

# Uranium in the Niger-Nigeria Younger Granite Province

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**ABSTRACT.** In Niger, uranium occurs in upper Palaeozoic and lower Mesozoic continental sedimentary basins west of the Air mountains, but the source of the uranium had not been identified. Geochemical studies and fission-track observations on alkaline ignimbrites preserved in two Palaeozoic anorogenic centres in Air show that uranium is concentrated in the matrix and on secondary iron-oxide coatings surrounding lithic and crystal fragments. Based on variable Th/U ratios and degree of oxidation, it is concluded that the original ignimbrite field was enriched in uranium, but that a considerable proportion was leached during the weathering of the volcanic pile. Tectonic uplift, anorogenic magmatism, followed by weathering and erosion of the volcanic cover, with sedimentation in nearby continental basins, have all contributed to the development of uranium mineralization in Niger. The petrological and geochemical similarities between the Palaeozoic ring complexes in Niger and the Nigerian Mesozoic ring structures suggest that sedimentary uranium deposits may also be found in Nigeria if the tectonic and sedimentological controls were favourable.

Enriched concentrations of uranium have been discovered in the exposed granitic roof zones of the Nigerian subvolcanic centres, with Th/U ratios approaching unity. Thus local vein deposits of uraninite, as well as dispersed uranium in recent sedimentary horizons, could be discovered particularly in the drainage systems entering the Chad Basin.

IN the Arlit region of the southern Sahara, uranium deposits occur 10-75 m below the surface, in Carboniferous deltaic sandstones overlain unconformably by Permo-Triassic arkosic sandstones and conglomerates (fig. 1). The geology of the Arlit region (fig. 2) has been fully described in

the French literature (Bigotte and Obellianne, 1968) with summaries in British mining journals (Moyal, 1968; Bigotte and Molinas, 1973). The discovery of what is now regarded as a 'major source of uranium' was by geologists of the BRGM and CEA.

In the first section of this paper the occurrence of economic uranium deposits in sedimentary rocks west of the Air massif is discussed. It is suggested that the ring structures in the Air massif represent the roots of volcanoes the eroded volcanic cover of which provided the source of uranium. The possibility that the younger Nigerian granite ring complexes and their eroded volcanic cover provided a source for uranium deposits in sedimentary horizons similar to those of Niger is also considered. The second section discusses the geochemical behaviour of uranium and thorium during cooling, consolidation and mineralization of Nigerian subvolcanic syenite-granite complexes.

## *Geological setting of uranium deposits in Niger*

The geology of central Niger is dominated by the crystalline massif of the Air which is a horst block of metamorphic rocks and calc-alkaline intrusives of Precambrian age, penetrated by over a dozen Palaeozoic (gabbro)-syenite-granite ring complexes. According to Bigotte and Obellianne (1968) the deposition of the Palaeozoic sedimentary rocks in this region was controlled by repeated movements along ancient lineaments. Major lineaments define north-south zones of alternately



FIG. 1. Arlit uranium pit showing overlying Permian Izegouande arkosic sandstone (upper 3 levels) resting unconformably on lower Carboniferous shales and sandstones. There is a thin series of finely bedded shales and siltstones forming a barren horizon above the deltaic carbonaceous sandstones in which uranium is concentrated.

uplifted blocks and depressions in central West Africa. It was within one of these depressions, which is intersected and controlled by major NE-SW or NW-SE lineaments that the Niger sedimentary rocks accumulated. The first stages of the development of individual basins were in the Ordovician with Caledonian epeirogenic movements, accentuated by north-south faults (Black and Girod, 1970). Caledonian uplift of the Air block resulted in the removal of the Ordovician cover so that lower Devonian strata directly overlie basement. Because of isostatic readjustments, uplift, and the change in direction of these movements towards the end of the Carboniferous, the sedimentary units were successively displaced southwards (fig. 2). The Palaeozoic facies were originally epicontinental-marine sediments but became lagoonal, deltaic, and ultimately continental in lower Carboniferous times. The change in sedimentation corresponded with major uplift along the Air axis. Throughout the Mesozoic era the uplifted massif was subjected to erosion by intermittent streams and rivers to form the continental arkosic sandstones, siltstones, shales, and conglomerates known as the 'continental intercalaire'. In the upper Cretaceous, marine conditions were re-established in the southern Sahara (Furon, 1963). The sedimentary deposits adjacent to the western edge of the Air massif, in

the Tin Mersoï basin [Arlit] and the more southerly In Gall basin [Agades] are the most important source of uranium. A schematic stratigraphic column for the region is presented in fig. 3. Uranium mineralization in the Jurassic sandstones of the In Gall basin was confirmed in 1962 (Bigotte and Molinas, 1973) at Imouraren, 60 km south of Arlit. But the most significant uranium occurrence was found by drilling in the Palaeozoic Tin Mersoï basin to the north where a deposit was discovered at Arlit in 1965, in a lower Carboniferous deltaic series of alternating shales and sandstones (Bigotte and Molinas, 1973). Uranium mineralization associated with abundant carbonaceous matter and pyrite occurs at several stratigraphic horizons in the Tagora series (fig. 3), near sandstone-shale boundaries. Faulting of the sedimentary succession has aided the localization and concentration of uranium mainly as pitchblende and coffinite (Bowie, 1979).

