Economic Geology
Vol. 75, 1980, pp. 71-82

Geochemical Characteristics of Tin-bearing and Tin-barren Granites, Northern Nigeria

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Abstract

The Jurassic Younger Granites of northern Nigeria are closely associated with tin and niobium deposits. Primary mineralization which is confined almost exclusively to the biotite granites occurs as disseminations in albitzed granites, and as greisen lodes and veins. Distributions of Sn and other trace elements in more than 200 samples from various but related intrusive phases of biotite granites are examined with the main objective of determining geochemical criteria that may be useful in discriminating between tin-bearing and tin-barren granites.

Concentrations of Sn are generally erratic, and mean values show only a subtle geochemical contrast between tin-bearing and tin-poor granites. However, a nonuniform distribution of Sn and a high coefficient of variance in which a large proportion of values exceed 25 ppm provide criteria for recognizing tin-bearing granites. The abundance and interrelationships of Rb, Li, K, Ba, Sr, Zr, Nb, Th, rare earth elements, and Mn are most useful as indicators of mineralizing processes and ore-bearing potential. Thus, the tin-bearing granites are characterized by low K/Rb and Ba/Rb and high Rb/Zr ratios.

However, the ability of the stanniferous biotite granites to yield tin deposits depends on the development of an alkali-volatile phase during crystallization of the magma, and ore formation is considered a product of postmagmatic processes.

Introduction

Most of the world's present production of tin is obtained from residual, eluvial, and alluvial deposits. As these easily worked secondary deposits are being depleted, considerable interest has been focused on finding alternative primary sources, especially lode tin mineralization and low-grade disseminated orebodies (Taylor, 1969; Sainsbury and Hamilton, 1967). However, it is well known that the majority of primary tin deposits are localized within, or adjacent to, granitic intrusives or effusives (Hosking, 1967). The close association of tin deposits with granitic rocks has prompted several studies on the essential geochemical characteristics of tin-bearing granites that separate them from tin-barren granites. (Rattigan, 1963; Hesp, 1971; Flinter, 1971; Sheraton and Black, 1973). Despite these efforts, no successful geochemical exploration method of universal application is available. This can be partly attributed to the fact that most previous studies have failed to take account of the variety in genetic types of granites, and also that individual plutons each evolve in a unique manner (Tauson and Kozlov, 1973; Smith and Turek, 1976).

The Jurassic Younger Granites of northern Nigeria are host to important deposits of cassiterite and columbite. Most of the tin is presently obtained from residual and alluvial deposits shed from the granites (Falconer, 1912). It is also known that some primary cassiterite occurs as lodes and greisens, as well as disseminations in albitized granites (Macleod et al., 1971). As the alluvial deposits become exhausted, the search for primary tin deposits has been intensified in recent years.

As part of an exploration project initiated at the University of Ibadan, geochemical investigations have been designed to explore the possibility of developing diagnostic criteria which can be used to identify granitic complexes that are potentially ore-bearing and those that are not. The choice of bedrock as a sampling medium can be partly attributed to the fact that the hilly and rocky topography of the Jos plateau has resulted in a poor development of residual soils, and partly to the abundance of uniformly distributed and relatively unweathered outcrops. Moreover, extensive alluvial mining has disturbed and contaminated the poor drainage systems which make stream sediments useless as a sampling medium.

In planning and executing this study, the following fundamental facts were taken into consideration.

1. The Jurassic Younger Granites comprising about 50 individual multiphase intrusions constitute a tin geochemical province in which most of the rocks have higher than normal concentrations of tin.

2. Although most of the granitic rocks including fayalite-, amphibole-, and biotite-bearing granites are high in tin (Williams et al., 1956; Bowden and Van

TABLE 1. Average Chemical Composition of the Main Younger Granite Rock Types (after MacLeod et al., 1971)

	Biotite granites	Hornblende granites	Riebeckite granites
wt %			
SiO_2	75.49	71.52	75.02
Al_2O_3	12.62	12.88	11.56
Fe_2O_3	0.62	1.26	1.53
FeO	1.02	2.68	1.11
MgO	0.16	0.26	0.21
CaO	0.54	1.17	0.50
Na_2O	4.18	4.29	4.84
K_2O	4.63	4.88	4.34
TiO_2	0.12	0.37	0.12
P_2O_5	0.03	0.06	0.02
MnO	0.02	0.09	0.0
Cl	0.02		0.04
F	0.20	0.12	0.49
S	0.02		
ppm			
Sn	<30	<30	<30–150
Nb	130 (50–300)[1]	85 (30–150)	350 (100–1,500)
Rb	405 (180–860)	200 (120–310)	510 (160–1,400)
Zr	260 (110–610)	400 (200–1500)	1330 (450–2,200)
Li	80 (14–347)	25 (5–53)	260 (25–630)
Ba	(<15–1,000)	440 (75–1,000)	39 (15–150)
Sr	(<15–100)	(15–300)	(<15–50)
Cs	(1–10)	(1–8)	(1–5)
Th	50 (33–74)		55
Ce	310 (78–780)	343 (225–460)	400 (172–630)
La	190 (20–1,000)	145 (20–575)	100 (70–600)
Y	200 (35–480)	95 (30–180)	420 (95–1,000)
Zn	(75–860)		(255–1,150)
Pb	30 (10–150)	30 (10–100)	80 (30–150)
F (tot.)	4,330 (2,200–6,000)	2,800 (1,200–5,500)	7,600 (3,000–12,400)

[1] Range of concentrations in parentheses.

Breemen, 1972), only the biotite granites are genetically related to tin and niobium mineralization or contain these metals in a form that can be economically extracted (Falconer, 1912; Mackay et al., 1949; Macleod et al., 1971). In particular, although the peralkaline albite-riebeckite granites contain high concentrations of tin together with enhanced Nb, Be, Th, Zr, and U (Table 1), the tin is held in the amphibole lattice and no economic cassiterite may be expected (Bowden and Turner, 1974).

