metal elements (As, Co, Cr, Cu, La, Li, Ni, Pb, Zr) in Tamiang, Aceh, Indonesia

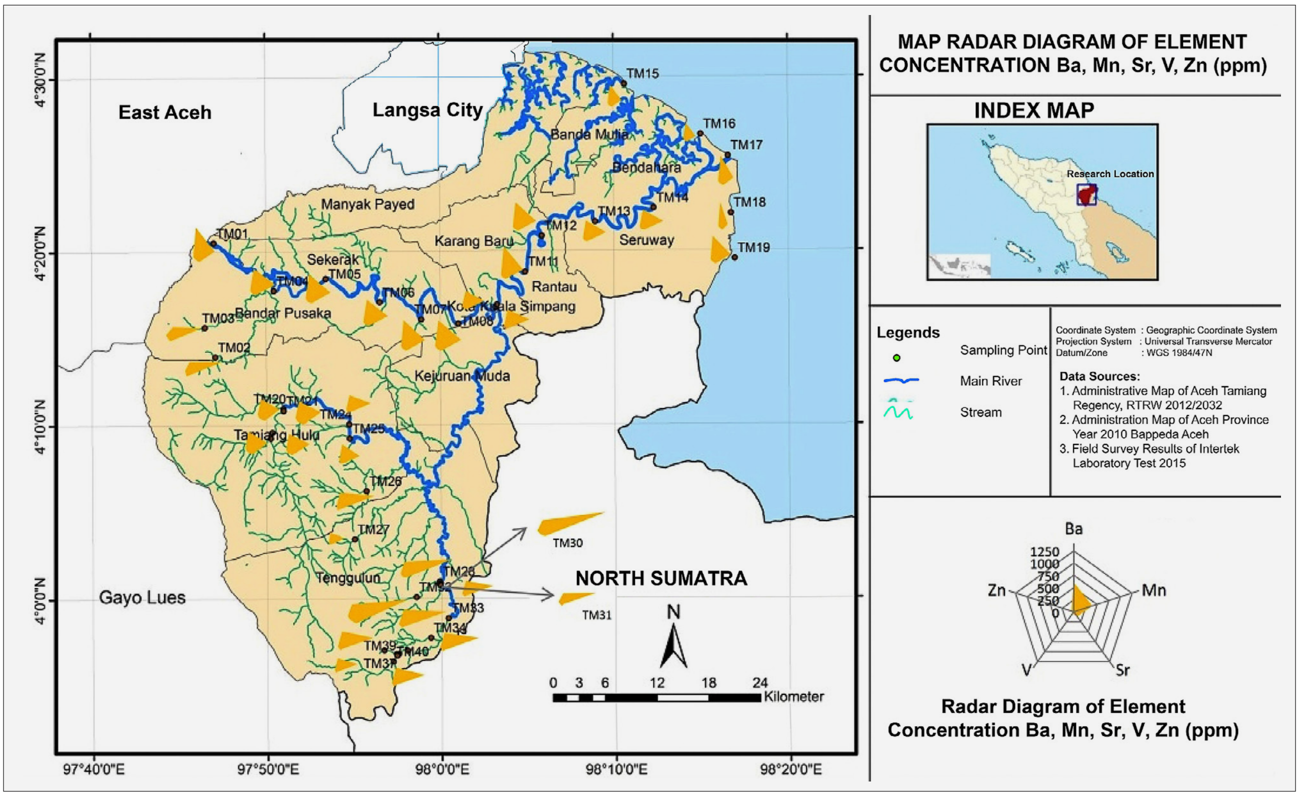

Figure 6: Distribution map of metal elements (Ba, Mn, Sr, V, Zn) in Tamiang, Aceh, Indonesia

maps (see **Figures 3–6**) by linking geochemical variations to lithological composition, weathering intensity, and potential mineralization indicators. The observed spatial patterns suggest that the geochemical variability across the study area is primarily governed by lithology, geomorphology, and surficial processes.

4.2.1. Major and Lithogenic Elements (Ca, K, Na, Ti, Fe, Al, Sr, Zr)

Major and lithogenic elements reflect lithology, mineral composition, and weathering intensity. These elements (Ca, K, Na, Ti) display widespread but generally low enrichment, consistent with their derivation from silicate and carbonate rocks (see **Figure 3**). Their geochemical signatures mainly represent geogenic sources and weathering processes typical of tropical environments. The highest concentrations were identified in Sekerak Village, Kuala Simpang City, Rantau, and Seruway Muara within the Aceh Tamiang region, Indonesia.