#### *Source of uranium in Niger*

*Suggarian basement.* A major source of the detritus and uranium which accumulated in the upper Palaeozoic sedimentary basin could have been derived from the Precambrian metamorphic and calc-alkaline rocks of the Air massif (Bowie,

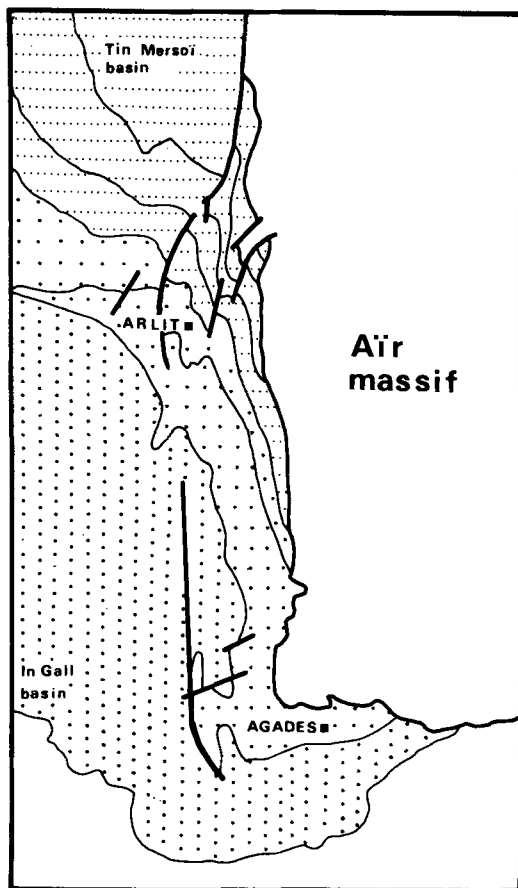


FIG. 2. Sketch geological map of the region to the west and south of the Air massif, scale 1:500 000, after Black *et al.* (1967). Horizontal dots—upper Palaeozoic sedimentary rocks; vertical dots—Permo-Triassic and Jurassic sedimentary rocks. Thick black lines represent post-depositional faults, related to continued movement of the Air block, providing 'traps' for the retention of uranium in carbonaceous sedimentary horizons.

1979). These rocks have been assigned, by French geologists, to one deposition-orogenic cycle called the 'Suggarian'. It is becoming clear, however, (cf. Brunnschweiler, 1974) that the varied assemblage of 'basement' rocks which give Pan-African (600 Ma) ages contain metamorphic associations, which have been overprinted by later events, as well as the igneous rocks that represent new additions to the continental crust. The extent of uranium addition or loss during this series of Proterozoic events is unclear (Sutton, 1979).

*Contributions from other sources.* Bigotte and Obellianne (1968) suggested that a major source of the detritus and uranium in the Mesozoic

sandstones of the In Gall basin was from weathering of rhyolitic volcanic rocks associated with the Tarrouadji alkaline ring complex which is the southern-most of a chain of such structures cutting the Suggarian basement. Furthermore, Brunnschweiler (1974) identified rounded pebbles of rhyolite in a basal conglomerate of the Triassic (Teloua) sandstone of the Agades series which he attributed to Palaeozoic igneous activity. Hence an igneous source readily accounts for the Jurassic uranium mineralization at Imouraren, near Agades. No volcanogenic sandstones have been recorded however in the Palaeozoic Tin Mersoï basin, nor has the source of uranium for the Arlit deposit been assigned to Palaeozoic igneous activity. However, geochronological studies have established a consistent but progressive Palaeozoic age variation from Ordovician to Devonian times for the subvolcanic centres (Bowden *et al.*, 1976; Karche and Vachette, 1976; 1978).

*Palaeozoic volcanic rocks as the major source of uranium in Niger.* Rb/Sr ages suggest that volcanic activity in the Air massif also began in Ordovician times and continued until the end of the Devonian. Sedimentological evidence in the southern part of the Air massif indicates that a major part of the uranium could have come from the erosion and unroofing of the volcanic complexes. If, as suggested by Faure (1976), there was progressive uplift from north to south associated with Palaeozoic anorogenic magmatism, then all major centres might have been potential sources of uranium. In order to test this hypothesis, two centres where volcanic rocks are relatively well preserved have been sampled and analysed for U and Th by INAA (Table I).

Two samples in particular [BL 11 (fig. 4) and GN 2] show substantial levels of Th and lower but important residual concentrations of uranium in secondary minerals. Fission track plates of ignimbrites suggest that uranium is concentrated around crystals and lithic fragments, associated with hematite (fig. 4). The Th/U ratios are variable and considerably higher than normal values for acid igneous rocks ( $\text{Th}/\text{U} \approx 3$ ), consistent with the greater mobility during surface chemical weathering and leaching of U than Th under supergene conditions (Rogers and Adams, 1978). The geochemical data (Tables I and II) are interpreted as representing a volcanic pile of rhyolitic ignimbrites of peralkaline affinity which have preferentially lost sodium and uranium, possibly as a sodium-uranyl complex (Bowie, 1979), and which have undergone variable amounts of oxidation. Indeed, the highest uranium concentration in the Niger ignimbrites is recorded in a sample (GN 2) which also has the lowest oxidation ratio [ $\text{Fe}_2\text{O}_3/(\text{FeO} + \text{Fe}_2\text{O}_3)$ ].

