Chapter 2
The Younger Granites

General Description

The Mesozoic Younger Granite ring complexes of Nigeria (Fig. 2.1) form part of a wider province of alkaline anorogenic magmatism. They occur in a zone 200 km wide and 1,600 km long extending from northern Niger to south central Nigeria. Rb/Sr whole rock dating indicates that the oldest complex of Adrar Bous in the north of Niger is Ordovician in age, with progressively younger ages southwards. The most southerly ring complex of Afu is Late Jurassic in age (Bowden et al., 1976). Aeromagnetic anomalies suggest that a series of buried NE–SW lineaments of incipient rifts controlled the disposition of the individual complexes (Ajakaiye, 1983).

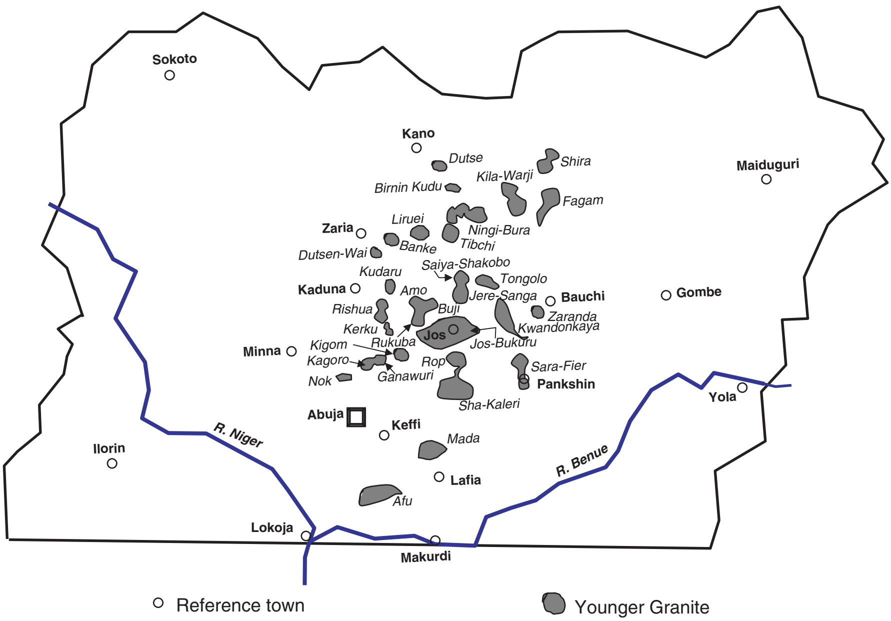

Fig. 2.1 Major Founger Granites localities in Nigeria

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The Younger Granites have been studied in most detail in Nigeria, partly for their intrinsic interest, providing comparative data for study of similar formations elsewhere in the world, but mainly because in the early 1900s they were recognized as the source of rich alluvial cassiterite deposits that had long been known to exist on and around the Jos Plateau Detailed filed mapping of the ring complexes has demonstrated a consistent succession of magmatic activity from volcanism to plutonism associated with the emplacement of mainly granite melts at high levels in the crust. The most striking petrographic feature of the whole province is the overwhelmingly acid nature of the rocks and the similarity of the rock types found in all areas. Over 95% of the rocks can be classified as rhyolites, quartz-syenites or granites, with basic rocks forming the remaining 5%. Many of the rocks have strongly *alkaline* to *peralkaline* compositions, other are *aluminous* to *peraluminous*.

More than 50 complexes occur in Nigeria varying from <2 to >25 km in diameter (Kinnaird, 1981). The ring complexes cover a total area of about 7,500 km^2 with individual massifs varying from 1,000 km^2 to <1 km^2. The majority are between 100 and 250 km^2 with circular or elliptical outlines (Figs. 2.2, 2.3, 2.4, 2.5, and 2.6). Each of the ring complexes, whether they consist of overlapping centres, as at Ningi-Burra, or individual centres, such as Ririwai, began as chains of volcanoes (Bowden and Kinnaird, 1984). Early ash-fall tufts and agglomerates were deposited