In the Tamiang Hulu area, Ca is the dominant element, suggesting the possible presence of carbonate rock formations or Ca-rich sediments derived from ancient marine deposits or lithological inputs from upstream river sources (**Debruyne et al., 2016**). Meanwhile, in Tenggulun, K is the most dominant element, reinforcing the hypothesis that this element has a widespread distribution in surface materials. The dominance of Ca in Tamiang Hulu and K in Tenggulun suggests localized lithological variations that should be validated through further petrographic and mineralogical analyses (**Halkoaho et al., 2020; Morin-Ka et al., 2025**). Elevated Ca concentrations in Tamiang Hulu indicate carbonate-bearing lithologies or Ca-rich alluvial sediments, whereas higher K contents in Tenggulun likely reflect feldspar-rich parent rocks and intense silicate weathering (**Debruyne et al., 2016; Halkoaho et al., 2020; Morin-Ka et al., 2025**).

Potassium reached a maximum value of 3.07%, which may be related to the presence of feldspar minerals in the parent rocks (**Halkoaho et al., 2020**). In contrast, Na exhibited the lowest content (0.93%). The relatively low Na concentrations and broad spatial distribution suggest pervasive weathering of silicate minerals and possible inputs from carbonate rocks in the Tamiang region (**Debruyne et al., 2016**). Na exhibits lower concentrations across most of the region, implying limited sodium-bearing mineral input or higher mobility during chemical weathering (**Debruyne et al., 2016**).

Titanium shows minimal variation, reflecting its occurrence in stable minerals such as ilmenite and rutile that resist decomposition and transport (**Morin-Ka et al., 2025; PWC, 2019; Syakti et al., 2015**). Ti represents the element with the lowest overall concentration across the entire Tamiang region (≈0.28%), consistent with its presence in weathering-resistant minerals such as ilmenite or rutile, which are generally not easily decomposed or dispersed during surface processes (**Morin-Ka et al., 2025; PWC, 2019; Syakti et al., 2015**). These spatial patterns provide insight into the geochemical conditions of the Aceh Tamiang region and can serve as indicators for evaluating mineral potential. Further studies integrating mineralogical and hydrological data are recommended to support sustainable resource utilization and environmental management in the region.

The spatial distribution of Fe and Al was recorded mainly in the upstream reaches of the Tamiang River, particularly in the Tamiang Hulu and Tenggulun areas, reaching maximum values of 7.82% and 4.48%, respectively (see **Figure 4**). Such enrichment is characteristic of tropical lateritic environments, where prolonged weathering and secondary mineral formation result in Fe- and Al-rich regoliths (**Asonye et al., 2022; Zhou et al., 2022**). The spatial trend, with decreasing concentrations downstream, indicates limited transport and dilution effects likely caused by geomorphological constraints and sediment retention in the upper catchment area.

Zr shows elevated values (42 ppm, 44 ppm, and 43 ppm at TM02–TM03), as illustrated in **Figure 5**, with concentrations primarily in Tenggulun and Bandar Pusaka. The localized enrichment in these areas indicates the influence of lithological and geochemical processes, particularly those associated with ultramafic–mafic source rocks and secondary weathering (**Eskdale et al., 2023; Shirazi et al., 2022**). Strontium (Sr) exhibits the highest concentrations in the Tenggulun and Tamiang Hulu areas, with an average of 119 ppm, a minimum of 12 ppm, and a maximum of 144 ppm (see **Figure 6**). Sr enrichment predominantly occurs in the upstream regions of the study area, forming clear spatial clusters consistent with carbonate-bearing lithologies and the occurrence of celestite–barite mineral assemblages (**Lyons et al., 2002**).

4.2.2. Ore-related (chalcophile) elements (As, Co, Cr, Cu, Ni, Pb, and Zn)

Ore-related or chalcophile elements may indicate possible mineralization or hydrothermal influence. These elements (As, Co, Cr, Cu, Ni, Pb, and Zn) exhibit localized enrichments primarily concentrated in the Tenggulun and Bandar Pusaka areas, as illustrated in **Figures 5** and **6**. In the Tenggulun area, arsenic (As) exhibits the highest recorded value of 38 ppm at TM37. In Bandar Pusaka, chromium (Cr) reaches its maximum concentration of 82 ppm at TM02, where Co and Cu also attain their highest levels (17 ppm and 89 ppm, respectively), suggesting a shared geochemical control or mineral association (see **Figure 5**). These anomalies likely coincide with zones underlain by volcanic and intrusive lithologies, indicating possible natural geochemical dispersion from sulfide-bearing rocks (**El-Makky & Sediek, 2012; Maier et al., 2016**).

