

Geochemical Characterisation and Tin Mineralisation Potential of Basement Rocks in Northwestern Wamba, Sheet 210 NW, North-Central Nigeria

Munir Muhammad Gali and Nathaniel G. Goki

Received: : 07 June 2026/ Accepted: 16 September 2026/Published: 24 September 2026

<https://doi.org/10.4314/cps.v13i10.4>

Abstract: This study investigated the geochemical characteristics and tin-bearing mineralisation potential of basement rocks in the northwestern part of Wamba Sheet 210 NW, North-Central Nigeria. Fifteen representative rock samples comprising pegmatite, biotite granite, migmatitic gneiss and basalt were collected and analysed using X-ray fluorescence (XRF) and atomic absorption spectroscopy (AAS). Major- and trace-element data were evaluated using Total Alkali–Silica (TAS) classification, alumina saturation indices, Harker variation diagrams and multi-element geochemical patterns to establish the petrogenetic evolution of the rocks and identify geochemical indicators of tin mineralisation. The major-element results show a wide compositional range, with SiO_2 concentrations varying from 46.10 to 80.94 wt.%. The felsic rocks contain approximately 70.10–80.94 wt.% SiO_2 and generally show decreasing CaO , MgO , Fe_2O_3 and TiO_2 with increasing SiO_2 , accompanied by relative enrichment in K_2O and Na_2O , indicating progressive magmatic differentiation and fractional crystallisation. The analysed samples also exhibit elevated concentrations of incompatible elements, including Rb, which ranges from approximately 31 to 166 ppm, while U ranges from 5 to 10 ppm in the reported samples. Tin concentrations range from below detection to approximately 209 ppm, with the highest concentration recorded in pegmatite sample WMP008 (≈ 209 ppm), followed by values of approximately 82, 77 and 69 ppm in other pegmatitic samples. In contrast, the biotite

granite, migmatitic gneiss and basalt generally contain negligible Sn concentrations. The inverse relationship between Sn and selected mafic oxides, together with the metaluminous to weakly peraluminous character of the felsic rocks and depletion of compatible elements, indicates advanced magmatic differentiation and enrichment of tin in late-stage pegmatitic melts. The results identify the pegmatites, particularly samples exhibiting elevated Sn concentrations, as the principal geochemical targets for further investigation of cassiterite and associated rare-metal mineralisation in the Wamba basement terrain.

Keywords: Cassiterite; Geochemical indicators; Tin mineralisation; Pegmatite; Basement rocks; Wamba; North-Central Nigeria.

Munir Muhammad Gali*

Department of Geology and Mining, Nasarawa State University, Keffi, Nasarawa State, Nigeria
² National Steel Council (NSC)

Email: gallium29@gmail.com

Nathaniel G. Goki

Department of Geology and Mining, Nasarawa State University, Keffi, Nigeria

Email: nathgoki@nsuk.edu.ng

1.0 Introduction

Tin is an economically and technologically important metal with extensive applications in solder, alloys, tinplate, chemicals, electronics, and other emerging technologies. Its economic importance has sustained exploration for tin



Corresponding Author: gallium29@gmail.com

deposits in a variety of geological environments, particularly in highly evolved felsic magmatic systems. Cassiterite (SnO_2) is the principal ore mineral of tin and is commonly associated with evolved granites, pegmatites, greisens, and late-stage hydrothermal systems. The concentration of tin in such environments is commonly related to prolonged fractional crystallisation, crustal melting, and late-stage magmatic-hydrothermal processes. During progressive magmatic differentiation, compatible elements such as Fe, Mg, Ti and Ca are preferentially incorporated into early-forming minerals, whereas incompatible elements, including Rb, Cs, Li, Sn, Nb and Ta, tend to become concentrated in residual melts. Consequently, highly evolved granitic and pegmatitic rocks may display enrichment in incompatible elements accompanied by depletion of elements such as Ba and Sr. These geochemical characteristics provide useful indicators for evaluating the fertility of felsic magmatic systems for rare-metal and tin mineralisation (El Bouseily et al., 1984).

The Nigerian Basement Complex forms an important component of the Pan-African mobile belt and hosts several occurrences of tin, tantalum, niobium and other rare-metal mineralisation. Tin mineralisation in Nigeria occurs in two broad geological environments: the Pan-African rare-metal pegmatite province and the younger Jurassic Younger Granite province. The Pan-African pegmatite belt extends across parts of North-Central Nigeria and includes the Wamba–Jema'a region, where numerous pegmatites have been emplaced within the crystalline basement rocks. These pegmatites are locally associated with cassiterite, columbite-tantalite and other rare-metal minerals. The Younger Granite province, by contrast, contains tin-niobium-tantalum mineralisation associated mainly with highly evolved granitic, greisen, and hydrothermal systems. The occurrence of these mineralisation styles highlights the importance of

magmatic differentiation and late-stage fluid processes in concentrating tin and associated incompatible elements within the Nigerian geological environment.

The Wamba region is particularly important within the Nigerian Pan-African pegmatite province because of the widespread occurrence of pegmatitic bodies and associated rare-metal mineralisation. Previous investigations have shown that pegmatites in the Wamba area occur mainly as intrusive bodies within migmatitic gneiss and related basement rocks. Some of these pegmatites are relatively simple, whereas others are complex and contain quartz, feldspar and mica together with accessory minerals such as tourmaline, garnet, beryl, cassiterite and columbite-tantalite. The occurrence of cassiterite and other rare-metal minerals in some of these bodies indicates that parts of the Wamba pegmatite field experienced substantial magmatic differentiation and late-stage element concentration. Chukwu and Obiora (2021) reported that the Wamba pegmatites comprise different compositional and mineralogical varieties, including pegmatites associated with rare-metal mineralisation. These observations establish the regional significance of Wamba as a prospective area for investigating the geochemical processes responsible for the concentration of tin and other incompatible elements.

Whole-rock geochemistry provides an effective approach for evaluating the petrogenetic evolution and mineralisation potential of basement rocks. Major-element compositions can be used to classify igneous rocks and establish trends associated with magmatic differentiation, while trace-element distributions provide additional information on mineral fractionation, source characteristics and residual melt evolution. In highly evolved felsic systems, increasing SiO_2 and alkali contents, accompanied by decreasing CaO , MgO , FeO_4 , and TiO_2 , may indicate progressive differentiation. Similarly,



Rb enrichment accompanied by Ba and Sr depletion may reflect progressive feldspar fractionation. The alumina saturation index, expressed as A/CNK, is also useful for assessing the peraluminous or metaluminous character of felsic rocks and for interpreting their petrogenetic evolution. In the context of tin exploration, the distribution of Sn and its relationship with elements associated with magmatic differentiation can provide additional evidence for identifying potentially fertile granite–pegmatite systems.

Previous studies of the Wamba region have established the occurrence of rare-metal pegmatites and have documented associations involving cassiterite, columbite-tantalite and other accessory minerals. However, most available investigations have focused on particular pegmatite bodies or specific aspects of their mineralogical and geochemical characteristics. Consequently, the geochemical relationships among the different lithological units in the northwestern part of Wamba Sheet 210 NW remain insufficiently constrained. In particular, we need to establish how the major- and trace-element compositions of migmatitic gneiss, biotite granite, pegmatite, and basalt vary across the study area, and whether the observed Sn distribution is associated with progressive magmatic differentiation. Establishing these relationships matters because pegmatites alone do not necessarily indicate significant tin mineralisation; instead, their degree of geochemical evolution and enrichment in incompatible elements must be evaluated.