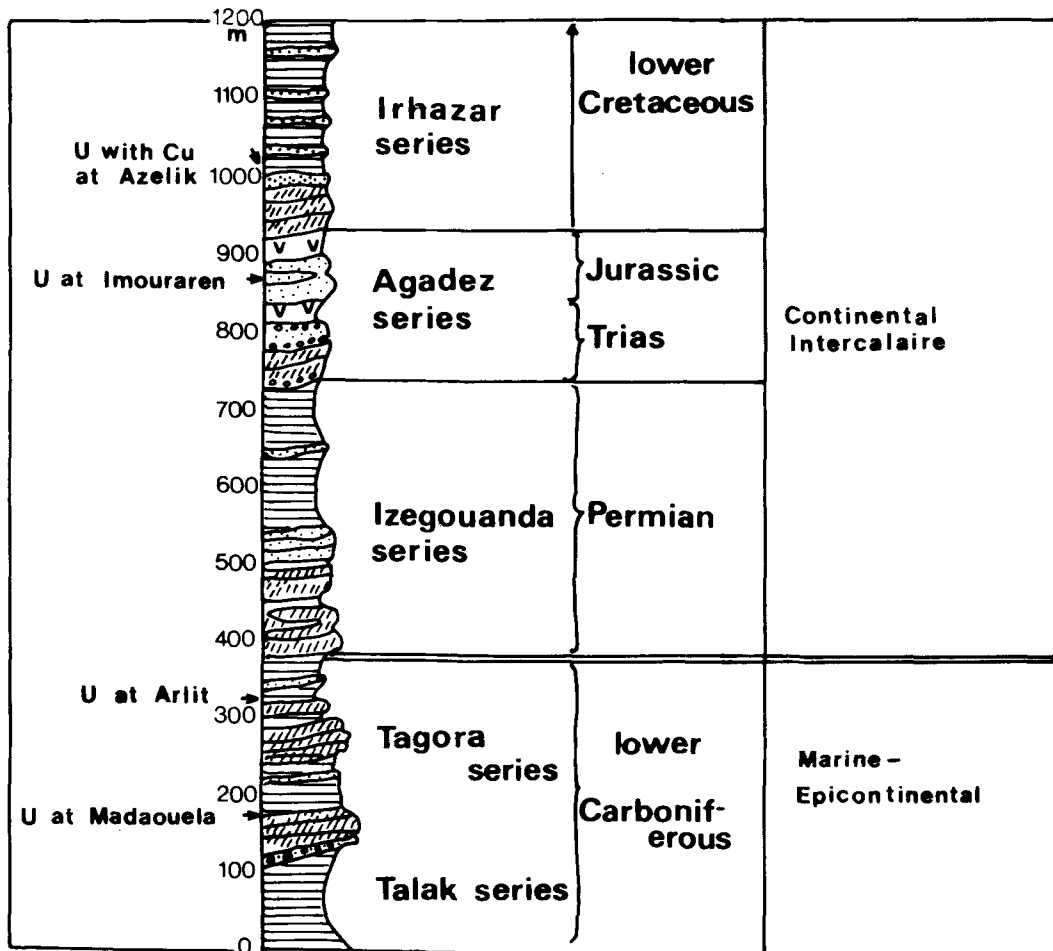


FIG. 3. Schematic stratigraphic column for sedimentary deposits adjacent to the Air massif (after Bigotte and Obellianne, 1968). Horizontal shading—shales/siltstones: dots—sandstones: diagonal etching—sandstones with current bedding: small circles—conglomerates: v—volcanogenic sandstones with analcime.

Hence partial uranium loss by weathering and percolating ground water could account for the distribution of U and Th at Bilete and Goundai (fig. 5).

Thus geochronological, geochemical, and sedimentological studies indicate that the eroded volcanic cover of the Palaeozoic ring-complexes in the Air massif could have provided the major source of uranium in lower Carboniferous [Arlit] and Jurassic sandstones [Imouraren]. Hence all major sandstone horizons adjacent to sub-volcanic ring complexes are potential sites of uranium mineralization in Niger, if the structural and sedimentological controls for trapping uranium solutions were favourable. This applies not only to sedimentary basins adjacent to the Air massif but

also the southern Hoggar (Algeria), southern Niger (Damagaran in the region of Zinder), and the Nigerian younger granite province.

#### *Uranium in the Nigerian Younger Granite Province*

The Nigerian younger granite province forms the southern series of volcanic centres which migrated episodically from the Cambrian (Hoggar) through Palaeozoic times (Niger) to the end of the Jurassic period (Nigeria). Since the complexes are petrologically similar it is suggested that the processes which formed the Niger uranium deposits may also have operated in Nigeria. In fig. 5, the volcanic feeders (Table III) exposed beneath the original volcanic cover (Zigau, Ririwai) are shown;

TABLE I. Trace element analyses for some Niger ignimbrites

Volcanic centre	Bilete			Goundaï					
	Sample no.	BL 5	BL 10	BL 11	GN 2	GN 3	GN 11	GN 13	GN 17
U		3.9	7.4	11	21	4.7	7.8	11	9.2
Th		28	40	62	100	37	33	56	42
Th/U ratio		7.2	5.4	5.6	4.8	7.9	4.2	5.1	4.6
Li		<2	65	49	190	<2	68	25	19
Zn		130	395	1300	115	34	245	35	77
Rb		175	455	545	590	190	260	575	455
Sr		<7	<7	7	<7	<7	<7	26	13
Cl		55	80	300	45	13	26	145	160
F		1100	2600	1400	2300	250	3550	60	3350

All values in ppm.