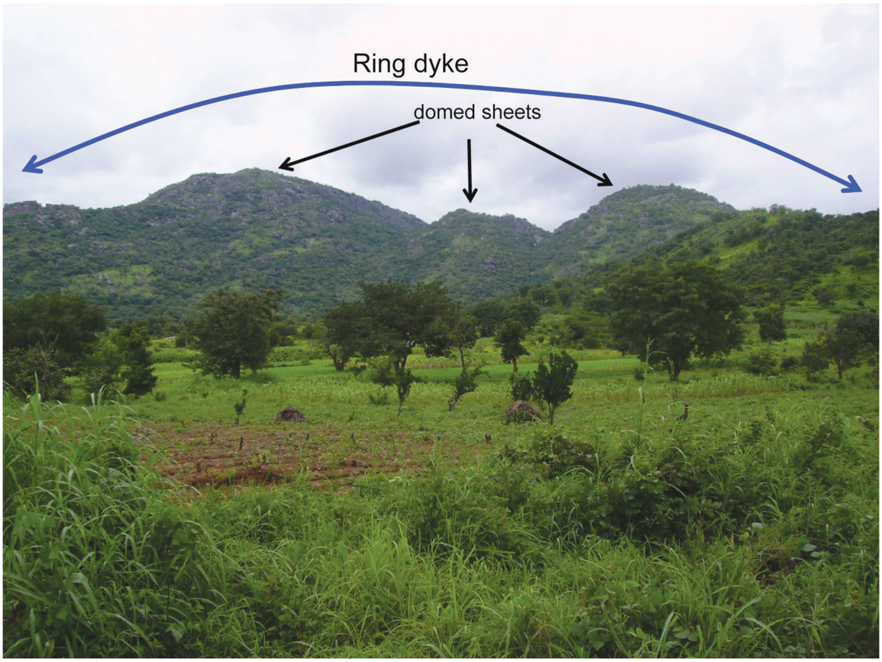

Fig. 2.2 A portion of the Mada Younger Granite complex near Akwanga in Nasarawa State. Note the migrating domed sheets and the circular nature of the complex

Fig. 2.3 Different views of a portion of the Kagoro Younger Granites visible on the Forest – Jos road. Domed sheets are less developed, but the dyke is extensive

from eruptions of explosive activity (Fig. 2.7). Abundant ignimbrites deposited from ash flows dominate the volcanics with only minor rhyolitic and thin basic flows. Volcanic feeder intrusions are a minor but important link during the caldera-forming stage, between the subvolcanic roots and the overlying volcanic pile. Fayalite hedenbergite quartz porphyry often has ignimbritic textures.

The Younger Granites are discordant high level intrusions (Figs. 2.2, 2.3, 2.4, 2.5, and 2.6) emplaced by means of piecemeal stoping through the collapsed central block. Initial stages in development of the complexes involved intrusion of vast amounts of acid lavas, tuffs and ignimbrites, now only partly preserved as a result of subsidence along ring faults. Almost everywhere these rhyolitic rocks directly overlie the metamorphic basement, which means that the younger granites were emplaced in uplifted areas that were undergoing erosion. Granitic *ring dykes* are the major component of most complexes, ranging from 5 km or less to over 30 km in diameter, and varying in plan from the polygonal to circular or crescent, and through

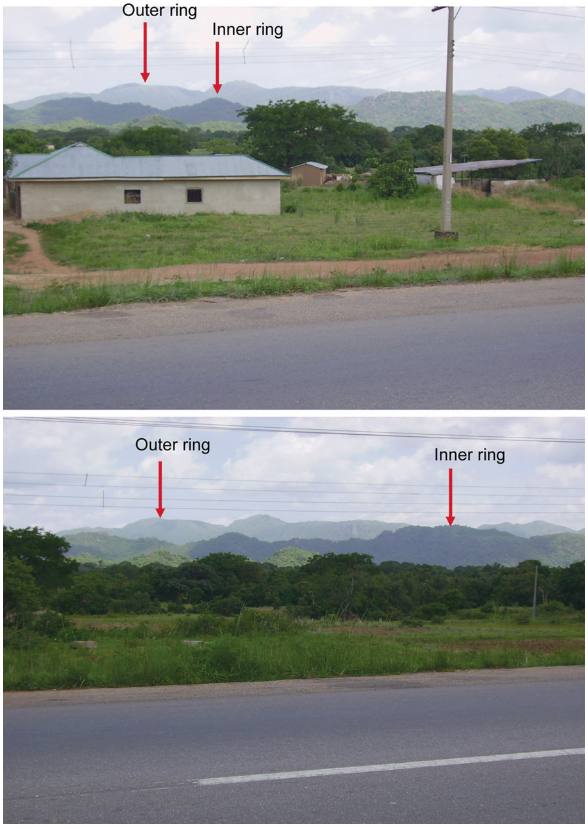

Fig. 2.4 Different views of the Jos-Bukurn Younger Granties complex. (Viewed approaching Jos from Tilde Fulani). Note outer ring and inner ring