This study therefore addresses the knowledge gap of limited integrated geochemical information on the relationship between basement lithologies and Sn enrichment in the northwestern part of Wamba Sheet 210 NW. Although the wider Wamba region is recognised for rare-metal and cassiterite-bearing pegmatites, the geochemical indicators of tin fertility within the specific lithological association investigated

in this study have not been sufficiently established. In particular, the extent to which major-element differentiation trends, alumina saturation, trace-element enrichment and Sn concentration distinguish the pegmatites from their associated basement rocks requires further investigation. Addressing this gap will provide a more reliable basis for interpreting the petrogenetic evolution of the rocks and assessing their potential significance for tin mineralisation. This study aims to characterise the major- and trace-element geochemistry of selected basement rocks in the northwestern part of Wamba Sheet 210 NW and evaluate geochemical indicators associated with potential tin-bearing mineralisation. Specifically, the study seeks to:

- (i) classify the investigated rocks using appropriate major-element geochemical classification diagrams;
- (ii) assess the degree of magmatic differentiation using major- and trace-element variation trends;
- (iii) determine the distribution and concentration of Sn among the different lithological units;
- (iv) evaluate the relationship between Sn and selected major and trace elements; and
- (v) identify geochemical characteristics of the granitic and pegmatitic rocks that may indicate potential Sn fertility.

The study contributes to understanding the geochemical evolution and mineralisation potential of the Wamba Basement Complex. By examining the distribution of major elements, trace elements and Sn across the different lithological units, the study provides information that can help distinguish relatively less evolved rocks from more highly differentiated and potentially Sn-fertile granitic–pegmatitic systems. The results may also provide a scientific basis for prioritising areas for subsequent detailed mineralogical, geochemical, geophysical and exploration investigations. In addition, the study contributes to the broader



understanding of the processes responsible for the concentration of Sn and other incompatible elements within the Pan-African basement rocks of North-Central Nigeria.

1.1 Study Area and Local Geological Setting

The study area is located in the northwestern part of Wamba Local Government Area of Nasarawa State, North-Central Nigeria, within the Wamba North-West topographic sheet (Sheet 210 NW). The area lies approximately between latitudes 8°55'28"N and 9°00'00"N and longitudes 8°38'06"E and 8°46'00"E, and covers approximately 40 km² at a map scale of 1:25,000 (Figure 1). The study area forms part of the Nigerian Basement Complex and lies within the North-Central Basement Complex terrain, which has experienced a complex history of deformation, metamorphism, crustal reworking, and magmatic activity, particularly associated with the Pan-African tectono-magmatic events.

The regional geology of the study area is characterised by crystalline basement rocks that include migmatitic gneiss, granitoids and associated pegmatitic bodies. Within the study area, the principal lithological units identified are migmatitic gneiss, biotite granite, pegmatite and basalt. Migmatitic gneiss and biotite granite constitute the dominant exposed rock types, whereas pegmatites occur as intrusive bodies of variable thickness, orientation and lateral continuity. Basaltic rocks occur as relatively minor bodies associated spatially with the crystalline basement lithologies. The distribution of these lithological units is shown on the geological map of the study area (Figure 2).

The migmatitic gneiss constitutes a major component of the basement terrain. The rock records a complex history of metamorphism, deformation and partial melting and provides an important geological framework for understanding the crustal evolution of the area. Its association with granitic rocks is particularly relevant to investigations of crustal melting and the generation or emplacement of felsic magmas.

However, the occurrence of migmatitic gneiss in association with granite and pegmatite does not, by itself, establish a direct genetic relationship among the lithologies; such relationships require support from field observations and geochemical evidence.

The biotite granite is another major lithological unit within the study area. Its relatively felsic composition makes it important for assessing magmatic-system evolution. Where progressive differentiation has occurred, granitic magmas may evolve toward residual melts enriched in incompatible elements. Consequently, the major- and trace-element composition of the biotite granite provides an important basis for evaluating its degree of evolution and its possible relationship with the associated pegmatites.

The pegmatites occur as intrusive bodies within the basement rocks and vary in size, orientation and degree of development. Their occurrence within the granitic and migmatitic basement is significant because pegmatites commonly represent late-stage products of highly evolved felsic magmas. The wider Wamba region is recognised for rare-metal pegmatites, some of which contain cassiterite and columbite-tantalite. The presence of pegmatites in the study area therefore provides an important geological basis for investigating Sn enrichment. Nevertheless, the occurrence of a pegmatite does not necessarily imply economic mineralisation, and its mineralisation potential must be evaluated using mineralogical and geochemical evidence.

The basaltic rocks occur as relatively minor bodies within the study area and provide a contrasting mafic component to the predominantly felsic basement assemblage. Their presence is useful for evaluating the compositional range of the rocks and for establishing major-element variation across the investigated lithological units. The basaltic rocks should not, however, be assumed to form part of the same magmatic differentiation sequence as the granitic and pegmatitic rocks without



supporting geochemical and petrological evidence. This study therefore evaluates their relationship with the other lithologies based on chemical characteristics rather than solely on spatial association.

The spatial occurrence of pegmatites as intrusive bodies within migmatitic gneiss and granitic rocks is also relevant to the structural control of late-stage magmatic emplacement. Fractures, joints, shear zones and other structural discontinuities can provide pathways for the emplacement of evolved felsic melts and associated fluids. In the wider Wamba region, pegmatitic dykes within basement rocks have been associated with the area's Pan-African tectono-magmatic evolution. Such relationships provide a geological framework for investigating whether the observed Sn enrichment is

associated with advanced magmatic differentiation and late-stage melt evolution.

Overall, the association of migmatitic gneiss, biotite granite, pegmatite and basalt provides a useful geological framework for evaluating variations in major- and trace-element composition across the study area. Particular attention is given to the pegmatitic rocks because highly evolved pegmatites are well associated with Sn-Ta-Nb mineralisation in the wider Wamba region. This study integrates lithological observations with major- and trace-element geochemistry to identify geochemical characteristics associated with Sn enrichment and assess the potential significance of the investigated rocks for further cassiterite exploration.