U, Th by INAA (East Kilbride), analysts J. E. Whitley and A. Wilson.

Li, Zn, Rb, Sr by atomic absorption, analyst Richard Batchelor.

F, Cl, colorimetric method, analyst Richard Batchelor.

TABLE II. Major element analyses of some Niger ignimbrites

Volcanic centre	Bilete			Goundaï					
	Sample no.	BL 5	BL 10	BL 11	GN 2	GN 3	GN 11	GN 13	GN 17
Weight %									
SiO <sub>2</sub>		76.5	75.9	74.6	75.1	78.0	76.6	75.5	77.5
TiO <sub>2</sub>		0.14	0.16	0.14	0.11	0.16	0.14	0.23	0.09
Al <sub>2</sub> O <sub>3</sub>		11.89	12.34	12.56	13.24	11.35	11.49	13.91	13.00
Fe <sub>2</sub> O <sub>3</sub>		1.28	1.92	1.02	0.43	1.05	0.96	0.65	0.46
FeO		0.50	0.35	0.85	1.05	0.20	1.42	0.75	0.20
MnO		0.03	0.02	0.02	0.01	0.02	0.04	0.02	0.01
MgO		0.15	<0.03	0.10	<0.03	0.04	0.02	0.34	0.23
CaO		1.04	0.49	0.46	0.45	0.10	0.31	0.30	0.23
Na <sub>2</sub> O		2.64	3.52	2.21	4.08	4.08	4.24	0.34	2.51
K <sub>2</sub> O		4.23	4.34	5.52	4.33	3.55	4.76	4.88	3.94
P <sub>2</sub> O <sub>5</sub>		0.01	<0.01	0.01	<0.01	<0.01	<0.01	0.09	<0.01
H <sub>2</sub> O <sup>+</sup>		1.07	0.70	2.00	0.28	0.62	0.30	2.95	1.84
H <sub>2</sub> O <sup>-</sup>		0.13	0.08	0.08	0.12	0.10	0.12	0.10	0.20
F		0.11	0.26	0.14	0.23	0.02	0.36	0.06	0.34
Less O ≡ F		0.05	0.11	0.06	0.10	0.01	0.15	0.02	0.14
Total		99.67	100.01	99.65	99.37	99.28	100.61	100.10	100.41
Fe <sub>2</sub> O <sub>3</sub>		0.72	0.85	0.55	0.29	0.84	0.40	0.46	0.70
FeO + Fe <sub>2</sub> O <sub>3</sub>									

Analysts: Richard Batchelor and A. G. Reid.

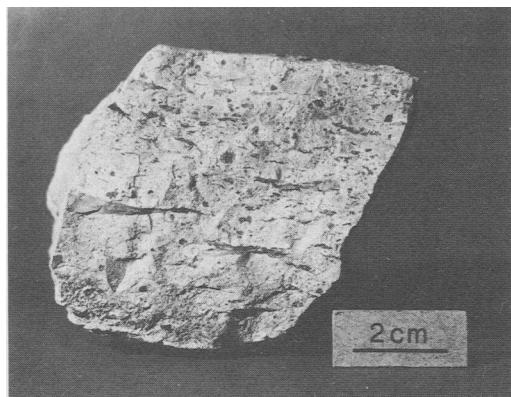


FIG. 4. Niger ignimbrite (BL 11) showing collapsed pumice (elongate dark grey zones) in a matrix of welded lapilli, crystal, and lithic fragments. The local dark 'spotty' areas are zones of hydrated iron oxide (now hematite) which have provided adsorption surfaces for the partial retention of uranium.

the area represents the U and Th concentrations based on random samples of volcanic rocks preserved by caldera collapse at several Nigerian centres (Table IV). The volcanic cover is not as well preserved as at Goundaï and Bilete in Niger. However, comparison of levels of U and Th of Nigerian and Niger samples (fig. 5) suggests that in Nigeria the volcanic rocks have lost greater quantities of uranium relative to thorium. Limited sedimentological studies indicate that drainage patterns and fault-controlled traps for uranium are less well developed in Nigeria.

Erosion of the Nigerian Jurassic volcanic cover continued during the Cretaceous and ended in the Tertiary when many mineralized granite roof zones were exposed at various centres. Palaeogeographic studies indicate that the Jos plateau was a topographic 'high' with a radial drainage pattern.

If sedimentary uranium deposits occur in Nigeria, the most likely horizons are in such Cretaceous continental sediments as the Bima sandstone in the Benue valley and Chad basin (Offadile, 1976; Matheis, 1976). But the widespread Coniacian marine transgression from the northern Saharan sea (Offadile, 1976) may have dispersed any concentrations of uranium. By Tertiary times, widely varying conditions of sedimentation had returned (lacustrine, deltaic, desert) with reworked material deposited to form the Kerri-Kerri formation (Matheis, 1976). Thus, although the volcanic cover of the Nigerian ring complexes may have been a source of uranium, tectono-sedimentary conditions were not favourable for its preservation although the roof zones of the centres may have provided a source of uranium.