The distribution of Ni in Bandar Pusaka may reflect minor mineralization derived from igneous or metamorphic rocks, which locally enriches the soil in trace metals (**Doherty et al., 2023; Savina et al., 2023**). Lead (Pb) shows its highest concentration in Tenggulun (83 ppm at TM30, **Figure 5**). The significant accumulation

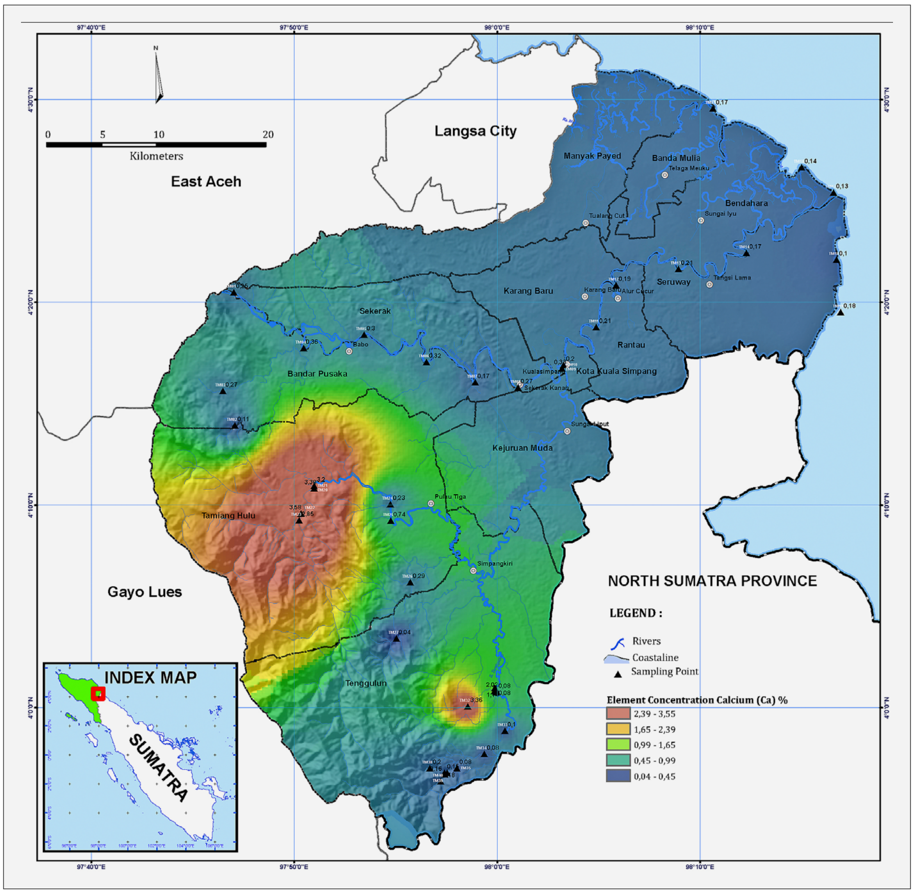

Figure 7: Spatial distribution of calcium anomalies in the Tamiang area, Aceh, Indonesia

of Pb and As at specific sites is noteworthy due to their environmental significance and potential mobility under fluctuating redox conditions (**Briseño-Bugarín et al., 2024; Coţac et al., 2024; Faz et al., 2025; Tan et al., 2018**). However, no mineralogical evidence currently supports active hydrothermal alteration or anthropogenic influence; thus, these enrichments are interpreted as lithologically derived rather than contamination-related. Zinc (Zn) occurs in concentrations ranging from 36 to 152 ppm (average ≈130 ppm), with the highest values found in Bandar Pusaka and Tenggulun (see **Figure 6**). The elevated Zn values likely reflect natural background variation associated with sulfide-bearing lithologies or secondary geochemical redistribution (**Moghimi et al., 2024; Yaisamut et al., 2023**).

4.2.3. REE and HFSE elements (Sc, Y, La, Li, Zr, Ti)

REE and HFSE elements reflect source rock composition as well as magmatic and weathering processes. These elements (Sc, Y, La, Li, Zr, Ti) show relatively uniform spatial distributions, indicating strong lithological control and minimal secondary mobility (see **Figures 3–5**). Ti (see **Figure 3**), although previously classified among the major and lithogenic elements, is discussed here owing to its dual geochemical behaviour.

Scandium (Sc) and yttrium (Y) exhibit similar upstream enrichment patterns, with maximum values of 9 ppm and 13 ppm, respectively. Their concentrations are highest in the Tamiang Hulu and Tenggulun areas (see **Figure 4**), suggesting that the upstream zones serve as primary sources of REE-bearing sediments. This trend reflects the influence of local lithology and weathering processes on elemental distribution. The co-occurrence of Sc and Y likely indicates their association with residual mineral phases such as goethite, hematite, and clay minerals enriched during lateritic weathering (**Aida et al., 2025; Chassé et al., 2017; Halkoaho et al., 2020; Zhou et al., 2022**). The spatial distribution of lanthanum (La), lithium (Li), and zirconium (Zr) is shown in **Figure 5**. Lanthanum (La) exhibits localized enrichment at Sekerak (TM05, 44 ppm), possibly associated with heavy minerals such as monazite or xenotime (**Fakolade et al., 2024**). The identified spatial associations among La, Y, and Sc suggest that REE enrichment is primarily controlled by residual mineral phases in weathered lithologies rather than by hydrothermal processes (**Chassé et al., 2017; Halkoaho et al., 2020; Zhou et al., 2022**).