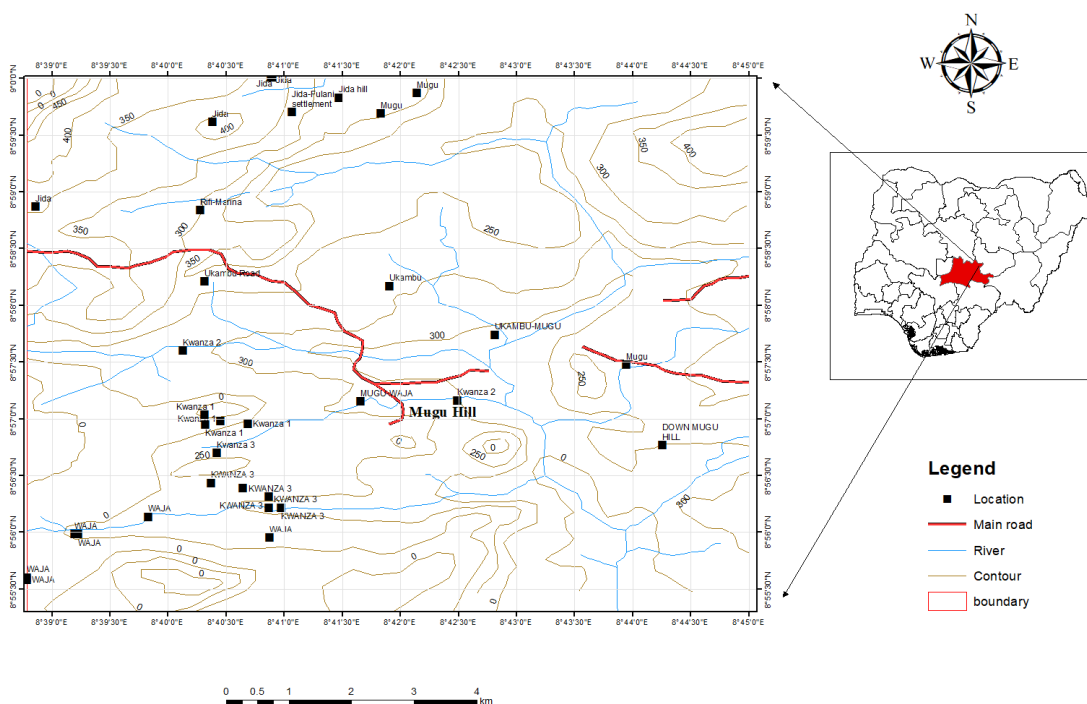


Fig. 1: Location and Accessibility map of the study area



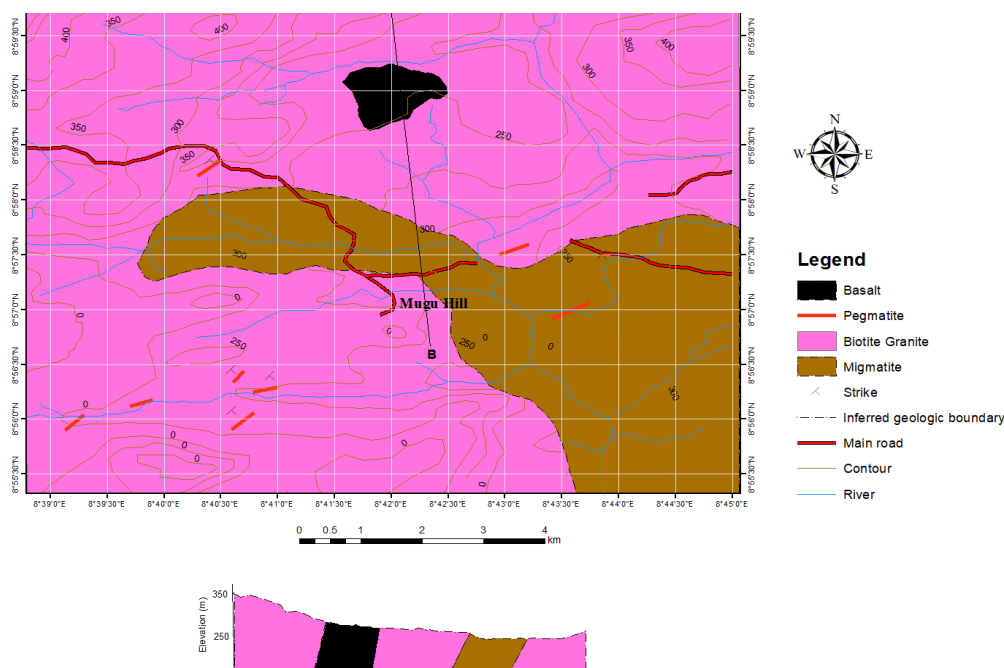


Fig. 2: Geologic Map of the Study Area, North-western part of Wamba

3.0 Materials and Methods

3.1 Sample Collection and Preparation

A total of 15 representative rock samples were collected from the study area. The samples comprised pegmatite, biotite granite, migmatitic gneiss and basaltic rocks, representing the major lithological units exposed within the study area. Sampling was undertaken at selected locations to obtain representative specimens of each lithological unit and to provide adequate coverage of the investigated area.

Each sample was assigned a unique identification number in the field and carefully packaged in clean sample bags to prevent contamination during transportation and storage. Representative portions of the samples were subsequently selected for laboratory analysis. The samples were oven-dried, crushed and pulverised to obtain homogeneous material suitable for geochemical analysis. The prepared samples were analysed for major and trace elements using X-ray fluorescence

(XRF), while selected pegmatite samples were further analysed for lithium (Li) using atomic absorption spectroscopy (AAS).

We selected 13 pegmatite samples for additional Li analysis because lithium enrichment can provide useful information on the degree of evolution in highly differentiated pegmatitic systems. The analytical results obtained from the different methods were integrated to evaluate the geochemical characteristics of the investigated rocks and their implications for potential tin-bearing mineralisation.

3.2 X-Ray Fluorescence (XRF) Analysis

X-ray fluorescence (XRF) spectrometry was employed to determine the concentrations of major oxides and selected trace elements in the rock samples. We weighed and homogenised about 10 g of each oven-dried, sieved sample before analysis. We crushed and pulverised the samples using an agate crusher to minimise contamination and obtain a sufficiently fine, homogeneous powder.



For pressed-pellet preparation, we compacted the powdered samples into 25-mm pellets using a hydraulic press at approximately 20 tons. Where fused-bead preparation was required, approximately 0.5 g of powdered sample was mixed with lithium-borate flux in a platinum crucible. The mixture was fused to produce a homogeneous glass bead, which was subsequently cooled and prepared for instrumental analysis. The appropriate preparation procedure was selected in accordance with the analytical requirements of the XRF determination and the laboratory protocol (Pott & Webb, 1992; Bruker, 2004).

The prepared samples were analysed using a PANalytical Axios wavelength-dispersive X-ray fluorescence (WDXRF) spectrometer at the National Steel Raw Materials Exploration Agency (NSRMEA) laboratory. The XRF technique was used to determine concentrations of major oxides and selected trace elements, including Sn, along with other elements relevant to interpreting the geochemical evolution and potential tin mineralisation of the study area.

The resulting elemental concentrations were used for lithological classification and for evaluating systematic variations among the rock samples. The data were subsequently subjected to graphical and geochemical analyses, including major-element variation diagrams, trace-element patterns and alumina saturation calculations, to assess the degree of magmatic differentiation and identify geochemical characteristics associated with potentially Sn-fertile rocks.

3.3 Atomic Absorption Spectroscopy (AAS)

Atomic absorption spectroscopy (AAS) was used to determine the concentration of lithium (Li) in selected pegmatite samples. Of the 15 rock samples collected, 13 pegmatite samples were selected for Li determination because lithium enrichment may indicate advanced magmatic differentiation in rare-metal pegmatitic systems.

Before AAS determination, the prepared rock samples underwent the appropriate laboratory digestion procedure to transfer the target element into solution. The resulting solutions were introduced into the AAS instrument and atomised in the flame. During measurement, ground-state atoms of the target element absorb radiation at characteristic wavelengths. We measured the resulting absorbance and compared it with calibration standards of known concentration to determine the Li concentration in the analysed samples.

We used the Li concentrations from the AAS analysis as supplementary geochemical information to assess the degree of evolution of the pegmatites. In combination with the XRF-derived Sn and other elemental concentrations, the Li data were used to evaluate whether the more evolved pegmatitic samples exhibited geochemical characteristics consistent with potential rare-metal and tin-bearing mineralisation.

3.4 Descriptive Statistics and Geochemical Data Analysis

Descriptive statistical analysis was carried out on the major-oxide and trace-element data obtained from the laboratory analyses. The statistical parameters calculated included the minimum, maximum, mean and standard deviation. These parameters summarised the concentration ranges and dispersion of major and trace elements among the investigated rock samples.

The geochemical dataset was further evaluated using appropriate classification and variation diagrams. These included Total Alkali–Silica (TAS) diagrams, binary variation plots, Harker variation diagrams, alumina saturation diagrams and multi-element spider diagrams. The TAS diagrams were used to provide a geochemical classification of the analysed igneous rocks based on their total alkali and SiO₂ contents. Binary and Harker variation diagrams were used to examine relationships between SiO₂ and selected major and trace



elements and to identify systematic elemental trends that may reflect magmatic differentiation and mineral fractionation.