#### Distribution of uranium and thorium in Nigerian subvolcanic syenites and granites

*Syenites and peralkaline granites.* According to Sørensen (1970) and Semenov (1974) agpaic nepheline syenites and peralkaline granites are richer in disseminated uranium than other igneous rocks. They also noted that 'albitized and otherwise altered alkaline rocks' are especially enriched in uranium, particularly in their roof zones. Although the Nigerian peralkaline syenites are quartz-normative, their mafic mineralogy is similar to uranium-rich undersaturated syenites at Ili-maussaq (Sørensen, 1970).

In the few samples which have been analysed for U and Th (Table V), it is apparent that peralkaline granites and syenites (fig. 6) are relatively enriched in both elements compared with their non-peralkaline counterparts.

In the Shira complex (Bennett, 1981) peralkaline syenites are enriched in U and Th compared with associated peralkaline granites. Chevkinite has been identified in one of the syenites (SH 105) but the mineral is absent from the granites. Thus early

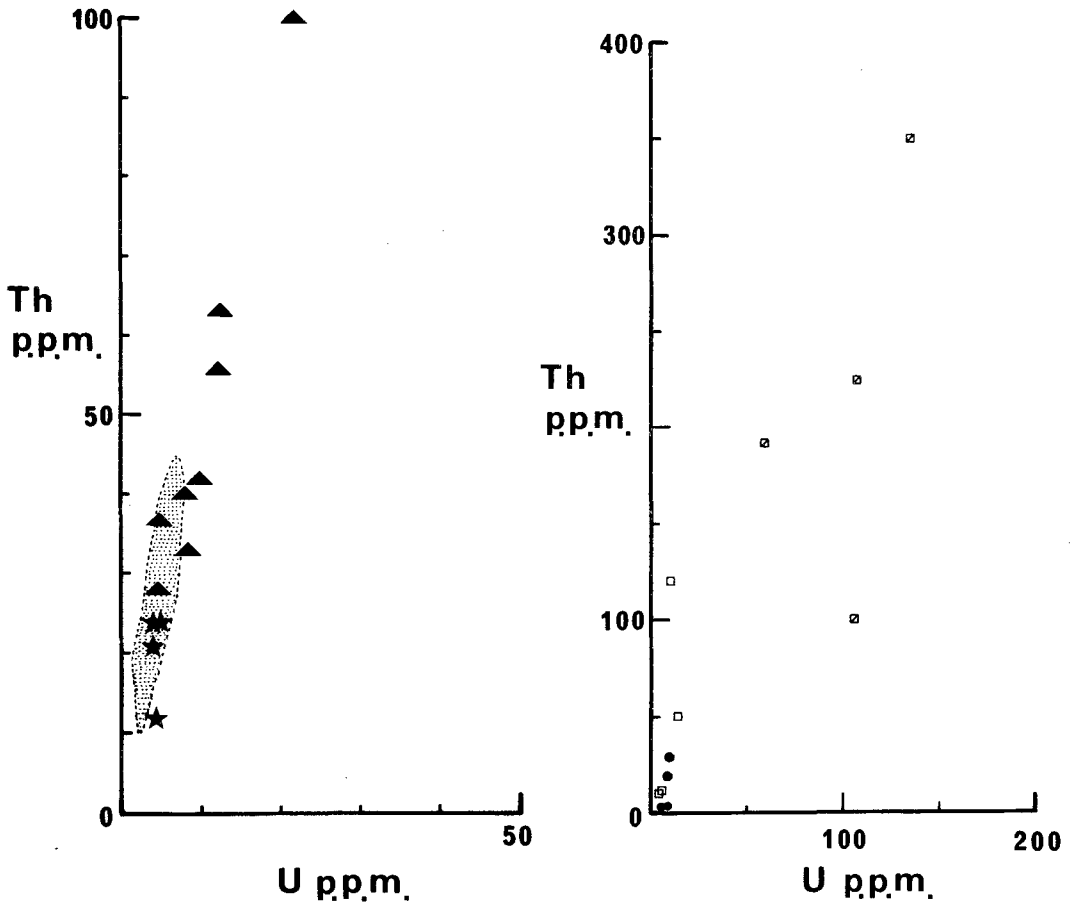
TABLE III. Major element and trace element analyses for some volcanic feeders: Niger-Nigeria province

Wt%	Bilete BL 1	Goundaï GN 33	Zigau ZG 1	Banke B 138	Ririwai N 96
SiO <sub>2</sub>	73.5	65.1	71.40	74.90	71.39
TiO <sub>2</sub>	0.37	0.50	<0.10	<0.10	0.28
Al <sub>2</sub> O <sub>3</sub>	12.34	14.38	13.72	11.48	13.39
Fe <sub>2</sub> O <sub>3</sub>	0.52	1.33	1.17	0.64	1.58
FeO	2.20	4.36	2.62	1.73	2.30
MnO	0.08	0.14	0.11	0.06	0.15
MgO	0.10	0.10	0.13	0.05	0.04
CaO	1.16	1.64	0.89	0.61	0.74
Na <sub>2</sub> O	3.78	4.54	4.54	3.29	4.20
K <sub>2</sub> O	5.41	5.83	5.13	5.19	5.17
P <sub>2</sub> O <sub>5</sub>	0.04	0.04	0.05	0.02	0.04
H <sub>2</sub> O <sup>+</sup>	0.32	0.36	0.63	0.25	0.24
H <sub>2</sub> O <sup>-</sup>	0.10	0.18	0.11	0.11	0.13
F	0.06	0.13	0.05	0.12	—
Less O ≡ F	0.02	0.05	0.02	0.05	—
Total	99.96	98.58	100.53	98.40	99.47
Fe <sub>2</sub> O <sub>3</sub>	0.19	0.23	0.31	0.27	0.41
FeO + Fe <sub>2</sub> O <sub>3</sub>					
ppm					
U	3.9	3.0	3.7	4.7	4.0
Th	24	24	12	22	21
Li	2	<2	33	15	24
Zn	220	180	110	130	175
Rb	140	125	75	150	125
Sr	13	13	22	<7	13
Th/U ratio	6.2	8	3.2	4.7	5.3
Cl	145	18	<2.5	<2.5	—
F	60	1300	540	1160	—