In the Bandar Pusaka area, Li and Zr show elevated concentrations (42 ppm and 43 ppm at TM02–TM03, respectively). Lithium enrichment at these sites likely reflects inputs from clay-rich sediments or pegmatitic sources (**Cameron et al., 2007; Rohiman et al., 2024**). Zirconium enrichment corresponds to detrital zircon grains within resistant lithologies, indicating limited transport and high mineral stability under tropical weath-

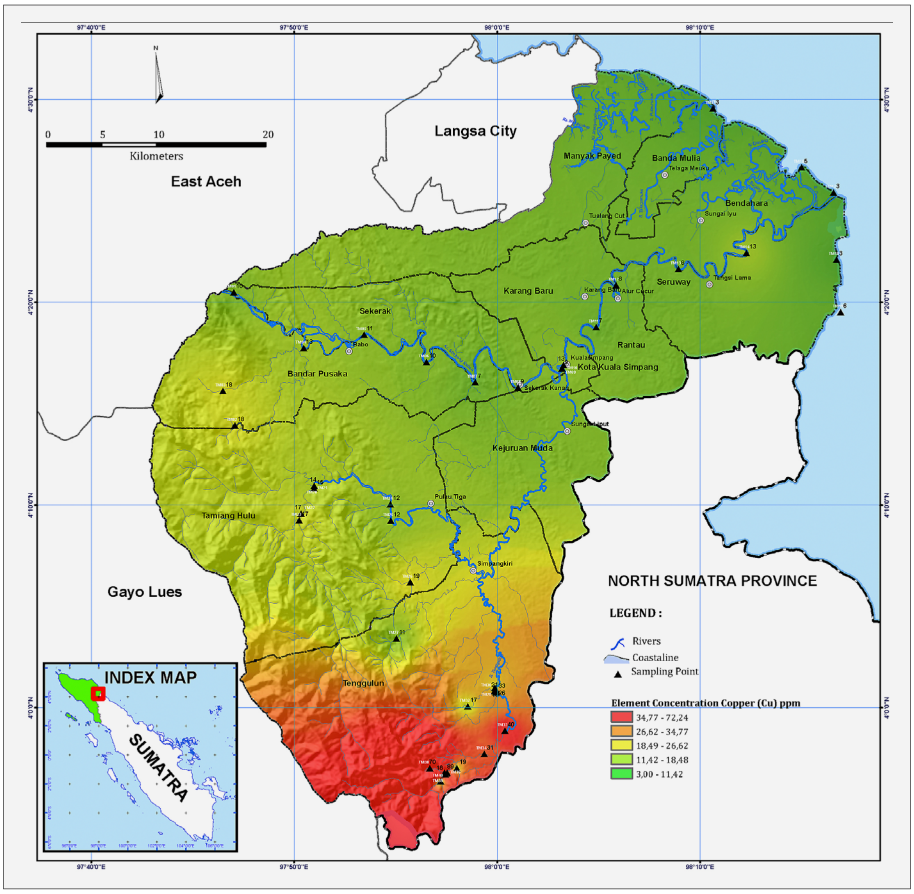

Figure 8: Spatial distribution of copper anomalies in the Tamiang area, Aceh, Indonesia

ering conditions (**Ali et al., 2022; Celis et al., 2022; Coţac et al., 2024**). Overall, the distribution of REE and HFSE elements in the Tamiang Basin highlights the dominance of lithological and weathering controls, with minimal evidence for hydrothermal remobilization.

4.2.4. Miscellaneous or ambiguous elements (Ba, Mn, Sr, V)

Miscellaneous or ambiguous elements may have mixed lithological or secondary origins. As shown in **Figure 6**, elements such as Ba, Mn, Sr, and V exhibit distinct spatial patterns that reflect combined lithological and secondary geochemical influences.

Barium (Ba) shows the highest concentrations in the Bandar Pusaka–Rantau sector, ranging from 207 ppm to 673 ppm (average = 578 ppm). Anomalies at TM01 and TM11 are likely related to detrital barite or Ba-bearing feldspar minerals (**Yaisamut et al., 2023**). These occurrences suggest that Ba is primarily derived from geogenic sources, possibly transported through fluvial or sedimentary processes (**Celis et al., 2022; Yaisamut et al., 2023**).