The alumina saturation characteristics of the felsic rocks were evaluated using the A/CNK ratio, calculated using equation 1

$$A/CNK = \frac{Al_2O_3}{CaO + K_2O + Na_2O} \quad (1)$$

where the oxide concentrations are expressed in molecular proportions. We used the resulting values to distinguish metaluminous and peraluminous compositions and to assess variations in the alumina-saturation characteristics of the investigated rocks.

We used multi-element spider diagrams to examine the relative enrichment and depletion of selected trace elements. For primitive-mantle-normalised diagrams, we normalised the measured concentrations to the selected primitive-mantle reference values. We used the resulting patterns to evaluate the behaviour of incompatible and compatible elements and to identify elemental signatures associated with progressive magmatic differentiation.

We focused on the distribution of Sn and Li and their relationships with major and trace elements in the pegmatitic and associated felsic rocks. We used descriptive statistics, geochemical classification diagrams, elemental variation trends, and trace-element patterns to evaluate the petrogenetic characteristics of the investigated rocks and identify geochemical indicators of potential tin-bearing mineralisation within the study area.

4.0 Results and Discussion

4.1 Major-Element Geochemistry

Tables 2a and 2 b present the major-element compositions of the 15 analysed rock samples. The dataset comprises samples of pegmatite, biotite granite, migmatitic gneiss and basaltic rocks from the northwestern part of Wamba Sheet 210 NW. The major oxides analysed include SiO₂, Al₂O₃, CaO, Fe₂O₃, K₂O, MnO, MgO, Na₂O, TiO₂, P₂O₅, ZrO₂ and Li₂O. The results reveal substantial chemical variation among the lithological units, reflecting

differences in their mineralogical composition and degree of magmatic evolution.

The SiO₂ contents range from 46.10 to 80.94 wt.% (Tables 2a and 2b). The lowest value occurs in sample WMB015, which represents the basaltic lithology, whereas the highest value occurs in WMP004. The relatively high SiO₂ contents of most of the samples indicate that the sampled lithological assemblage is dominated by felsic rocks, particularly granitic and pegmatitic compositions. The broad SiO₂ range reflects the contrasting compositions of the mafic and felsic lithologies exposed in the study area.

The basaltic sample WMB015 is characterised by relatively high CaO (7.30 wt.%), Fe₂O₃ (11.51 wt.%) and MgO (5.95 wt.%) compared with the felsic samples (Table 2b). It also contains the highest TiO₂ concentration (1.74 wt.%). These characteristics are consistent with its mafic composition and distinguish it chemically from the granitic and pegmatitic rocks.

In contrast, the felsic samples generally contain low CaO, MgO, Fe₂O₃ and TiO₂. The decrease in these mafic oxides relative to SiO₂ is particularly evident among the highly evolved samples (Tables 2a and 2b). These relationships are consistent with progressive removal of ferromagnesian, calcic, and Ti-bearing minerals during magmatic differentiation. However, the individual lithologies may have different petrogenetic histories, so interpret the major-element relationships alongside the trace-element data and field relationships.

K₂O ranges from 0.87 to 9.84 wt.%, with the highest value occurring in WMP002 (Table 2a). Na₂O ranges from 0.19 to 7.17 wt.%, with the maximum value recorded in WMP010 (Table 2b). The relatively high concentrations of K₂O and Na₂O in several felsic samples are consistent with the abundance of alkali-bearing minerals and the chemical evolution of felsic magmas.



Table 2a. Major oxide concentrations of rocks from the study area (WMP001–WMP008)

Oxide (wt.%)	WM P001	WM P002	WM P003	WM P004	WM P005	WM P006	WM P007	WM P008
SiO ₂	76.15	74.80	76.01	80.94	76.15	76.09	75.10	75.26
Al ₂ O ₃	12.48	11.25	10.13	11.45	12.49	12.17	12.47	12.05
CaO	0.51	0.38	0.11	0.37	0.51	0.22	1.00	0.57
Fe ₂ O ₃	0.50	0.37	0.38	0.53	0.50	1.11	0.47	2.42
K ₂ O	4.43	9.84	8.41	3.09	4.43	4.18	4.46	4.66
MnO	0.01	0.03	0.12	0.14	0.01	0.03	ND	0.10
MgO	0.19	0.10	0.15	0.09	0.19	0.26	0.35	0.35
Na ₂ O	4.06	0.21	0.19	0.41	4.06	4.39	3.73	4.04
TiO ₂	0.06	0.06	0.03	0.04	0.06	0.02	0.47	0.26
P ₂ O ₅	ND	ND	0.01	0.07	ND	0.01	0.03	0.08
ZrO ₂	0.04	0.04	0.03	0.03	0.04	ND	0.01	0.18
Li ₂ O	0.08	0.14	0.40	0.40	0.03	0.04	0.01	0.06

Note: ND = not detected. Source: XRF analytical results from the present study.

Table 2b. Major oxide concentrations of rocks from the study area (WMP009–WMB015)

Oxide (wt.%)	WM P009	WM P010	WM P011	WM P012	WM P013	WM G014	WM B015
SiO ₂	76.26	72.38	75.09	75.02	70.10	70.18	46.10
Al ₂ O ₃	10.86	12.34	12.02	11.56	12.22	16.66	10.44
CaO	0.37	0.17	0.54	0.50	1.15	0.22	7.30
Fe ₂ O ₃	1.23	1.96	0.62	1.53	1.11	4.91	11.51
K ₂ O	4.65	4.17	4.63	4.34	4.28	3.01	0.87
MnO	0.03	0.05	0.02	0.05	0.06	0.06	0.40
MgO	0.18	0.16	0.16	0.21	0.40	0.67	5.95
Na ₂ O	4.68	7.17	4.18	4.84	4.05	2.64	2.52
TiO ₂	0.11	0.07	0.12	0.12	0.60	0.56	1.74
P ₂ O ₅	0.01	0.01	0.03	0.02	0.05	0.01	0.07
ZrO ₂	0.10	0.37	ND	ND	ND	ND	ND
Li ₂ O	0.02	0.02	0.01	0.02	ND	ND	ND

Note: ND = not detected. Source: XRF analytical results from the present study.

The Li₂O data are also of interest. Values up to 0.40 wt.% occur in WMP003 and WMP004, whereas Li₂O is either very low or below detection in several of the other samples (Tables 2a and 2b). Because lithium is strongly incompatible in many common rock-forming minerals, its enrichment in selected pegmatitic samples may indicate concentration in late-stage residual melts. The Li results should, however, be interpreted

alongside the AAS results and mineralogical data.

Overall, the major-element compositions show a pronounced contrast between the basaltic sample and the felsic granitic–pegmatitic samples. The felsic rocks are characterised by high SiO₂ and relatively low concentrations of CaO, MgO, Fe₂O₃ and TiO₂, providing evidence of substantial magmatic evolution.



4.1.1 Trace-Element Geochemistry

Tables 3a and 3 b present the trace-element concentrations from the XRF analyses. The elements analysed include S, K, Sc, V, Cr, Ni, Cu, Zn, As, Rb, Sr, Zr, Nb, Mo, Ba, Sn, Pb, Th

and U. Particular attention is given to Sn, Rb, Sr, Ba, Zr and Nb, because these elements provide useful information on the degree of magmatic differentiation and the potential fertility of felsic rocks for rare-metal mineralisation.