Analysts: Richard Batchelor, J. E. Whitley, and A. Wilson.

crystallization of light rare-earth enriched chevkinite could have depleted the remaining liquids in U and Th. Apart from magmatic variations in the relative concentrations of U and Th, average Th/U ratios approach a value of 3. Mineralogical and geochemical studies indicate however that the uranium concentration and the Th/U ratio may be affected by rock-fluid interaction during cooling, consolidation, and mineralization. Samples from the Ririwai complex studied by Stavrakis (1975) and plotted in fig. 6 provide examples. Two samples of peralkaline granites (N83, N80) from Ririwai show a particularly marked increase in the Th/U ratio from 3.6 to 12. The texture of these rocks is unusual, with 'worm-like' tubules of quartz replacing perthitic alkali feldspar as well as apgaitic

crystallization of quartz and arfvedsonite, with minor astrophyllite and annitic mica. The quartz-feldspar intergrowths cannot be explained simply as cotectic crystallization of a peralkaline granitic liquid, but may represent post-magmatic silification of a peralkaline quartz syenite. Other peralkaline granite facies in Nigeria are albite-granites; these show exceptionally high concentrations of both elements and a decrease in the Th/U ratio from 3.1 to 0.95 (Table V). A sample from Ririwai was assessed for niobium and uranium (Mackay and Beer, 1952) and shown to contain accessory pyrochlore, Th-rich monazite, cryolite, and an alkali amphibole (arfvedsonite). The crucial factor is the modal proportion of albite, which may represent either low-temperature crystallization of



FIGS. 5 and 6. 5 (left). U and Th distribution in volcanic rocks and volcanic feeders for the Niger-Nigerian anorogenic province. Filled upright triangles—Niger ignimbrites; closed stars—volcanic feeders; shaded area—Nigerian volcanic rocks. 6 (right). U and Th distribution in syenites and peralkaline granites from four Nigerian anorogenic subvolcanic centres. Closed circles—syenites; open squares—arfvedsonite granites; open squares with diagonal line—arfvedsonite albite granites. Data given in Table V.

a solidus-depressed granite magma (Manning, 1981), or intense albitization, to produce a distinctive suite of rocks greatly enriched in uranium and thorium.

**Biotite granites.** In order to understand the problems of sampling this type of granite and of interpreting the U-Th data it is useful to consider the mechanism of emplacement. It is suggested that a cupola, or small stock, of crystallizing granite magma is emplaced at a high level with a concentration of residual fluid towards the roof. Depending upon several variables, the interaction of fluid with the cooling granite may be intense near the roof but diminish with depth. Such events would be repeated where the igneous centre contains multiple intrusions. Furthermore, depending on the degree of cooling of the granite body, rock-fluid interaction may be pervasive and percolate along intergranular boundaries. At lower temperatures fluids may be restricted to cooling joints or fractures so that more localized fluid interaction forms greisen veins, lodes, and stockworks, with associated wall-rock alteration. Two major periods of rock-fluid metasomatism are indicated.

(1) Dispersed mineralization associated principally with columbite, thorite, xenotime, monazite, and minor cassiterite.

(2) Vein-controlled mineralization associated principally with sphalerite and cassiterite, and minor oxides with sulphides of copper, lead, bismuth, iron, and cadmium (Kinnaird, 1979).

The geochemistry of U and Th in magmatic processes is reasonably well understood. U and Th are incompatible, with distribution coefficients for major rock-forming minerals less than one (Rogers and Adams, 1978). U and Th should therefore concentrate in residual liquids to high concentrations provided early crystallization of substantial amounts of accessory minerals such as zircon and monazite does not occur. In a peralkaline acid environment these minerals are inhibited from early crystallization, but under more aluminous conditions (e.g. biotite granites) they may crystallize early. Furthermore, little is known about crystal-fluid distribution coefficients during post-magmatic processes. Using these constraints some examples of the distribution of U and Th in granites collected as surface samples in the recently exposed roof zone, and in a core sample (L 13) which penetrated albitite at 400 m depth in the Ririwai complex are considered. Two other samples with less disturbed Th/U ratios from Jos, and Amo are included in Table V and fig. 7 for comparison.