more irregular shapes to simple stocks and bosses. Some complexes have a broadly concentric pattern, indicating that the activity was confined to one area, but others have overlapping rings, because the centre of activity migrated with time. Erosion of the volcanics in the more southerly complexes has revealed good exposures of granite. Even where ring complexes have no associated volcanic at all, this is probably because they have been removed by erosion rather than because they were never erupted. The ring dykes were probably emplaced by mechanisms involving underground *cauldron subsidence* (Fig. 2.7). The granitoid suite is more than 95% granite. Intermediate and basic rocks constitute less than 5% of the area. There are several distinctive granite types:

(i) Peralkaline granites and related syenites (with alkali or calcic amphibole in the compositional range ferrorichterite to arfvedsonite in the granites and ferrodenite to ferroactinolite in the syenites) plot close to Q-A join in the Streckeisen Q-A-P plot;
(ii) Peraluminous biotite alkali feldspar granites and biotite syenogranites plot close to the boundary between the two fields on the Streckeisen diagram;

Fig. 2.5 Different views of the southern end of the outer ring of the Jos-Bukurn Younger Granites complex (**a**) viewed from the Police Staff College Jos on the approach to the Pankshin Junction roundabout (**b**) on the approach to the Police Staff College Jos from the Pankshin junction roundabout

(iii) Metaluminous fayalite and hornblende-bearing granites and porphyries with amphiboles or biotite plot in the granite field.

The granites of the Younger Granites series are mainly in the form of ring complexes, of soda pyroxenes and amphiboles, biotite, and fayalite granites, syenites and trachytes with minor gabbros and dolerites. Rhyolites, tufts and ignimbrites are rarely preserved. The centres normally overlap one another, and there is a general tendency for a southern shift in intrusion. However, NE trending alignments of complexes are noticeable, perhaps reflecting deep seated zones of weakness in the basement, but there are no obvious surface relationships between location and regional tectonic features (Black and Girod, 1970). The complexes have been well studied, partly because of their classical structures, petrographic type, and mid-plate anorogenic character, but not least for their economic interest since they are associated with considerable cassiterite, wolframite, scheelite and zinc mineralization, and have sustained an important alluvial tin mining industry. Fifteen of the complexes

Fig. 2.6 Different views of the Kwandonkaya Younger Granite complex on the Jos – Bauchi road

have been isotopically dated and a perceptable trend in the north from 213 ± 7 Ma (Dutse), 186 ± 15 Ma (Zaranda) and 183 ± 7 Ma (Ningi-Burra) to those in the south at 151 ± 4 Ma (Pankshin), 145 ± 4 Ma (Mada), and 141 ± 2 Ma (Afu) is discernable. This progressive change in age, and the fact that similar alkali granite ring complexes in southern Niger and further north in Air are Carboniferous, Devonian and Ordovician in age has prompted authors (e.g. Bowden et al., 1976) to advocate a sequential age trend covering some 500 Ma over a distance of more than 2,000 km. More recently Rahaman et al. (1984) and Bowden and Kinnaird (1984) have provided further isotopic evidence of this age progression. Of all the African ring complex provinces the Younger Granites of Nigeria have been most studied, and although providing fine examples of ring structures and petrogenetic evolution, these features can be as well seen in other provinces. They are however, economically more significant (Kinnaird, 1984) than any of the other groups, excluding the carbonatite complex of Palabora (Bowden and Kinnaird, 1984). Major characteristics of the Nigerian Younger Granite rocks in comparism to the Older Granite suites are given in Explanatory Note 3.