Table 3a. Trace-element concentrations of rocks from the study area (WMP001–WMP008)

Atom	WM P001	WM P002	WM P003	WM P004	WM P005	WM P006	WM P007	WM P008
S	220	600	500	300	700	225	200	250
K	36,7 69	81,672	69,803	25,647	36,769	34,694	37,018	38,678
Sc	10	11	16	12	12	11	11	11
V	21	23	29	70	87	67	120	112
Cr	50	72	41	50	80	50	50	54
Ni	10	20	20	10	20	20	20	20
Cu	10	22	26	30	33	33	50	27
Zn	15	20	54	30	40	29	40	27
As	17	21	19	2	2	2	47	11
Rb	31	—	—	—	—	—	—	—
Sr	—	—	—	—	—	—	—	—
Zr	2,654	3,249	804	2,403	2,184	3,180	1,633	611
Nb	20	22	—	—	—	—	—	—
Mo	26	11	2	2	2	10	2	2
Ba	130	220	112	311	270	131	210	207
Sn	77	2	69	2	29	49	2	209
Pb	28	5	17	68	83	5	5	5
Th	5	5	5	5	5	5	5	5
U	5	5	5	5	20	5	5	5

Note: — indicates that the value could not be read reliably from the supplied low-resolution table image and should be checked against the original laboratory dataset. Source: XRF analytical results from the present study.

The trace-element data show substantial variation among the lithologies (Tables 3a and 3b). The most important feature for this study's objective is the distribution of Sn. Tin concentrations range from 2 to 209 ppm, with the highest concentration recorded in WMP008 (209 ppm). Other relatively elevated Sn concentrations occur in WMP001 (77 ppm), WMP003 (69 ppm), WMP005 (29 ppm), WMP006 (49 ppm), WMP011 (82 ppm), WMP012 (51 ppm) and WMB015

at approximately 49 ppm in the supplied data (Tables 3a and 3b).

The concentration of Sn is therefore variable across the sampled lithologies, but the highest value occurs in a pegmatitic sample. This distribution supports the interpretation that the pegmatitic rocks represent the principal geochemical targets for further investigation of tin mineralisation in the study area. Nevertheless, whole-rock Sn concentration alone does not demonstrate that the Sn occurs



as cassiterite. Mineralogical confirmation would be required to establish the specific Sn-bearing phase.

The trace-element distribution also shows relatively elevated Rb and Zr concentrations in several felsic samples (Tables 3a and 3b). Rb is an incompatible element that commonly becomes concentrated in residual melts during

progressive crystallisation. Its enrichment, particularly when accompanied by depletion in Sr and Ba, can therefore indicate advanced feldspar fractionation. Zr may also become enriched in evolved felsic systems, although its behaviour depends on the stability and crystallisation of zircon and other Zr-bearing phases.

Table 3b. Trace-element concentrations of rocks from the study area (WMP009–WMB015)

Atom	WM P009	WMP 010	WMP 011	WMP 012	WMP 013	WMG0 14	WMB 015
S	450	500	225	200	300	200	200
K	38,5 95	34,61 1	38,429	36,022	35,524	24,983	7,221
Sc	10	10	10	11	10	15	17
V	200	214	122	118	115	225	200
Cr	60	77	41	77	90	90	200
Ni	20	20	20	20	20	20	25
Cu	25	42	42	31	20	20	25
Zn	42	31	33	21	20	67	50
As	14	14	20	30	49	2	2
Rb	—	—	—	—	—	—	—
Sr	—	—	—	—	—	—	—
Zr	3,45 3	679	626	2,944	152	154	50
Nb	—	—	—	—	—	—	—
Mo	2	2	2	11	10	4	120
Ba	680	626	294	152	154	50	130
Sn	2	2	82	51	2	49	49
Pb	48	21	17	21	5	5	5
Th	5	5	5	5	5	5	5
U	5	5	5	5	5	10	5

Note: — indicates that the value could not be read reliably from the supplied low-resolution table image and should be checked against the original laboratory dataset. Source: XRF analytical results from the present study.

The relatively low concentrations of compatible or mafic-associated trace elements in the evolved felsic samples, compared with the basaltic sample, are consistent with the major-element evidence for differentiation. The basaltic sample contains comparatively high V and Cr, reflecting its mafic character, whereas the highly siliceous rocks generally contain lower concentrations of these elements (Tables 2a, 2b, 3a and 3b).

4.2 Geochemical Classification of the Rocks

4.2.1 Total Alkali–Silica Classification

The analysed samples were classified using the Total Alkali–Silica (TAS) diagram, and the resulting distribution is presented in Figure 3. The samples occupy a broad compositional range extending from mafic to highly felsic compositions. The basaltic sample plots within the mafic field, whereas the granitic and



pegmatitic samples occupy the high-SiO₂ portion of the diagram.

The TAS classification is consistent with the major-element compositions presented in Tables 2a and 2b. The high SiO₂ contents of the granitic and pegmatitic samples distinguish them clearly from the basaltic sample. The pegmatitic samples occupy the most evolved

portion of the compositional range, consistent with their high silica and alkali contents.

The distribution of the samples in Fig. 3 therefore confirms that the study area contains chemically contrasting mafic and felsic lithologies. The TAS diagram, however, should be regarded primarily as a classification tool and not as independent evidence of a common parental magma.

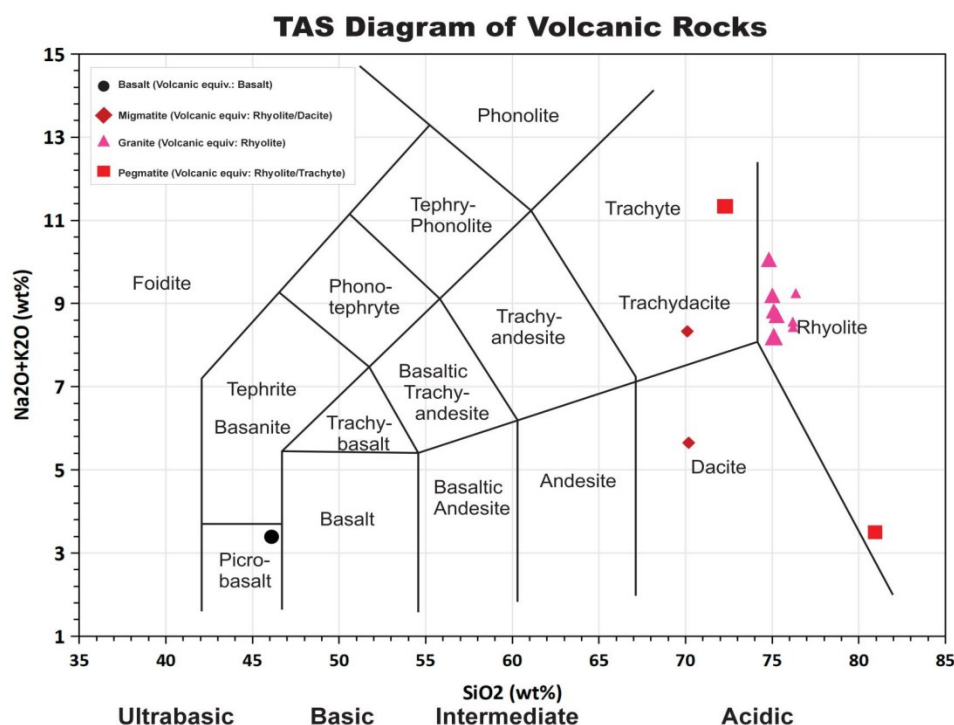


Fig 3. Rock classification from Northwestern part of Wamba, using TAS diagram. Modified After (Le Bas *et al.*, 1986).

4.2.2 Major-Element Variation and Magmatic Differentiation

The relationships between SiO₂ and selected major oxides are shown in Figs. 4a–4h. These diagrams were used to evaluate systematic changes in major-element composition with increasing silica and to assess the degree of magmatic differentiation.

The relationship between SiO₂ and Al₂O₃ is presented in Fig. 4a. The samples show relatively limited variation in Al₂O₃ compared

with the large variation in SiO₂. The distribution may reflect the combined effects of feldspar crystallisation and differences in the source and evolutionary history of the lithologies.