TABLE IV. Major element analyses and uranium-thorium values for some Nigerian volcanic rocks

Complex	Buji	Buji	Ririwai	Ririwai	Ririwai	Jos	Saiya Shokobo	Buji	Kila	Warji	Buji
Sample nos.	N 1-69	N 2-69	N 81-69 (X 1612)	N 82-69	N 85-69 (X 1531)	L 364	MB 696	L 814	DT 834	DT 837	L 939
Wt %											
SiO <sub>2</sub>	75.09	73.85	74.10	73.87	69.63	73.55	74.80	76.26	75.10	72.23	75.68
TiO <sub>2</sub>	0.12	0.12	0.20	0.35	0.45	0.15	0.11	tr.	tr.	0.35	0.17
Al <sub>2</sub> O <sub>3</sub>	13.65	13.66	10.88	11.96	13.97	13.34	11.74	13.09	11.51	13.29	12.36
Fe <sub>2</sub> O <sub>3</sub>	0.93	1.24	3.24	0.74	3.62	0.13	1.29	0.44	3.07	2.88	1.73
FeO	0.28	1.17	1.15	3.47	0.69	2.58	2.10	0.95	0.78	1.50	0.25
MnO	0.03	0.08	0.08	tr.	0.05	0.05	0.11	0.03	0.05	0.04	0.04
MgO	tr.	0.15	tr.	0.08	0.22	0.37	tr.	tr.	tr.	0.25	0.19
CaO	0.20	0.35	0.26	0.14	0.58	0.47	0.10	0.18	0.03	0.37	0.10
Na <sub>2</sub> O	4.18	3.30	4.43	4.48	3.62	1.79	3.97	4.14	4.55	4.54	3.22
K <sub>2</sub> O	4.72	5.61	4.09	4.51	5.42	6.14	4.50	4.53	4.29	3.61	4.35
P <sub>2</sub> O <sub>5</sub>	tr.	0.01	tr.	0.01	0.14	0.02	0.03	tr.	tr.	0.07	0.01
H <sub>2</sub> O <sup>+</sup>	0.31	0.81	0.31	0.41	0.70	0.69	0.38	0.41	0.29	0.21	0.70
H <sub>2</sub> O <sup>-</sup>	0.11	0.13	0.11	0.09	0.19	0.07	0.11	0.08	0.06	0.09	0.37
Total	99.31	100.48	98.85	100.19	99.28	99.35	99.24	100.11	99.73	99.43	99.17
Fe <sub>2</sub> O <sub>3</sub>	0.77	0.51	0.74	0.18	0.84	0.05	0.38	0.32	0.80	0.66	0.87
FeO + Fe <sub>2</sub> O <sub>3</sub>											
ppm											
U	4.0	2.8	8.9	7.3	0.8	2.6	3.4	5.9	9.0	6.4	4.5
Th	20	17	40	37	17	14	21	20	34	24	17
Th/U ratio	5	6.1	4.5	5.1	21	5.4	6.2	3.4	3.8	3.8	3.8

Major element analyses: Sandra West.

U and Th determined by INAA (East Kilbride), analyst J. E. Whitley.

tr.—trace usually less than 0.01%.

Note: sample number prefixes X-, L-, MB- refer to original descriptions in Jacobson *et al.* (1958).



TABLE V. U and Th values for some Nigerian syenites, granites, albite granites, and albitites

Sample no.	Description		U (ppm)	Th (ppm)	Th/U
SYENITES					
DT 25	alkali-feldspar syenite	Dutse	2.2	7.8	3.5
KW 6	syenite with plagioclase (An <sub>50-35</sub> )	Kila Warji	1.8	6.8	3.8
SH 105	peralkaline quartz syenite	Shira	7.4	20	2.7
SH 51	peralkaline syenite	Shira	8.1	30	3.7
PERALKALINE GRANITES					
DT 23	arfvedsonite granite	Dutse	4.6	14	3.0
SH 5	arfvedsonite granite	Shira	3.9	12	3.1
SH 90	aegirine microgranite (dyke)	Shira	7.0	5.5	0.79
N 83	arfvedsonite granite	Ririvai	14	51	3.6
N 80	arfvedsonite granite	Ririvai	10	120	12
ALBITE-GRANITES					
N 87	arfvedsonite albite granite	Ririvai	60	190	3.2
N 88	arfvedsonite albite granite	Ririvai	105	100	0.95
N 89	arfvedsonite albite granite	Ririvai	105	225	2.1
N 86	arfvedsonite albite granite	Ririvai	145	350	2.4
AF 40	zinnwaldite albite granite	Afu	105	190	1.8
BIOTITE GRANITES					
N 151	biotite syenogranite	Jos	5.4	22	4.1
N 25	biotite syenogranite	Amo	5.2	21	4.0
N 77	biotite granite	Ririvai	7.5	41	5.5
N 91	biotite granite	Ririvai	7.3	50	6.8
N 92	biotite granite	Ririvai	8.0	62	7.8
N 75	biotite granite	Ririvai	10	83	8.3
SH 21	biotite granite	Shira	13	47	3.6
Core L 13 in biotite granite					
L 13-10	core sample at 10 m depth	Ririvai	30	25	0.83
L 13-205	core sample at 205 m depth		53	51	0.96
L 13-310	core sample at 310 m depth		58	56	0.97
Core L 13 in albitite					
L 13-411	core sample at 411 m depth	Ririvai	81	73	0.90
L 13-440	core sample at 440 m depth		66	69	1.05

Analysts: J. E. Whitley, A. Wilson, S. I. Abaa, and P. Stavrakis.

*Ririvai biotite granite.* The exposed surface of biotite granite represents a zone in the shallow-dipping roof from which the volcanic cover has been removed relatively recently. Chilled margins remain as isolated areas of microgranite within variably textured biotite granite. Textures range from coarsely porphyritic to medium-grained equigranular, both on the surface and underground to depths of at least 400 m.