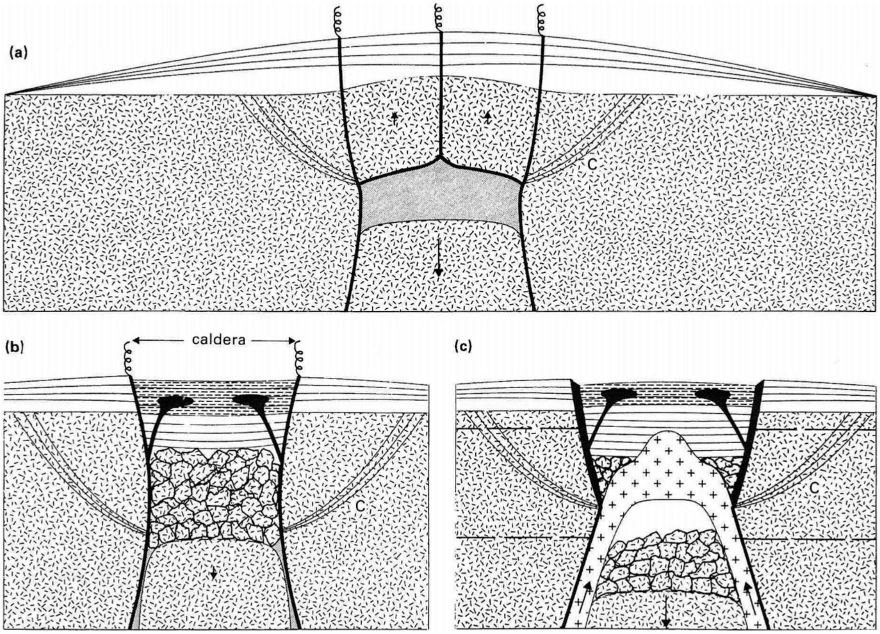

Fig. 2.7 Schematic cross section to show stages in the development of Younger Granite complexes (After Wright, 1985) **a**) A mass of granite (shaded) rises high into the crust (basement gneisses, migmatites and granites), supplied along ring fractures from below. Emplacement is accompanied by doming or swelling of the overlying crust and by initial subsidence of the underlying crustal block. Cone sheets (C) may be emplaced. Predominantly rhyolitic magmas are erupted, mainly as ignimbrites, from acuate vents along the ring fracture and also from central vents. **b**) Rapid eruption of ignimbrites empties the magma chamber so that the overlying crustal cylinder breaks up and collapses into the resulting void, and there may also be further subsidence of the crustal block beneath. Early volcanics are downfaulted into the surface calders, which is filled by eruptions of later rhyolites in the form of both ignimbrites (dashes) and viscous lava masses (black). These are minly supplied by magma rising along the ring fractures. Caldera subsidence continues during eruption of the rhyolites. **c**) Eruptions cease and the ring fractures are filled with grantie porphyries to form marginal ring dykes (black). Emplacement of granites (crosses) occurs by subterranean cauldron subsidence: intermittent large-scale sinking of the roughly cylindrical crustal block beneath. The granites are emplaced into the upper crust, intruding and sometimes doming the earlier doming the earlier volcanics. The heavy briken lines indicate approximate upper and lower limits of presentday levels seen in complexes in different places

Hydrothermal Alteration

In the anorogenic ring complexes, a series of hydrothermal alteration processes with related mineralization was recognized by Kinnaird (1979). Early sodic metasomatism may affect both peralkaline and peraluminous granites whilst later processes, beginning with potash metasomatism, affect only the biotite granites. Subsequent acid metasomatism results in processes of greisenization and silicification – each with a clearly defined sequence of ore deposition. Chloritization and argillization

1. Anorogenic; the Older Granites are orogenic
2. Intrude the basement discordantly to form highly steeped hills; basement complex rocks are generally flat/low lying and lowly steeped
3. Occur generally as ring dykes and cone sheets, sometimes with outer and inner rings; Older Granites occur as massive batholiths
4. The Younger Granites are of Jurassic age; the Older Granites are Precambrian (Pan African)
5. The Younger Granites are generally peralkaline (high amounts of Na and K: feldspars are albitic, pertitic, K-feldspars; sodic amphiboles like arfvedsonites and riebeckites, alkaline pyroxenes like aegerines are very common); Older Granites are generally calk-alkaline and peraluminous.

Explanatory Note 3: Perculiarities of the Younger Granites

are important but more restricted processes. These processes have been discussed in detail in Bowden and Kinnaird (1984), Kinnaird (1985) and Kinnaird et al. (1985) and are briefly summarized below.