SiO₂–CaO relationship

The SiO₂–CaO relationship is shown in Fig. 4b. CaO generally decreases as SiO₂ increases. This negative relationship is compatible with progressive removal of Ca-bearing minerals, particularly plagioclase,



during differentiation. The very low CaO concentrations in the highly felsic samples are

consistent with advanced evolution of the residual melt.

Multiple plot of SiO_2 vs. Al_2O_3 , CaO, K_2O , MgO, Na_2O , TiO_2 , P_2O_5 , FeOt

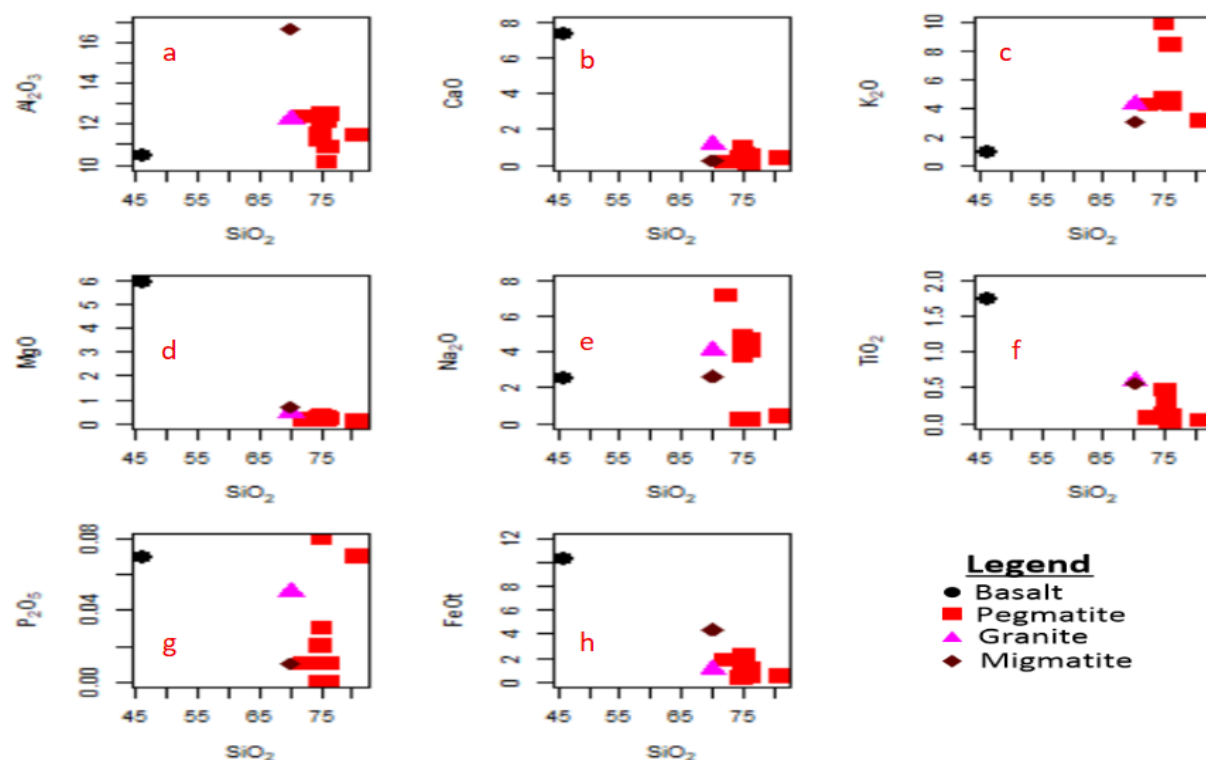


Fig. 4. Hacker's Variation diagram showing relationship between major oxides and SiO_2 (Modified after Hacker, 1909)

The relationship between SiO_2 and K_2O is presented in Fig. 4c. The felsic rocks generally have relatively high K_2O contents. The enrichment of K_2O in several of the evolved samples may reflect the increasing contribution of K-bearing minerals and the concentration of potassium in residual felsic melts.

SiO_2 –MgO relationship

The SiO_2 –MgO relationship is presented in Fig. 4d. MgO decreases substantially with increasing SiO_2 . This trend is consistent with progressive removal of Mg-bearing ferromagnesian minerals during magmatic differentiation. The low MgO concentrations of the granitic and pegmatitic rocks contrast strongly with the high MgO concentration of the basaltic sample shown in Table 2b.

The SiO_2 – Na_2O relationship is presented in Fig. 4e. Na_2O shows considerable variation

among the felsic samples. The relatively high Na_2O concentrations of some samples may reflect feldspar-related processes during differentiation. However, specific processes such as albitisation should only be invoked where supported by petrographic or mineralogical evidence.

The SiO_2 – TiO_2 relationship is presented in Fig. 4f. TiO_2 generally decreases with increasing SiO_2 , indicating depletion of Ti during the evolution of the felsic rocks. This behaviour is consistent with the crystallisation and removal of Ti-bearing minerals such as Fe-Ti oxides, biotite or titanite.

The SiO_2 – P_2O_5 relationship is shown in Fig. 4g. P_2O_5 is generally low in the analysed felsic samples. Its depletion during increasing SiO_2 may reflect the crystallisation of apatite or



other P-bearing phases during magmatic differentiation.

The relationship between SiO_2 and Fe_2O_3 is shown in Fig. 4h. Fe_2O_3 generally decreases with increasing SiO_2 , with the basaltic sample showing the highest concentration. This relationship indicates a strong contrast between the mafic and evolved felsic rocks and is compatible with the progressive removal of Fe-bearing minerals during magmatic evolution.

Collectively, the Harker diagrams (Fig. 4a–4h) show that increasing SiO_2 is generally accompanied by depletion in CaO , MgO , TiO_2 , P_2O_5 and Fe_2O_3 . These relationships, together with the major-element concentrations in Tables 2a and 2b, are broadly consistent with progressive magmatic differentiation. The trends should nevertheless be interpreted in conjunction with trace-element patterns because differentiation may involve more than simple closed-system fractional crystallisation.

4.2.3 Trace-Element Distribution and Magmatic Evolution

The multi-element primitive-mantle-normalised spider diagram is presented in Fig. 5. The trace-element pattern shows relative enrichment and depletion among the analysed elements, with notable behaviour of large-ion lithophile and high-field-strength elements.

The enrichment of incompatible elements in the evolved felsic rocks is consistent with progressive concentration of these elements in residual melts. In contrast, depletion in elements such as Ba and Sr may indicate feldspar fractionation because these elements are readily incorporated into feldspar during crystallisation. The relative depletion of Ti is also compatible with the removal of Ti-bearing phases during magmatic evolution.

The trace-element results presented in Tables 3a and 3b support this interpretation. The elevated Rb concentrations in several felsic

samples, together with the behaviour of Sr and Ba, are consistent with advanced differentiation. The relatively high Zr and Nb concentrations observed in some samples further indicate enrichment of incompatible elements during the evolution of the felsic system.

The spider diagram in Fig. 5 therefore provides additional evidence that the granitic and pegmatitic rocks represent relatively evolved compositions. However, the trace-element pattern alone should not be used to establish a specific source or tectonic setting without additional isotopic, mineralogical or petrographic evidence.

4.2.4 Alumina Saturation and Geochemical Character of the Felsic Rocks

The alumina saturation characteristics of the investigated rocks were evaluated using the A/CNK versus A/NK diagram, presented in Fig. 6. The samples generally occupy the metaluminous to weakly peraluminous fields.