Manganese (Mn) is particularly enriched in the Tenggulun area, with concentrations between 160 ppm and 1350 ppm (average ≈ 1008 ppm). Such enrichment is characteristic of weathering of Mn-bearing rocks and secondary oxide deposition under fluctuating redox conditions typical of tropical environments (**Tonggiroh, 2020**). The observed Mn distribution highlights zones of enhanced geochemical mobility influenced by hydrological and geomorphological factors.

Strontium (Sr) exhibits elevated levels in the Tenggulun and Tamiang Hulu areas (TM21–TM32), with concentrations ranging from 12 ppm to 144 ppm (average = 119 ppm). Its occurrence is consistent with carbonate-bearing lithologies and celestite–barite mineral assemblages (**Akintola AI et al., 2013; Li et al., 2020; Smith et al., 2009; Wang, 2025**). Elevated Sr values often correspond to celestite and barite formation, the main natural sources of Sr (**Lyons et al., 2002**). The concurrent enrichment of Ba and Sr likely indicates localized barite–celestite mineralization, while high Mn concentrations support the presence of manganese-rich lateritic or sedimentary deposits (**Lyons et al., 2002; Tonggiroh, 2020**).

Vanadium (V) concentrations range from 22 ppm to 101 ppm (average = 89 ppm), with the highest values recorded in Bandar Pusaka. Its spatial distribution appears controlled by local geological substrates containing V-bearing minerals (**Irzon, 2018; Pourret & Dia, 2016**). The occurrence of V suggests additional metallogenic potential in the region and warrants further petrological and geochemical investigation (**Irzon, 2018; Moghimi et al., 2024; Pourret & Dia, 2016; Yaisamut et al., 2023**).

Overall, Ba, Mn, Sr, and V display distinct spatial clustering patterns, predominantly in upstream regions

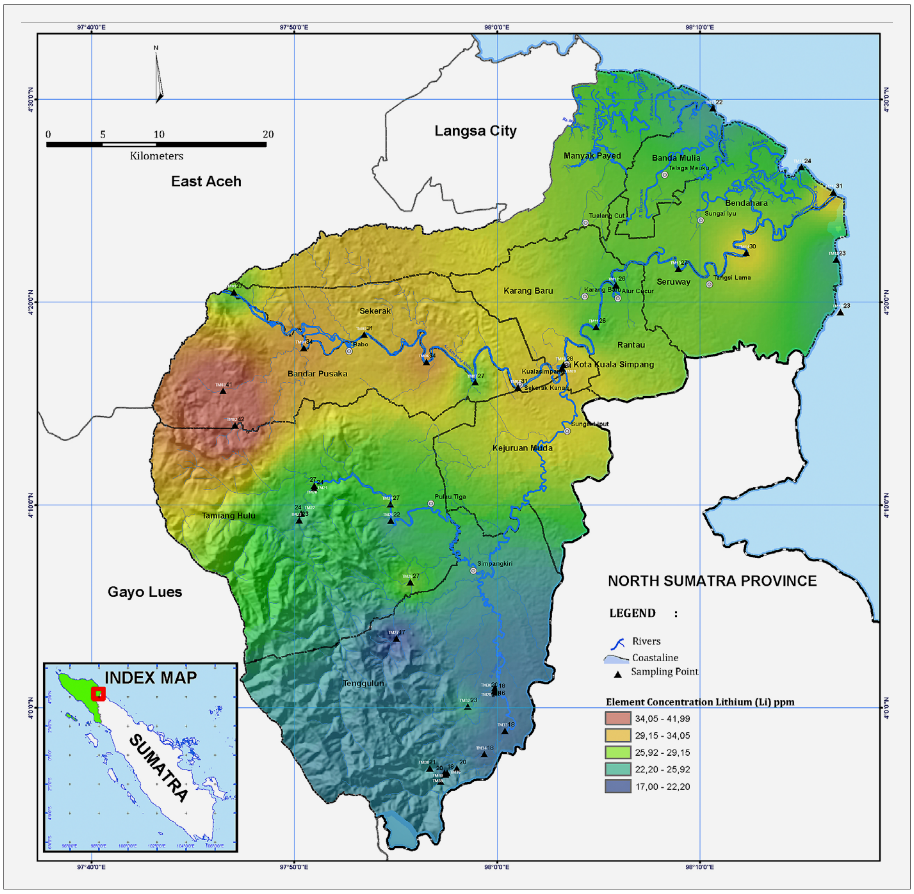

Figure 9: Spatial distribution of lithium anomalies in the Tamiang area, Aceh, Indonesia

of the Tamiang Regency. Their distribution reflects the interplay of lithology, sediment provenance, and surface geochemical processes (**Tan et al., 2018; Wang et al., 2022**). The resulting elemental maps provide a comprehensive baseline for understanding regional geochemical variation and support future integration with mineralogical and hydrological data to refine geological interpretations of the area (**Cameron et al., 2007; Debruyne et al., 2016; Tonggiroh, 2020**).