3. Although most biotite granites contain some tin, not all can be considered as stanniferous or mineralized (Williams et al., 1956; Macleod et al., 1971).

For the above reasons, most of the sampling was confined to the biotite granites, and several samples were collected per intrusive phase to permit statistically significant interpretations. The inclusion of some samples of hornblende granites is only meant to demonstrate the generally high tin content of the granites.

This paper attempts to define and interpret diagnostic trace element characteristics of tin-bearing and barren granites in northern Nigeria, and is in part based on detailed prior knowledge and may not be directly applicable elsewhere.

General Geology and Mineralization

Rock types

The Jurassic Younger Granites of northern Nigeria form a consanguinous series of high level, anorogenic ring complexes emplaced within Precambrian basement gneisses and granites. More than 40 composite intrusive complexes have been recognized. The most typical of these are usually circular to elliptical in outline, about 10 to 25 km in diameter and comprise an outer ring dike of fayalite granite porphyry surrounding downfaulted volcanic and basement rocks, and a core of composite granitic intrusions (Bowden and Turner, 1974). The principal granitic phases are biotite granites, hornblende granites, and riebeckite- and fayalite-bearing granites emplaced as individual or overlapping complexes (Macleod et al., 1971).

The biotite granites which are the most widespread rock type are medium to coarse grained, consisting of about 25 percent clustered quartz, 40 to 50 percent orthoclase-microcline perthites, 10 to 20 percent albite, and about 5 percent biotite. Accessory minerals include cassiterite, columbite, fluorite, thorite, and monazite. Generally, any single intrusive phase of biotite granite shows a good consistency in mineral composition and texture, although the degree of albitization may vary considerably (Turner, 1976).

Average major and trace element compositions of the main Younger Granite rock types are shown in Table 1.

Mineralization

Primary tin mineralization in the Younger Granites is confined almost exclusively to the biotite granites (Williams et al., 1956; Buchanan et al., 1971) and occurs in two forms; as disseminations and as greisen veins.

(i) Disseminations of accessory cassiterite commonly occur in association with columbite in the margins and roof zones of biotite granites. This form of mineralization is usually accompanied by intense albitization—a process involving the growth of albite at subsolidus temperatures in relation to either autometasomatism or early postmagmatic recrystallization (Bowden et al., 1976). Notable examples of dispersed mineralization occur within the Rayfield-Gona granite (Jos-Bukuru complex) and the Odegi granite (Afu complex) (Fig. 1), where extensive zones exceeding 0.1 percent Sn and 0.2 percent Nb are common (Olade, unpub. data). Most of the residual deposits mined from decomposed granites and a considerable amount of the alluvial deposits are derived from this primary source (Buchanan et al., 1971).

(ii) Lodes and fracture-controlled greisen veins contain cassiterite commonly in association with sphalerite, galena, and wolframite. This type of mineralization is hydrothermal and emplaced after the host rocks had consolidated (Buchanan et al., 1971; Bowden and Kinnaird, 1978). In some of these veins and lodes, wall-rock alteration is well developed and characterized by outer envelopes of reddened granite (K-feldspar ± hematite ± sericite) surrounding zones of greisenized granite and greisen with central quartz veins. Most commonly, cassiterite is found predominantly within the greisens and sphalerite within the massive and vuggy quartz (Olade and Ekwere, in press).

Materials and Methods

Sampling

Two hundred and one rock-chip samples were collected from the Jos-Bukuru, Rop, and Liruei granitic complexes (Figs. 2 through 4). Although these ring complexes are widely separated, they belong, however, to the same petrographic- geochemical province and are characterized by similar rock types, the same sequence of crystallization, and similar petrogenesis (Jacobson et al., 1958; Butler et al., 1962; Bowden, 1970). Each intrusive complex comprises several distinct phases of fayalite-, amphibole-, and biotite-bearing granites of which only a few contain tin mineralization.

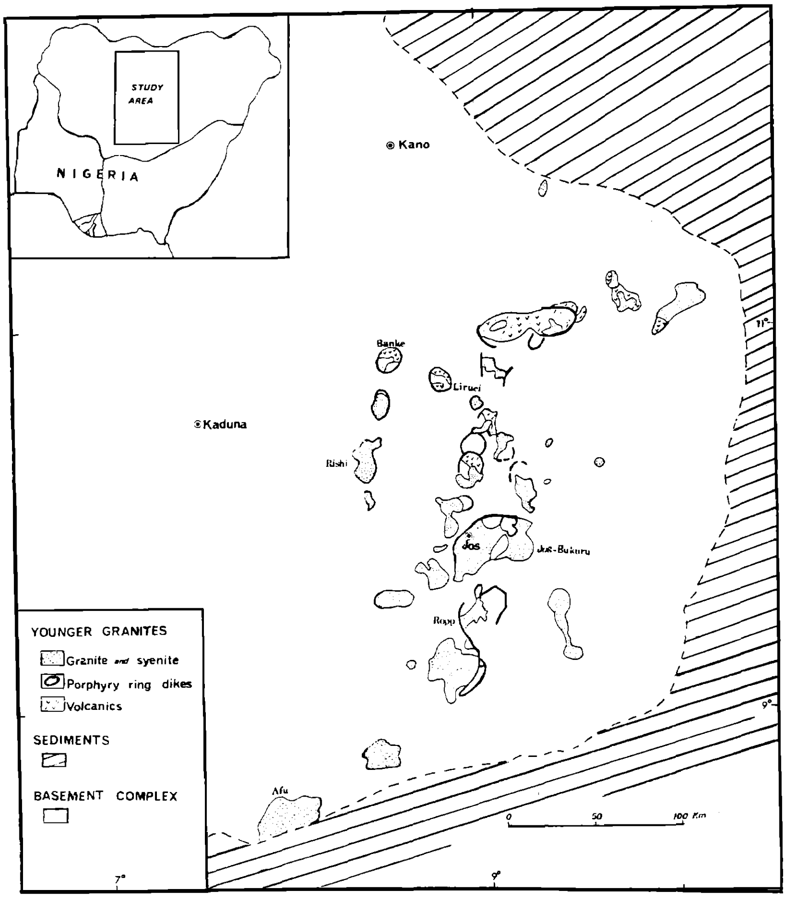

FIG. 1. Location and simplified geological map of the Younger Granite province, northern Nigeria.