The A/CNK ratio provides information on the relative abundance of Al_2O_3 compared with CaO , Na_2O and K_2O and is useful for assessing the alumina saturation characteristics of felsic igneous rocks. The distribution observed in Fig. 6, together with the major-element compositions in Tables 2a and 2b, indicates that the felsic rocks display variation from metaluminous toward weakly peraluminous compositions. The metaluminous to weakly peraluminous character of the analysed felsic rocks is compatible with evolved granitic compositions. However, alumina saturation alone is not sufficient to establish Sn fertility. The interpretation becomes more meaningful when the A/CNK characteristics are considered together with the Sn concentrations, incompatible-element enrichment and major-element differentiation trends shown in Tables 3a and 3b and Figs. 4–6.



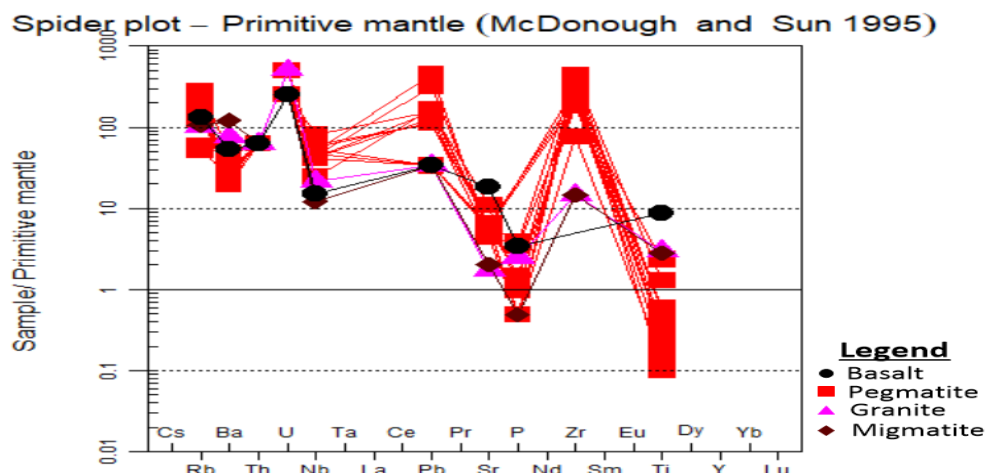


Fig 5 Multi-Element Spider Plot showing enrichment in large ion lithophile elements (LILE), (modified after MacDonough and Sun 1995)

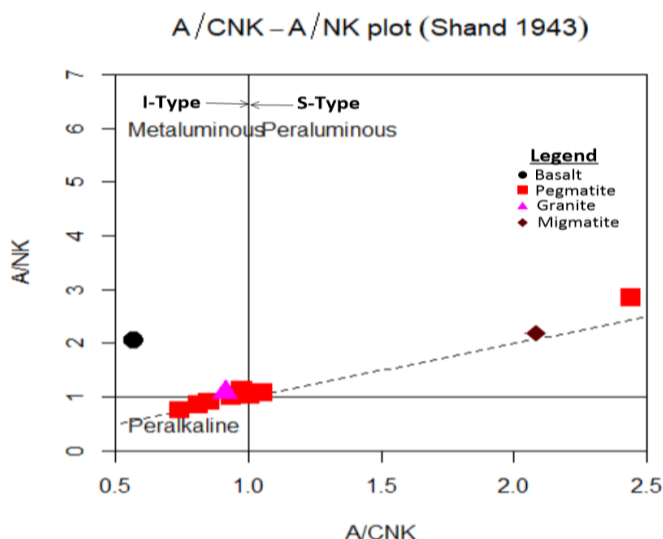


Fig. 6. Alumina Saturation Index (Modified after Shand, 1943)

4.2.5 Relationship between Tin and Mafic Components

Figs. 7a and 7b. Fig. 7a presents the relationship between Sn and Fe_2O_3 , whereas Fig. 7b shows the relationship between Sn and the combined concentration of $\text{Fe}_2\text{O}_3 + \text{MgO} + \text{CaO}$.

The plots show that the higher Sn concentrations are generally associated with relatively low concentrations of the selected mafic components. This relationship is

particularly important because Sn behaves as an incompatible element during much of the crystallisation history of granitic magmas. As early-forming mafic and calcic minerals crystallise and are removed from the melt, Sn may become progressively concentrated in the residual melt.

The highest Sn concentration of 209 ppm in WMP008 occurs in a highly evolved pegmatitic sample, while other elevated Sn values occur in samples WMP001, WMP003,



WMP006, WMP011 and WMP012 (Tables 3a and 3b). The association between elevated Sn and depletion in Fe_2O_3 , MgO and CaO therefore supports the interpretation that the Sn-enriched samples represent relatively evolved portions of the felsic magmatic system.

The negative relationship between Sn and the mafic components shown in Fig. 7a and 7b is consistent with progressive differentiation. Nevertheless, this relationship should not be interpreted as definitive evidence of economic cassiterite mineralisation. Whole-rock Sn concentration indicates elemental enrichment but does not establish the mineralogical host of Sn. Confirming cassiterite requires mineralogical investigation using appropriate techniques such as petrography, X-ray diffraction, scanning electron microscopy, or electron-microprobe analysis.

4.2.6 Pegmatite Evolution and Tin Mineralisation Potential

The combined major- and trace-element results provide evidence that the pegmatites represent relatively evolved members of the felsic lithological assemblage. Their generally high SiO_2 contents, low concentrations of several mafic oxides, enrichment in selected incompatible elements and elevated Sn concentrations distinguish them from the less evolved lithologies (Tables 2a–2b and 3a–3b). The Li_2O data provide additional evidence of compositional evolution. Li_2O concentrations up to 0.40 wt.% in selected samples (Table 2a) indicate that lithium concentrated in some evolved felsic rocks. Because Li is strongly incompatible in many early-forming rock-forming minerals, its concentration in residual melts can increase during progressive differentiation. The presence of Li enrichment together with Sn enrichment may therefore indicate advanced evolution of selected pegmatitic melts.

The trace-element patterns in Fig. 5 provide further support for this interpretation. Relative enrichment of incompatible elements, together

with depletion of elements commonly associated with feldspar and mafic mineral fractionation, is compatible with evolution toward residual melts from which pegmatites may crystallise.

The geochemical evidence therefore indicates that the pegmatitic rocks in the study area possess geochemical characteristics favourable for further investigation of Sn-bearing mineralisation. The term “potential” is appropriate because the present study is based principally on whole-rock geochemistry. Establishing the economic significance of the Sn enrichment would require additional work involving detailed mapping, petrography, mineral chemistry, cassiterite identification, stream-sediment or soil geochemistry, and possibly geophysical investigations.

4.2.7 Integrated Interpretation

Integration of the major- and trace-element data indicates a clear chemical contrast between the mafic and felsic lithologies of the study area. The basaltic sample is characterised by relatively low SiO_2 and comparatively high Fe_2O_3 , MgO, CaO and TiO_2 , whereas the granitic and pegmatitic rocks are characterised by high SiO_2 and relatively low concentrations of these mafic components (Tables 2a and 2b). The Harker variation diagrams (Figs. 4a–4h) demonstrate systematic changes in major-element composition with increasing SiO_2 . The general decrease in CaO, MgO, Fe_2O_3 and TiO_2 is compatible with progressive removal of mafic, calcic and Ti-bearing minerals during magmatic differentiation. The trace-element data (Tables 3a and 3b) provide complementary evidence through the enrichment of selected incompatible elements in the more evolved felsic rocks.