4.2.5. The Most Pronounced Elemental Anomalies (Ca, Cu, Li, Na)

The most pronounced geochemical anomalies are illustrated on individual maps to highlight their spatial distribution patterns across the study area. Calcium (Ca), a major and lithogenic element, in **Figure 7**; Copper (Cu), representing ore-related (chalcophile) elements, is shown in **Figure 8**; lithium (Li), a trace element associated with REE-bearing minerals, in **Figure 9**; and sodium (Na), an alkali lithogenic element, in **Figure 10**.

This mapping approach enables clearer recognition of localized enrichment zones and facilitates interpretation of spatial geochemical variability within the Tamiang region, Aceh, Indonesia. By displaying elements with contrasting geochemical behaviours separately, the maps provide valuable insight into the lithological and weathering controls influencing metal distribution across the basin.

Figure 7 demonstrates that calcium (Ca) is enriched in the Tamiang Hulu area, where red contours indicate concentrations exceeding 2.39%. The elevated calcium content is most likely associated with the weathering of carbonate-rich lithologies exposed in this region, including the Bohorok Formation (Puk), Kaloi Limestone (MPkl), and Bruksah Formation (Tob) (**Cameron et al., 2007**). Compared to the copper anomalies observed in Tenggulun (see **Figure 7**), the spatial distribution of calcium exhibits a distinct geochemical pattern, reflecting the predominance of carbonate formations over intrusive lithologies. This spatial trend underscores the strong lithological control on the geochemical characteristics of the study area and emphasizes the role of carbonate weathering processes in generating calcium enrichment.

Figure 8 illustrates that copper (Cu) exhibits elevated concentrations in the southern part of the Tamiang region, particularly around Tenggulun, where red contours indicate values exceeding 35 ppm. These elevated Cu levels represent one of the most pronounced geochemical anomalies in the study area. The anomaly is interpreted to be associated with mineralized and lithologically distinct source rocks exposed in the region, including the Mikrogranit Dalam (MPid), the Serbajadi Batholith (MPisj), as well as limestones of the Bohorok Formation (Puk) and the Kaloi Limestone (MPkl) (**Cameron et al., 2007**). The spatial distribution pattern of Cu provides important insight into the potential influence of

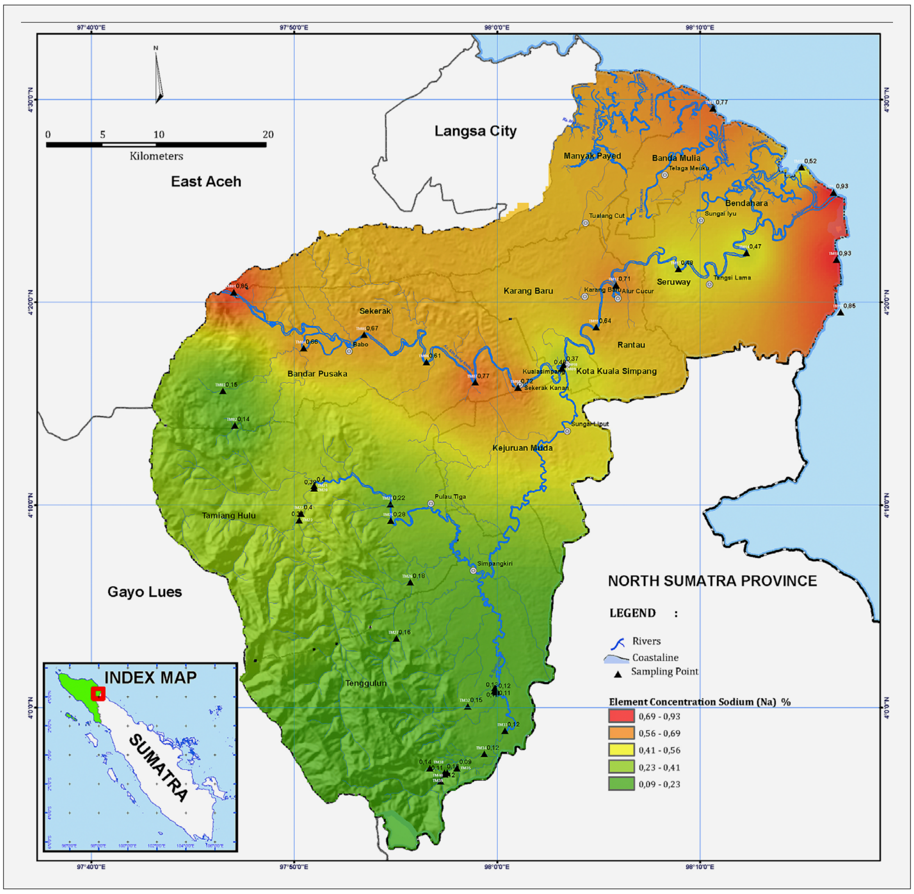

Figure 10: Spatial distribution of sodium anomalies in the Tamiang area, Aceh, Indonesia

local lithology and mineralization processes that have shaped the geochemical landscape of Tenggulun (**Ayuso et al., 2010; Cooke et al., 2020; Müller et al., 2025**).