Sodic Metasomatism

The mineral assemblages generated during sodic metasomatism depend on the intensity of rock-fluid interaction, the strongly peralkaline granites showing the greatest effect (Bowden and Kinnaird, 1984). The process is responsible for the pervasive alteration of potash feldspar to albite, desilication when the process becomes intense, and enrichment in trace and rare elements. In the Nigerian province it is the albitized granites that have the highest uranium enrichment (Bowden et al., 1981). If the sodic metasomatic process is continued to lower temperatures then mineral assemblages characteristic of propylitic alteration may be generated. Such assemblages include albite, epidote and chlorite. Sodic metasomatism is economically important for the introduction of Nb-bearing ore minerals occurring as columbite in peraluminous biotite granites and as pyrochlore in the peralkaline granites and, of less importance, as fergusonite in metaluminous hornblende biotite granites.

Peralkaline granites: In the peralkaline granites, the process of sodic metasomatism is characterized by the development of albite, aegirine and alkali amphiboles in the compositional range riebeckite to lithian arfvedsonite accompanied by pyrochlore, Th-rich monazite, cryolite, astrophyllite and sometimes by narsarsukite and chevkinite (Bennett, 1981).

Peraluminous Biotite granites: In the apical region of a biotite granite cupola, the original perthitic feldspar is albitized and there is a development of new mica. The albitization process is characterized by a textural change from medium or fine grained equigranular or porphyritic perthitic granite to a sacchroidal fine grained albite protolithionite granite or, more rarely, to albite zinnwaldite or lepidolite granite (Bowden and Kinnaird, 1978). There is a destruction of original Ti-Fe oxides, enrichment in uranium, and the introduction of columbite with minor cassiterite, thorite, xenotime, Th-rich monazite and Hf-rich zircon. Surface samples of the Ririwai complex, compared with drill-core samples, show that there is a diminishing proportion of albite within replacement perthite as depth increases (Kinnaird et al*.,* 1985). At a depth of 295 m the biotite granite consists of quartz, microcline perthite – showing little or no evidence of albitization and annitic mica. In contrast, at 400 m, in the roof zone of another biotite granite, an albite-rich, almost monomineralic rock is encountered (Kinnaird, 1984).

This evidence therefore suggested that sodic metasomatism was concentrated in the apical region of a granite cupola although in many of the complexes the petrological evidence was not well preserved. Such lack of evidence was probably due either to erosion below the apical zone or to continued fluid reactions which had masked the earlier sodic metasomatism.

Metaluminous (hornblende-biotite) granites: Sodic metasomatism may also affect the metaluminous granites to a limited extent. In the hornblende-biotite alkali feldspar granites the perthite feldspar domains have dentate margins with small intergranular grains of ordered albite (Bowden, 1982) Fergusonite, a rare-earth niobate, is common in placer deposits derived from these rocks. The best known localities are in the Sara Fier and Jarawa complexes.

Potassic Metasomatism

Potassic metasomatism is characterized by the development of intermediate to ordered microcline with mica in the compositional range from annite to siderophyllite and chloritization of original mica (Bowden and Kinnaird, 1984). Accessory monazite, zircon, cassiterite, TiO_2 minerals, molybdenite and occasionally wolframite are associated with phyllosilicate minerals. At the same time as K for Na exchange, iron is released from the feldspar lattice and forms minute haematite rods which give a distinctive red colouration to the microcline. As with sodic metasomatism there is desilication when the potassic process becomes intense. When the potassic process is extreme the desilication produces a honeycomb textured microclinite. Where the process of potassic metasomatism is less intense a monomineralic rock is not produced; the original perthitic feldspar is altered to reddened microcline, the quartz remains and the original biotite of the granite is modified. This modification may take the form of chloritization, or pale coloured overgrowths of new Li-Al-rich mica rim the original Fe-Ti-rich dark green/brown biotite. The process of microclinization occurs in two different geological environments within a granite pluton: (1) as the dominant wallrock alteration process along major fractures in the Ririwai and Tibchi complexes; (2) in greisen bordered pockets at biotite granite margins. The pockets are clearly related to an early stage of vapour separation. They are lined by small pink microcline crystals which may be accompanied by euhedral cassiterite up to 2 mm diameter and tiny transparent spheres of fluorite

Acid (Hydrogen Ion) Metasomatism and Hydration

There may be a gradual change in the mineral assemblage generated during lower temperature metasomatism in response to the changing K^+/H^+ ratio in the fluid. Such acid metasomatism is characterized by the breakdown of granitic minerals to produce a new mineral assemblage. However, since acid metasomatism can be superimposed on various earlier mineral assemblages the petrological characteristics depend on the intensity of earlier sodic or potassic metasomatism. Acid metasomatism of an unaltered perthitic alkali feldspar granite results in the formation of a sericite-topaz-quartz assemblage conforming to a classic greisen. In contrast, in granites affected by sodic metasomatism, albite destabilizes to form fluorite, cryolite and topaz with some montomorillonite. In granites affected by potash metasomatism, microcline is transformed into micaceous aggregates, chlorite or, more rarely, kaolinite where the cation/H^+ ion ratio was low enough to enter the kaolinite field. Thus the effect of the acid metasomatism and the resulting mineral assemblage depends on the initial mineral assemblage.