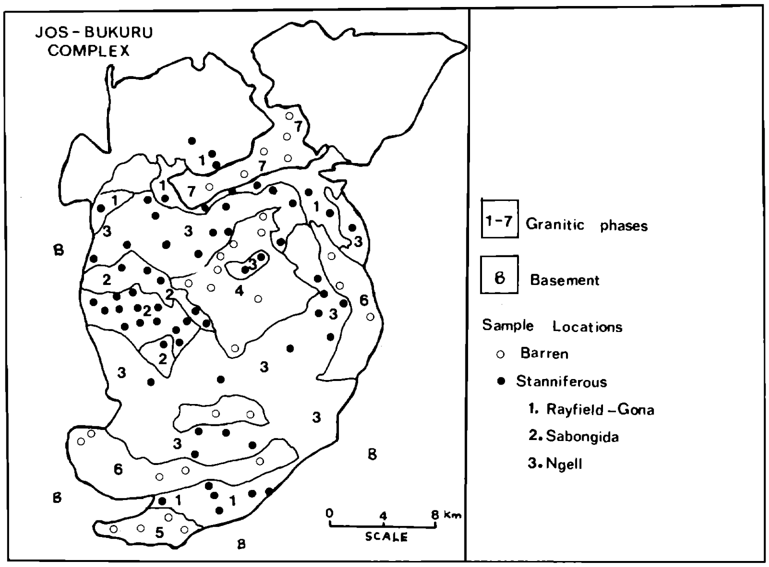

FIG. 2. General geology and sample locations, Jos-Bukuru complex.

To facilitate sampling and interpretation of geochemical data, the biotite granite intrusions were classified into three categories based on their ore-bearing characteristics, as follows; barren, stanniferous, and mineralized. The main criteria used are the ability to give rise to economic deposits and the type of mineralization (discrete or lode type). By definition, therefore;

(a) Barren granites—may contain a certain amount of tin but do not give rise to tin mineralization;

(b) Stanniferous granites—contain anomalous tin and give rise to tin mineralization in the form of disseminated or dispersed cassiterite; and

(c) Mineralized granites—contain anomalous tin and give rise to economic tin mineralization in lodes and veins.

It must be emphasized that this classification is based on a detailed prior knowledge of the Younger Granite mineralization and may therefore not be directly applicable elsewhere.

For the purpose of this study, 43 rock samples from the Jos, Kuru, and Bukuru phases of the Jos-Bukuru complex (Fig. 2) and the Kassa, Kaskara,

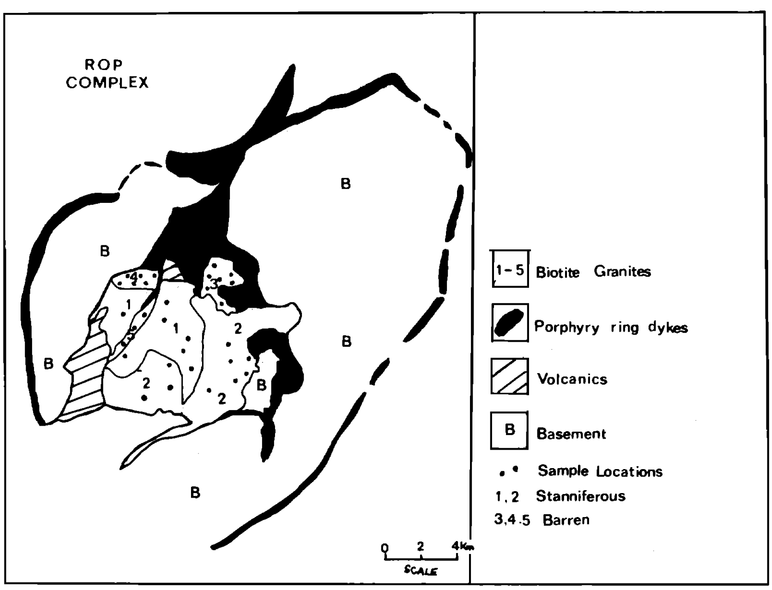

FIG. 3. General geology and sample locations, Rop complex.