Figure 9 illustrates that lithium (Li) exhibits elevated concentrations in the Bandar Pusaka area, where red contours indicate values exceeding 34 ppm. The observed lithium enrichment is interpreted to be associated with source rocks closely related to the Lokop Granite (Til), Tampur Limestone Formation (Totl), and Bruksah Formation (Tob) (**Cameron et al., 2007**). In contrast to copper, which demonstrates a strong affinity with mineralized intrusive bodies in Tenggulun, and calcium, which reflects carbonate weathering in Tamiang Hulu, the lithium distribution in Bandar Pusaka underscores the geochemical influence of granitic intrusions interacting with adjacent carbonate sequences. This pattern suggests that the interplay between granitoid sources and carbonate host rocks exerts a major control on lithium enrichment within this part of the study area (**Cardoso-Fernandes et al., 2022**).

Figure 10 illustrates the distribution of sodium (Na), which displays elevated concentrations along the main course of the Sungai Besar, extending from the inland areas around Rantau to the river mouth near Seruway, where red contours indicate values exceeding 0.69%. The relatively widespread occurrence of sodium within this fluvial system is interpreted as the result of weathering processes affecting igneous rocks, siliciclastic formations, and feldspar-bearing minerals (**Kirkwood et al., 2016**). In the upstream regions, the Lokop Granite (Til) serves as a potential source, while the river also traverses several sedimentary formations, including the Baong Formation (Tmb), Keutapang Formation (Tuk), Seuleula Formation (Tps), Idi Formation (Qpi), and Quaternary alluvial deposits (Qh) (**Cameron et al., 2007**). These lithological units likely contribute feldspar fragments that account for the sodium enrichment observed in the sediments and waters of the Sungai Besar system.

The elements emphasized in the graphical presentation were selected for their distinct geochemical anomalies and geological relevance. The elevated levels of Cu, Co, Zn, and Pb in Tenggulun are consistent with geochemical patterns seen in skarn-related mineralization; however, mineralogical and structural data are needed to verify this association (**Freitas et al., 2024; Pirajno, 2010; Xie et al., 2022**). The enrichment of Ca and Sr in Tamiang Hulu corresponds to carbonate lithologies and fluid–rock interactions (**Cooke et al., 2020; Nyakairu & Koeberl, 2001; Taylor & McLennan, 1985**). In Sekerak and Bandar Pusaka, the presence of La and Li, together with relatively immobile elements such as Ti, V, and Zr, reflects felsic or alkali-rich source rocks (**Kirkwood et al., 2016; McClenaghan et al., 2021; Müller et al., 2025; Zhao et al., 2025**). Conversely, anomalies of Na and K in Rantau and Seruway are consistent with tropical silicate weathering and leaching processes (**Kirkwood et al., 2016; Xu et al., 2025**). Collectively, these element-specific anomalies emphasize the strong lithological and geochemical controls governing metal distribution and mineralization potential across the Tamiang region. The observed geochemical signatures thus provide an essential foundation for guiding future exploration efforts and for understanding the geological evolution of this part of Aceh, Indonesia.

5. Conclusions

This reconnaissance geochemical survey provides the first comprehensive dataset of a) major and lithogenic; b) ore-related (chalcophile); c) REE and HFSE; and d) miscellaneous or ambiguous elements in the Tamiang region, Aceh, Indonesia. The results reveal distinct spatial variations that are primarily governed by lithological composition, geomorphological setting, and surface weathering processes. Major and lithogenic elements (Ca, K, Na, Fe, Al, Ti, Sr, Zr) display widespread enrichment patterns, reflecting their lithology, mineral composition, and weathering intensity. Elevated Ca and Sr contents in Tamiang Hulu indicate contributions from carbonate-bearing and feldspar-rich lithologies. In contrast, enrichment in Na and K occurs in Seruway, Ti and Zr in Banda Pusaka, and Fe in Tenggulun. Ore-related elements (Cu, Pb, Zn, As, Co, Ni, and Cr) exhibit localized enrichments, particularly in Tenggulun and Bandar Pusaka, suggesting potential geochemical anomalies related to volcanic and intrusive lithologies rather than active mineralization. The REE and HFSE element anomalies (Sc, Y, La, Li, Zr, Ti) in Bandar Pusaka exhibit relatively uniform distributions, indicating a predominant lithological control with minimal secondary alteration, and reflecting the composition of the source rocks as well as the influence of primary magmatic and weathering processes. Their enrichment in upstream areas supports the interpretation of lateritic weathering over felsic to intermediate parent rocks. Miscellaneous or ambiguous elements (Ba, Mn, Sr, V) display significant spatial clustering, with elevated Ba–Sr values linked to barite–celestite mineral assemblages, while Mn and V enrichment likely reflects redox-driven accumulation in tropical soils. These patterns suggest mixed lithological and secondary origins, with elevated Ba and V observed in Banda Pusaka, and Mn and Sr in Tenggulun.