The primitive-mantle-normalised spider diagram (Fig. 5) further demonstrates characteristic enrichment and depletion patterns associated with evolved felsic magmatism. The alumina saturation diagram (Fig. 6) indicates metaluminous to weakly peraluminous compositions, while the Sn-



mafic oxide relationships (Figs. 7a and 7b) show that elevated Sn concentrations occur preferentially in chemically evolved samples. Of particular significance is the occurrence of 209 ppm Sn in sample WMP008, together with other elevated Sn concentrations in several pegmatitic samples (Tables 3a and 3b).

The association of Sn enrichment with high silica, low mafic-oxide concentrations and enrichment in selected incompatible elements indicates that the pegmatitic rocks are the most geochemically evolved and potentially Sn-fertile lithologies identified in the study area.

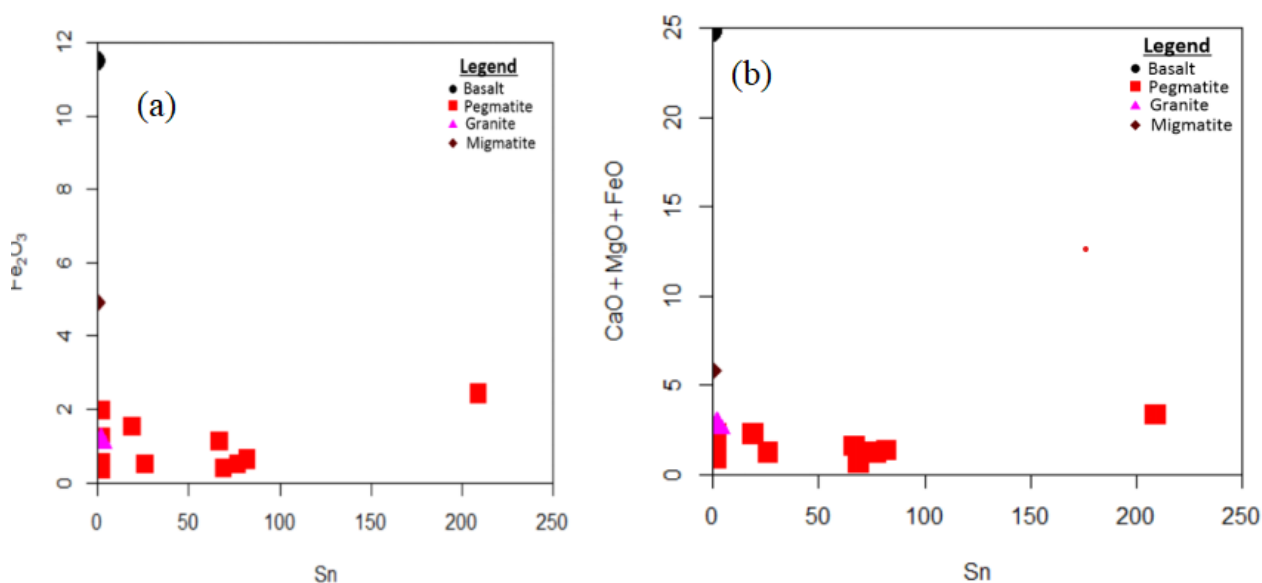


Fig. 7 (a) Binary plots of Sn versus Fe₂O₃, (b) Sn versus (Fe₂O₃ + MgO + CaO) (after Ratcliffe *et al.*, 2007)

The results therefore support the interpretation that progressive magmatic differentiation and residual-melt enrichment played an important role in concentrating Sn in the pegmatitic rocks of the northwestern part of Wamba Sheet 210 NW. The data provide a geochemical basis for considering these pegmatites prospective for further investigation of cassiterite and associated rare-metal mineralisation. However, confirmation of cassiterite mineralisation and assessment of its economic significance require detailed mineralogical and exploration studies beyond the scope of the present whole-rock geochemical investigation.

4.3 Summary of Major Geochemical Findings

The principal findings from the geochemical investigation can be summarised as follows:

- (i) The analysed rocks display a broad compositional range from mafic basaltic to highly felsic granitic and pegmatitic compositions, as demonstrated by the TAS classification in Figure 3.
- (ii) The major-element data in Tables 2a and 2b show that increasing SiO₂ is generally associated with decreasing CaO, MgO, Fe₂O₃ and TiO₂, consistent with progressive magmatic differentiation.
- (iii) The felsic rocks exhibit enrichment in K₂O, Na₂O and selected incompatible elements, indicating substantial chemical evolution of the felsic magmatic system.
- (iv) The trace-element data in Tables 3a and 3b show significant variation in Rb, Sr,



- Ba, Zr, Nb and Sn, providing evidence for differential enrichment and depletion during magmatic evolution.
- (v) The primitive-mantle-normalised pattern in Figure 5 indicates enrichment and depletion patterns compatible with advanced differentiation and feldspar-related fractionation.
 - (vi) The A/CNK–A/NK diagram in Figure 6 indicates predominantly metaluminous to weakly peraluminous compositions among the investigated felsic rocks.
 - (vii) Tin concentrations range from approximately 2 to 209 ppm, with the highest concentration occurring in pegmatite sample WMP008 (Tables 3a and 3b).
 - (viii) The relationships between Sn and Fe_2O_3 and between Sn and $\text{Fe}_2\text{O}_3 + \text{MgO} + \text{CaO}$ (Figures 7a and 7b) indicate that higher Sn concentrations are generally associated with chemically evolved compositions depleted in several mafic components.
 - (ix) The combined geochemical evidence identifies the pegmatitic rocks as the principal targets for further investigation of Sn-bearing mineralisation in the study area.

5.0 Conclusion

This study evaluated the geochemical characteristics and tin-bearing mineralisation potential of basement rocks in the northwestern part of Wamba Sheet 210 NW, North-Central Nigeria, using major- and trace-element geochemistry. The investigated rocks comprise pegmatite, biotite granite, migmatitic gneiss and basalt, representing a broad compositional range from mafic to highly evolved felsic lithologies.

The major-element results indicate pronounced chemical differentiation, characterised generally by increasing SiO_2 and decreasing CaO , MgO , Fe_2O_3 and TiO_2 in the evolved

felsic rocks. The trace-element patterns further indicate enrichment of selected incompatible elements and depletion of elements associated with feldspar and mafic mineral fractionation. These features collectively suggest substantial magmatic differentiation and evolution of the felsic rocks. The alumina saturation characteristics indicate predominantly metaluminous to weakly peraluminous compositions.

Tin concentrations vary considerably among the analysed samples, with the highest concentration of approximately 209 ppm recorded in pegmatite sample WMP008. Other elevated Sn concentrations were also recorded in several samples. The association of elevated Sn with chemically evolved, silica-rich and relatively mafic-oxide-depleted rocks suggests that the pegmatitic units represent the principal geochemical targets for further investigation of tin mineralisation.

Overall, the geochemical evidence indicates that progressive magmatic differentiation and residual-melt enrichment contributed to Sn concentration in parts of the Wamba basement terrain. The study therefore identifies the investigated pegmatites as prospective targets for further exploration of cassiterite and associated rare-metal mineralisation. Detailed petrographic and mineralogical studies, supported by systematic soil and stream-sediment geochemistry and additional exploration, are recommended to confirm the mineralogical host of Sn and determine the extent and economic significance of the mineralisation.

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Declaration

Funding

This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors, based on the information supplied.

Conflict of interest

The authors declare that they have no conflict of interest.

Ethical Consideration

Not applicable

Author Contributions

Munir Muhammad Gali and Nathaniel G. Goki investigated the geochemical characteristics and tin-bearing mineralisation potential of basement rocks in northwestern Wamba, Nigeria. They collected and analyzed fifteen rock samples using XRF and AAS. Their findings identified pegmatites as principal targets for cassiterite mineralisation, showing that advanced magmatic differentiation and fractional crystallisation significantly enriched tin in late-stage melts.