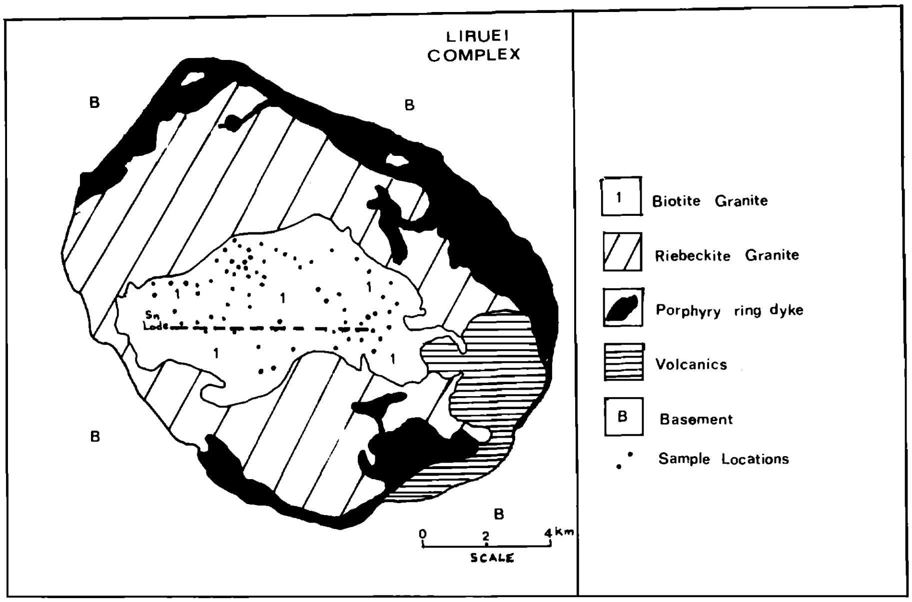

FIG. 4. General geology and sample locations, Liruei complex.

and Kwop phases of the Rop complex (Fig. 3) are classified as barren; 73 samples of biotite granites from the Rayfield, Sabongida, and Ngell phases (Jos-Bukuru complex) and the Bukka-Bokwai and Gana phases (Rop complex) are considered as stanniferous; whereas 67 samples from the Ririwai biotite granite intrusion of the Liruei complex are placed in the category of mineralized granites (Fig. 4). Eighteen samples of hornblende granites from the Shen, Vom (Jos-Bukuru complex), and Sho (Rop complex) intrusive phases are included only for comparison. It is emphasized that this attempt to classify granites into categories is at best approximate because of the high background content of tin. For example, the Bukuru biotite granite which is classified as barren contains a little amount of dispersed cassiterite.

Rock samples weighing about 3 kg comprised numerous fist-sized chips collected within a distance of 3 m around a central sampling point. As much as possible, only unweathered samples were collected, and obviously mineralized or altered samples were avoided. Chip samples were reduced to −150 mesh by successive crushing and pulverizing in a jaw crusher and roll mill, and finally by splitting and grinding a small portion in an agate ball mill.

Analytical methods

Sample powders (5 g) mixed with a binder (20% elvacite/acetone) were pelletized and analyzed by X-ray fluorescence for Sn, Nb, Zr, Rb, Sr, Ba, La, Y, Cs, and Ce using a semiautomatic Philips PW 1210 spectrometer. Instrumental settings and procedures described by Leake et al. (1969) were used. Calibration curves were obtained by using certified international standard rocks of granitic composition, and, where necessary, by spiking with spectrographically pure chemicals. Cu, Zn, Pb, Mn, K, and Na were determined by atomic absorption spectrophotometry after total decomposition with $HF\text{-}HClO_4\text{-}HNO_3$ acid mixture (Olade and Fletcher, 1974). Water-extractable F and Cl were determined by selective-ion electrodes (Olade, 1976) and Li, Be, and B in selected samples by semiquantitative DC-arc spectrography at the University of Utrecht (M. G. Oosterom, pers. commun.). Check determinations on several samples were also performed at Utrecht for Sn, Nb, Rb, Ba, Sr, Ce, Cs, and Zr. Analytical precision from replicate analyses is generally better than $\pm$ 20 percent for X-ray fluorescence, and $\pm$25 percent for atomic absorption analyses at a 90 percent confidence level.

Geochemistry in Relation to Ore-bearing Potential

Average concentrations and ranges for selected trace and minor elements in the various categories of granites are presented in Table 2.

Tin

The abundance of Sn is one of the most widely used criterion in differentiating between tin-bearing and barren granites (Flinter, 1971). Concentrations in the barren granites range from 2 to 32 ppm and average 10 ppm (Table 2). This average value is more than three times the clarke of 3 ppm for

TABLE 2. Means, Ranges and Coefficient of Variance (C.V.) of Trace Elements in Tin-bearing and Barren Granites, Northern Nigeria

	Mean and range (n = 67) Mineralized	C.V.	Mean and range (n = 73) Stanniferous	C.V.	Mean and range n = 43 Barren	C.V.	Mean and range n = 18 Hornblende Granites
Sn	22 (2–117)	126	22 (2–114)	93	10 (2–32)	70	4 (2–21)
Nb	156 (22–450)	49	136 (5–295)	38	96 (4–280)	75	68 (2–136)
Rb	699 (29–1,000)	26	651 (300–1,080)	23	517 (226–870)	40	231 (60–500)
Zr	262 (11–570)	49	177 (58–400)	58	203 (18–540)	52	471 (70–710)
Li	120 (50–350)	69	84 (50–200)	43	65 (50–100)	36	<50
Ba	79 (3–1,000)	244	68 (3–356)	91	166 (3–625)	110	324 (5–1408)
Sr	5 (2–27)	126	7 (2–31)	81	24 (3–220)	183	31 (5–170)
Cs	2 (1–19)	154	5 (1–20)	46	5 (2–8)	27	4 (2–7)
Th	48 (2–115)	60	46 (3–105)	46	31 (2–69)	64	22 (4–52)
Ce	369 (45–1,210)	79	111 (47–293)	38	130 (104–170)	22	188 (143–228)
La	137 (5–1,000)	124	99 (24–560)	93	85 (35–160)	44	98 (24–155)
Y	211 (3–700)	79	157 (35–392)	43	152 (29–333)	41	110 (8–183)
Be	6 (2–15)	54	14 (2–50)	87	6 (5–10)	36	<5
Zn	234 (8–875)	47	166 (32–800)	62	157 (24–360)	46	202 (80–400)
Pb	56 (8–327)	94	24 (7–60)	45	29 (10–58)	50	27 (10–96)
Cu	16 (5–91)	101	16 (4–56)	65	16 (5–56)	80	16 (5–32)
F[1]	158 (23–500)	60	141 (44–270)	33	166 (120–220)	24	115 (42–220)
Cl[1]	19 (6–62)	64	13 (7–32)	35	31 (11–85)	58	19 (13–36)
B	3 (1–5)	51	3 (1–5)	50	2 (1–2)	10	2 (1–2)
Mn	113 (20–240)	34	170 (80–320)	33	193 (80–440)	45	434 (80–920)
V	5 (2–11)	43	14 (6–24)	31	16 (11–45)	62	47 (18–100)