The most pronounced anomalies, namely Cu, Ca, Li, and Na, highlight distinct geochemical zones corresponding to lithological transitions and hydrological boundaries within the Tamiang Basin. Conversely, three elements Al, Sc, and Y exhibit the lowest concentrations and show no significant anomalies. These patterns collectively indicate that the geochemical variability of the basin is primarily controlled by lithology, surface processes, and sediment provenance, rather than by anthropogenic or hydrothermal inputs. Overall, these geochemical patterns suggest localized metal enrichment rather than confirmed mineralization or deposit types. The results emphasize the importance of regional geological control on metal distribution and highlight zones of interest that warrant further detailed investigation. However, given the reconnaissance scale of this study, the limited sampling density, and the absence of mineralogical or structural verification, interpretations should be considered preliminary. Despite these limitations, this work establishes a valuable baseline geochemical dataset for the Tamiang region. The findings provide an initial framework for understanding regional geochemical variability and serve as a foundation for future, more detailed geological, mineralogical, and geophysical studies aimed at assessing the area's resource potential in a sustainable and scientifically robust manner.

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SAŽETAK

Preliminarno geokemijsko istraživanje u regiji Tamiang, Aceh, Indonezija

Regija Tamiang, u pokrajni Aceh, Indonezija, geološki je složena i nedovoljno istražena, s dostupnim samo osnovnim geokemijskim podatcima. Ova studija predstavlja preliminarno geokemijsko istraživanje za procjenu prostornih razlika u koncentracijama metala i njihove geološke kontrolirajuće faktore. Analizirano je četrdeset uzoraka potočnih sedimenata iz različitih drenažnih sustava na području regije. U uzorcima je mjerena koncentracija 22 kemijska elementa (Al, As, Ba, Ca, Co, Cr, Cu, Fe, K, La, Li, Mn, Na, Ni, Pb, Sc, Sr, Ti, V, Y, Zn, Zr) metodom ICP-OES. Devetnaest elemenata pokazuje anomalne koncentracijske vrijednosti, a najvišim anomalijama ističu se Cu, Ca, Li, i Na. Koncentracije Al, Sc, i Y ostale su u granicama pozadinskih vrijednosti. Temeljem njihova geokemijskog ponašanja kemijski elementi mogu se grupirati u glavne litogene elemente, kao što su Al, Fe, Ca, K, Na, Ti, Sr, i Zr, koji upućuju na litologiju i intenzitet trošenja, te na rudne kemijske elemente, koji uključuju Cu, Pb, Zn, As, Co, Ni, i Cr, koji mogu označavati lokalizirana obogaćenja metalima. Elementi rijetkih zemalja i elementi visokoga naboja, kao što su La, Y, Sc, Li, Zr, i Ti pružaju uvid u sastav izvorišnih stijena te magmatske procese i procese trošenja, dok ostali elementi koji uključuju Mn, Ba, i Sr imaju miješano litološki i sekundarno porijeklo. Prostorni raspored ovih anomalija može upućivati na lokalno metalno obogaćenje povezano sa specifičnim litološkim zonama. Unatoč preliminarnom mjerilu i ograničenoj gustoći uzorkovanja ovi rezultati pružaju temeljni geokemijski okvir Tamian regije te čine osnovu za buduća geološka i geokemijska istraživanja i doprinose pouzdanim znanstvenim procjenama područja.

Ključne riječi:
preliminarna geokemija, potočni sediment, mineraloška prospekcija, geokemijsko kartiranje, Aceh, Indonezija

Author's contribution

Gartika Setiya Nugraha (Dr): conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, resources, software, supervision, validation, visualization, writing – original draft and writing – review & editing, investigation, data collection, and investigation. **Ibnu Rusydy** (MSc): project administration, data curation, and supervision. **Hamzah Nailan Edward** (MSc): software, editing article, formal analysis, and visualization. **Muhammad Taufiq** (B.Eng.): data collection, software, and formal analysis.
All authors have read and agreed to the published version of the manuscript.