Samples N 77, N 91, N 92, and N 75 (fig. 7) represent progressive uranium loss relative to Th of surface samples in the roof zone of biotite granite at Ririvai. If mineralization represents the degree of rock-fluid interaction, then the biotite granite at Ririvai has suffered intense post-magmatic alteration. The U-Th variation for surface samples

(fig. 7) is interpreted as the result of uranium mobilization to higher levels of the complex which have subsequently been eroded with Th retained in accessory minerals. In fig. 7 the open circles represent drill core samples taken at different intervals below the present erosional surface, close to a major tin lode. Samples L 13-10 (at 10 m), L 13-205 (at 205 m) and L 13-310 (at 310 m) listed in Table V show a progressive increase of U and Th with depth; this feature also occurs in other provinces where it has been attributed to element mobility at low temperatures (Chatterjee, 1981). Samples taken at 411 m and 440 m are albitites, and represent a zone of intense albitization at depth similar to that discovered in other tin deposits associated with acid magmatism in the

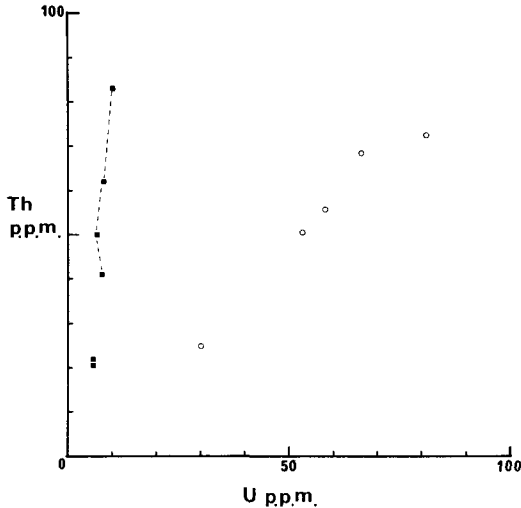


FIG. 7. U and Th distribution in biotite granites and related rocks from Nigeria. Closed squares—biotite granite; open circles—drill core L 13 from the Ririwai complex. Data presented in Table V. Samples N 77, N 91, N 92, and N 75 form a series of linked closed squares parallel to the Th axis.

Czechoslovakian Bohemian massif (Stemprok, 1974) and the French Massif Centrale (Leroy, 1978). Thus hydrothermal processes in the mineralized biotite granites from Ririwai, modified the concentrations of U and Th. Depending on the location within the cupola and on the intensity and type of fluid interaction (e.g. albitization, greisenization), relative concentrations of uranium and thorium, and hence the Th/U ratios, may vary considerably.

### Conclusions

Volcanic and subvolcanic anorogenic magmatism in the Niger–Nigeria younger granite province may have provided localized concentrations of U and Th in the continental crust during Palaeozoic and Mesozoic times. Crystallization of both peralkaline and aluminous granites leads to enriched concentrations of U and Th in residual fluids. There is evidence of considerable mobility of both U and Th during post-magmatic periods of rock–fluid interaction, leading to considerable enrichment of uranium. Loss of uranium relative to thorium occurred during the leaching of the volcanic pile of rhyolitic ignimbrites at each centre providing a source of detritus and mineralizing solutions in Niger, and probably in Nigeria.

The uranium was trapped in subsiding, southerly migrating basins along the western edge of the Aïr

massif during Palaeozoic and early Mesozoic times. Post-depositional faulting provided tectonic traps, in which uranium was retained by organic matter. Similar geological conditions favourable to uranium concentration do not appear to have operated in Nigeria during the erosion of the Mesozoic volcanic centres. However, variable concentrations of U and Th, as represented by Th/U ratios, varying from 0.95 to 8.3, suggest relative mobilization of uranium in the exposed subvolcanic roof zones. Thus local vein deposits of uraninite, as well as dispersed uranium in some recent sedimentary horizons could be discovered particularly in the drainage patterns leading to the Chad basin.

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### APPENDIX

#### *Determination of uranium and thorium in Niger–Nigerian igneous rocks by epithermal neutron activation analysis*

*Method.* Uranium and thorium were determined by instrumental epithermal neutron activation analysis, as described by Brunfelt and Steinnes (1969). 0.2 g samples of powdered rock and standards prepared by evaporating solutions containing 10  $\mu\text{g}$  of U and Th respectively on to discs of filter paper were sealed in aluminium envelopes and irradiated in a cadmium box of 1 mm wall thickness for 6 hours in a flux of  $3.6 \times 10^{12}$  thermal n.  $\text{cm}^{-2} \text{sec}^{-1}$  ( $1 \times 10^{12}$  epithermal n.  $\text{cm}^{-2} \text{sec}^{-1}$ ). Four days after irradiation the samples were counted with a 25  $\text{cm}^3$  Ge(Li) detector (with a resolution of 2.3 KeV at 1.33 MeV) associated with an EGG and ORTEC 4032 data acquisition and analysis system. Counting times were usually 1 hr per sample but were extended for samples of low U content. Results were calculated by comparing the activities induced in the 278 keV photopeak of  $^{239}\text{Np}$  (for U) and 311 KeV photopeak of  $^{233}\text{Pa}$  (for Th) in the rocks and the standards. The accuracy of results derived from counting statistics was generally better than  $\pm 1\%$ .

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