[1] Water extractable F and Cl.

low Ca granites (Turekian and Wedepohl, 1961) and reflects the generally high background contents of Sn in granites of the province. The stanniferous and mineralized granites (as defined in this study) are similar in their Sn contents with a mean value of 22 ppm which is just twice that of the barren granites. However, the mineralized granites show the highest degree of variability in their Sn contents compared to the stanniferous and barren granites (Table 2).

Frequency distributions of Sn are generally positively skewed (Fig. 5), although those for the stanniferous and mineralized granites seem bimodal. A visual examination of the distributions shows that 30 percent of the sample population in the stanniferous granites compared to 24 percent in the mineralized granites exceed the provisional cut-off value of 25 ppm Sn (mean + 2 s.d. of barren granites). The relatively higher proportion of anomalous values (>25 ppm) in the tin-disseminated stanniferous granites relative to the lode-bearing mineralized granites may be attributed to the mode of occurrence of cassiterite in the two groups. This is reflected in the more uniform frequency distribution obtained for the stanniferous granites compared to the more erratic distribution in the mineralized granites.

Thus, the contrast in the average Sn values for tin-rich and tin-poor granites may not be very diagnostic in the Younger Granite province, rather the extent of variability as reflected in high coefficient of variation is most useful in defining mineralization (Beus and Gregorian, 1975; Tàuson and Kozlov,

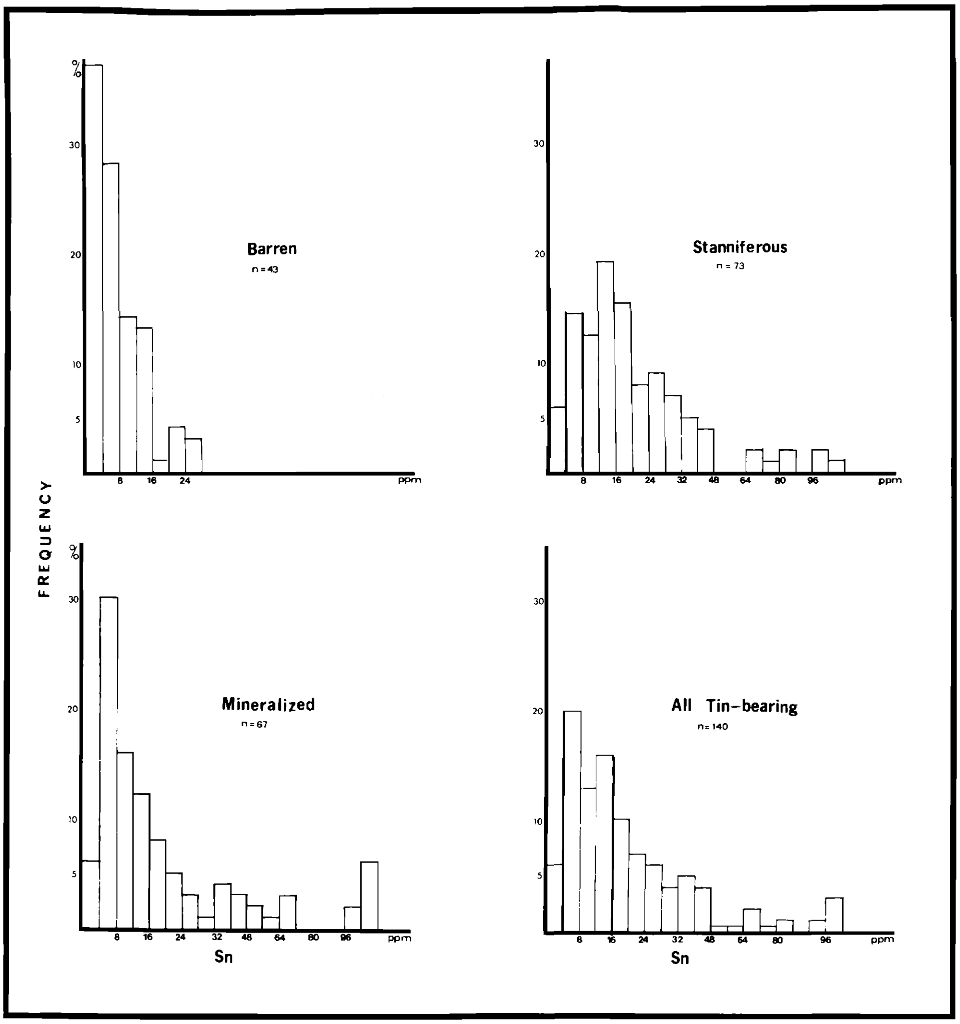

FIG. 5. Frequency distributions of tin in various categories of Younger Granites.

1973; Smith and Turek, 1976). Furthermore, a high proportion of samples with >25 ppm Sn may indicate a tin-bearing potential.

Pathfinder elements (Nb, Th, Rb, Li, rare earth elements, Zr, Ba, Sr, Cs)

Several workers have suggested that the enrichment of certain elements, such as Nb, Rb, Li, F, and impoverishment of Zn, Ba, Sr, and others, may be an indication of mineralization (Stemprok, 1970; Tauson and Kozlov, 1973; Smith and Turek, 1976; Haapala, 1977). The average concentrations and ranges of a selected suite of potential pathfinder elements are given in Table 2.

Niobium is closely associated with tin mineralization in the Younger Granites where it occurs as columbite. This association is reflected in the enhanced values both in the stanniferous and mineralized granites (136 and 156 ppm, respectively), compared to the mean value of 96 ppm in the barren granites. These differences are statistically signicant at the 95 percent confidence level.

Thorium shows a dispersion similar to Nb (Table 2), although the differences are more subtle. The higher values of Th in the stanniferous and mineralized granites may reflect the presence of thorite which often accompanies columbite and cassiterite in the albitized biotite granites (Macleod et al., 1971; Bowden and Kinnaird, 1978). This association is reflected in the significant positive correlations between Sn, Nb, and Th (Table 3).

Rubidium and Li concentrations have been widely considered as good indicators of tin-bearing potential (Hosking, 1967; Flinter, 1971; Tauson and Kozlov, 1973; Beus and Gregorian, 1975). In this study, Rb and Li concentrations are higher in both the mineralized and stanniferous granites compared to the barren ones (Table 2). The considerably enhanced

TABLE 3. Interelement Correlations in Tin-bearing Granites (values in coefficients of correlation)

	Tin-bearing granites	
	Mineralized (66)[1]	Stanniferous (73)[1]
Sn-Nb	+0.25	+0.15[2]
Sn-Zr	+0.43	−0.35
Sn-Th	+0.46	+0.27
Sn-Li	+0.36	+0.35
Sn-Rb	+0.20	+0.38
Sn-Na	−0.35	−0.07
Sn-K	+0.24	+0.28
Sn-Zn	+0.21	+0.52
Sn-Pb	+0.20	+0.33
Nb-Zr	+0.36	+0.41
Nb-Th	+0.44	−0.26
Nb-Rb	+0.07[2]	−0.24
Rb-Th	+0.36	+0.27
Rb-Na	−0.29	+0.24
Rb-K	+0.18	+0.29
Rb-Ba	−0.20	−0.21
Rb-Zr	+0.15[2]	−0.60
Rb-Mn	−0.08[2]	+0.28

[1] Number of samples in parentheses.
[2] Not significant at the 0.05 probability level.

Li values in the mineralized granites may in part reflect the genetic association of these granites with Li-rich greisens. A positive correlation exists between Li and Sn in both the tin-bearing granites, whereas such a correlation between Rb and Sn is weak although statistically significant.

Cerium, La, Y, and Be also show relatively enhanced values in the stanniferous and mineralized granites. This probably reflects the occurrence of these rare earth elements in accessory minerals such as xenotime, allanite, and monazite. Bowden and Van Breemen (1972), Bowden et al., (1976), and Aleksiyev (1970) noted the same enrichment pattern and attributed this to postmagmatic processes of albitization and mineralization.

Zirconium which occurs dominantly in accessory zircon shows a distribution that reflects the nature of the mineralizing process. The barren granites contain relatively high Zr values compared to the stanniferous granites which show a strong depletion, especially where strongly albitized. Bowden (1966), who noted a similar relationship, concluded that the depletion in Zr may be attributed to metasomatic imprint related to postmagmatic processes (Bowden et al., 1976). However, in the mineralized granites where greisenization is dominant, Zr shows slightly enhanced values relative to the other granites (Table 2). A similar pattern was noted in greisenized grants from Cornwall (Hall, 1969).

Barium, Sr, and Cs show similar distributions in that they are depleted in the mineralized and stanniferous granites compared to the barren granites (Table 2). Although tin-bearing granites such as those in Cornwall (Hall, 1969) are enriched in Cs, the low values obtained in this study, coupled with the fact that Cs distribution does not follow Rb and Li (Goldschmidt, 1954), have been noted within the Younger Granites (Bulter and Thompson, 1963; Bowden, 1966). Such anomalous behavior has been attributed to the unusually low concentrations of Cs in the magmas of the granites (Bowden et al., 1976).

Other elements (Zn, Pb, Cu, Mn, V, F, Cl, B)

Zinc and Pb show significant positive correlations with Sn, with relatively higher values in the mineralized and stanniferous granites (Table 2). These elements occur as sulfides within tin-bearing lodes, and their enrichment in the biotite granites could be magmatic. In contrast, Cu values do not show appreciable differences.

Manganese and V are generally impoverished in both the mineralized and stanniferous granites and may reflect their inability to be incorporated into the postmagmatic volatile-rich phase during crystallization.

Fluorine concentrations in relation to ore-bearing potential cannot be fully assessed because of the water-extractable procedure used in the analysis. There is no statistically significant difference in the H_2O extracted F contents of the three categories of biotite granites; although the relatively high levels reflect similarly high total F in the granites (partial extraction procedure extracts 1–5% total F). Badejoko and Imeokparia (in press) have reported enhanced values of >8,000 ppm total F in the stanniferous biotite granites of the Jos-Bukuru complex compared to <4,000 ppm in the barren granites.

Cl and B are volatile elements which are unusually impoverished in rocks of the Younger Granite province (Bowden et al., 1976). This is reflected in the generally low contents obtained in the barren and tin-bearing granites (Table 2), although in the case of Cl the barren granites contain relatively higher values. Thus, it is considered that Cl and B are not important components of the volatile phase associated with tin mineralization. This is consistent with the absence of tourmaline within the Younger Granite mineralized zones.

Element ratios

Interelement relationships and ratios have been used as reliable indicators of the ore-bearing potential of granitic rocks (Tauson and Kozlov, 1973; Beus and Gregorian, 1975; Smith and Turek, 1976). This application is based on the differences in the migration characteristics of related elements during magmatic and postmagmatic processes. In this study, Rb shows enrichment in the mineralized and stanniferous granites, whereas the reverse is true for Ba. This is reflected in the significant negative correlation between the two elements (Table 3). Consequently low Ba/Rb ratios characterize the tin-bearing granites. A plot of Ba versus Rb (Fig. 6) shows that the Ba/Rb ratio of 0.5 adequately separates the stanniferous from the barren granites. Also, low K/Rb ratios (<100) characterize the stanniferous and mineralized granites. These relationships suggest that Rb is considerably enriched relative to Ba and K during postmagmatic processes related to mineralization.

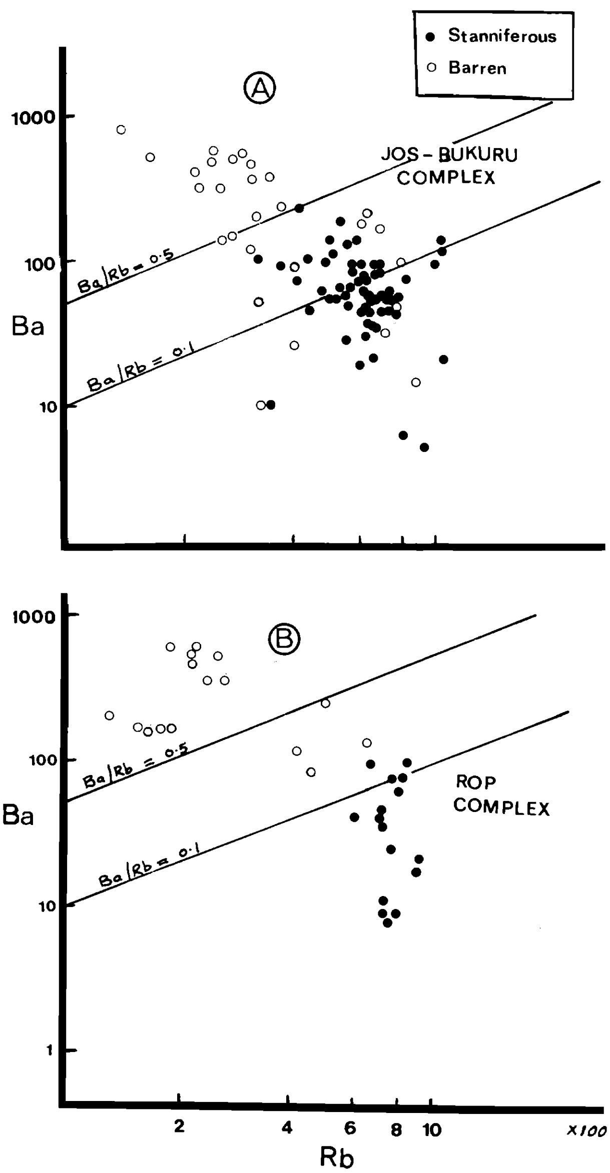

FIG. 6. Plot of barium versus rubidium in stanniferous and barren granites: (A) Jos-Bukuru, (B) Rop complexes. (Values in parts per million.)

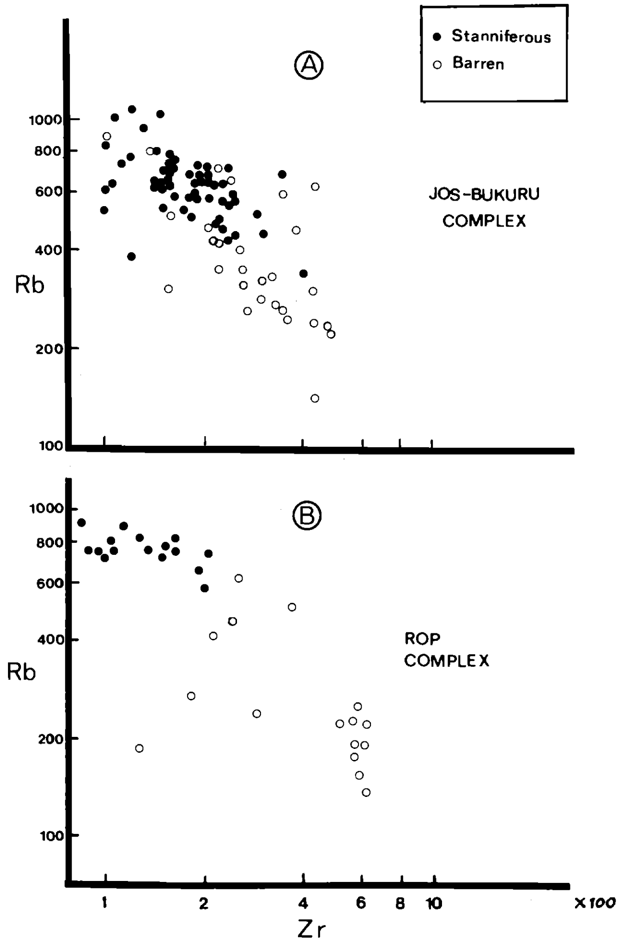

FIG. 7. Relationships between rubidium-zirconium in stanniferous and barren granites: (A) Jos-Bukuru, (B) Rop complexes. (Values in parts per million.)

The relationships between Zr and Rb in the barren and stanniferous granites of the Jos-Bukuru and Rop complexes are presented graphically in Figure 7. A strong negative correlation ($r = -0.60$) exists between Zr and Rb in the stanniferous granites, although such a relationship is not apparent for the mineralized granites (Table 3) due to reasons earlier mentioned. As shown in Figure 7, a Rb/Zr ratio exceeding 2.0 is characteristic of the stanniferous granites.

It has also been observed in this study that Na is strongly depleted in several samples of the lode-bearing mineralized granites as a result of hydrothermal leaching associated with incipient greisenization, and consequently higher K/Na ratios are obtained for the mineralized granites ($K/Na > 1.5$).

Discussion

The search for tin deposits in a defined geochemical and metallogenic province will definitely be made easier if suitable host rocks are first identified and their geochemical characteristics studied in relation to ore-bearing potential (Smith and Turek, 1976). In the Younger Granite province, it is a well established fact that the biotite granites are genetically, as well as spatially, related to tin mineralization (Falconer, 1912; Williams et al., 1956; Macleod et al., 1971; Bowden and Kinnaird, 1978). Why this is so, has been a subject of speculation. Part of the explanation lies in the fact that in the other types of granite, the tin is locked up in the riebeckite, fayalite, and hornblende minerals which crystallized early in the paragenetic sequence. This is confirmed by the high contents of Sn and other elements such as Nb in these rocks, particularly the peralkaline riebeckite granites (Bowden and Van Breemen, 1972). In contrast, biotite crystallized late within the biotite granites, consequently Sn and other elements were able to be concentrated into the volatile-rich fraction of the melt and subsequent mineralizing fluids.

Despite the close genetic association between tin mineralization and biotite granites, only a small proportion of these are mineralized even within the same intrusive complex, where they are considered consanguinous and similar in their mode of crystallization and major element composition (Bowden and Turner, 1974). Thus, the ability to yield economic concentrations of tin most probably depends dominantly on the geochemical nature of the magma and the character of related postmagmatic processes (Beus and Gregorian, 1975). If, therefore, tin mineralization is a product of ore-forming fluids developed during evolution of the host intrusions, there is a high probability that this may be reflected in the trace element contents and their distribution patterns in rocks.

Results obtained in this study show that the absolute concentration of Sn in the Younger Granites is generally high but do not provide adequate contrast between tin-bearing and barren granites. Moreover distribution patterns are erratic and individual samples may have relatively high or low Sn contents. This may be attributed to the mode of occurrence of Sn as dispersed or fracture-controlled mineralization. However, where several samples are involved, a large proportion containing more than 25 ppm Sn may indicate tin-bearing potential. Furthermore, a nonuniform distribution of Sn or an appreciable increase in the variance of such a distribution may be indicative of mineralization. Similar observations have been reported by other workers (Flinter, 1971; Tauson and Kozlov, 1973; Beus and Gregorian, 1975).

Enrichment in Rb, Li, Nb, Th, rare earth elements, Zn, and Pb in the tin-bearing granites compared to the barren granites is characteristic of the Younger Granite and other tin metallogenic provinces (Hosking, 1967; Stemprok, 1970; Smith and Turek, 1976; Haapala, 1977). As suggested by Alexsiyev (1970) and Bowden and Van Breemen (1972), the enrichment of these elements and Sn in the stanniferous granites is connected with albitization and the trace-element overprinting by postmagmatic solutions. Chemically, the petrographically obvious albitization—a product of subsolidus recrystallization—is not generally accompanied by enhanced Na but by enrichment in trace elements such as Rb, Nb, Sn, etc. and depletion in Ba, Sr, and Zr. This pattern of trace element association may be attributed to the development of an alkali-volatile-rich phase during evolution of the granitic magmas. The lode-bearing mineralized granites show a pattern of enrichment in trace elements similar to the tin-disseminated stanniferous granites. According to Bowden and Kinnaird (1978), this may be due to the fact that both types of mineralization are related products of a continuum of ore-forming process; an early dispersed phase of mineralization associated with alkali-volatile-rich, early postmagmatic fluids, and a later phase of fracture-controlled mineralization associated with acidic hydrothermal solutions in which sulfides are common. This is consistent with the occurrence of both phases of mineralization within the same intrusive body.

Although the ore-forming fluids are derived from magmas, the exact source of the metals cannot be easily ascertained. Strontium and lead isotopic data (Bowden and Van Breemen, 1972; Bowden et al., 1976; Grant, 1971) suggest that the Younger Granite magmas and associated metals are derived from the partial melting of metal-rich sialic crust, most probably Precambrian gneisses and tin-rich Older Granites. Sillitoe (1974) has speculated that the tin deposits were probably generated by hotspot activity. Consequently, the source of heat required for melting may be derived from mantle plume activity. This is consistent with the decreasing age trends from north to south within the Younger Granites which are attributed to mantle plume traces (Rhodes, 1971; Van Breemen and Bowden, 1973).

Conclusions

In the regional exploration for tin deposits in the Younger Granite province of northern Nigeria, trace element characteristics of the biotite granites can be useful in identifying individual intrusive complexes that are potentially ore-bearing. Frequency distributions of Sn in stanniferous and mineralized granites are positively skewed and bimodal, with a relatively large proportion of values exceeding 25 ppm. Elemental concentrations and relationships of the lithophile elements, especially Rb, Li, Zr, Ba, K, and Nb are the most reliable indicators of ore-forming processes and tin-bearing potential. However, actual mineralization within the biotite granites is mainly dependent on the development of an alkali-volatile-rich phase during evolution of the magma, and most of the tin deposits, either dispersed or vein-type, are products of postmagmatic mineralization processes.

Acknowledgments

I am highly indebted to Prof. M. O. Oyawoye for his encouragement, and Prof. R. D. Schuiling and Dr. M. G. Oosterom of the University of Utrecht for organizing the check analyses on many of the samples. Thanks are due to G. Imeokparia and S. Ekwere for assistance in data collection and P. Anten and A. H. van de Kraats (Netherlands Technical Assistance Team) of the University of Ibadan for organizing sample analyses and data computation. Library and computer facilities at the Geological Survey of Canada, Ottawa, were utilized in this study, for which I am very grateful. This paper has also benefited from discussions with P. Bowden, J. Kinnaird, M. Oosterom, and T. A. Badejoko.

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May 23, 1978; August 8, 1979

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