The acid metasomatism may be a disseminated process or form pervasive pockets associated with microclinite; it may diffuse along zones or may occur in fissure-filling veins. The accessory minerals associated with acid metasomatism are commonly concentrated in the mica clusters. The assemblage of ore minerals is mainly of oxides, but in the later stages of deposition, sulphide minerals also occur.

Chloritic (Propylitic) Alteration and Fluorization

Chloritic alteration is characterized by the chloritization of annitic mica, alteration of perthitic feldspar to pale coloured micaceous aggregates, lack of leaching of alkalis, introduction of appreciable iron, reduction in silica and the transformation of biotite and/or feldspar to chlorite. This process of alteration has been described as propylitic alteration. Chlorite alteration tends to be strongest in granite basement rocks adjacent to younger biotite granite contacts. The intensity of alteration is greatest at the contact, grading outwards to merge with normal deuteric or metamorphic alteration phenomena. Abundant sulphide deposition appears to be related to a strong fluorization that often accompanies the chloritic alteration. This is dominated by sphalerite and chalcopyrite. The abundance of fluorite and the low percentage of quartz associated with some chlorite alteration suggest SiO_2 removal in HF-rich fluids.

Silica Metasomatism

Silica metasomatism is characterized by an increase in the modal proportion of quartz relative to all the other minerals in the altered rock. Like potash and hydrogen ion metasomatism, the process may be pervasive or vein-controlled. Quartz may be pervasively deposited into vugs in a cupola created by the earlier potash or hydrogen ion metasomatism, or it may replace all earlier formed minerals. Even more common, are the quartz fissure-filling veins which are found in virtually all biotite granite masses. There is a major sulphide deposition of ores dominated by sphalerite associated with quartz vein development, particularly in lodes at Ririwai and Tibchi. Early cassiterite is followed by abundant dark brown sphalerite, chalcopyrite galena and sometimes arsenopyrite or pyrite.

Argillic Alteration

Argillic alteration is a late stage process, characterized by the formation of clays in the kaolinite and montmorillonite groups at the expense of the feldspars. Argillic alteration is very limited. It is only an important process in three areas and in each of these there has been an earlier extensive albitization of the feldspars during sodic metasomatism. In these areas, the granite has been pervasively reduced to the consistency of clay. Elsewhere the formation of clays is very patchy. Clay minerals may infill vugs in major veins, or coat crystals and fill intracrystal voids in smaller veins. An argillic alteration halo or zone which is commonly associated with porphyry copper deposits does not surround similar mineralized veins in Nigeria.

Geochemistry of the Alteration Processes

Geochemical data have indicated that each of the alteration processes is characterized by a change in alkali element ratios accompanied by an enrichment in specific trace elements (Kinnaird, 1984). Each process can also be distinguished by normative variations in Q-Or and Ab. The early fluids responsible for soda metasomatism, in addition to concentrations of Na, contained Fe combined with Nb, Y, U, Th, Zr, and HREE relative to unaltered granite. Potash metasomatism is characterized by an increase in K_20, Rb, Li and Zn, a loss of Na_2O and trace element depletion. Chemically, H^+ ion metasomatism and greisen development is characterized by a marked decrease in K and AI due to feldspar breakdown with a complementary increase in Si. The chondrite-normalized rare-earth spectrum shows an enrichment in light rare-earth elements, a slight enrichment in Eu, coupled with increasing Yb and Lu (Kinnaird et al., 1985; Bowden, 1985). The silicification process shows the obvious increase in Si balanced by a decrease in all the other major elements except Fe in some cases. There is an increase in Sn, Zn, W, Bi, Cu and Pb. Norm calculations by Kinnard et al. (1985) show that soda metasomatism is characterized by increasing Ab. As potash metasomatism progresses this normative Ab is dramatically reduced and balanced by an increase in normative Or so that the compositions plot away from the central biotite granite field towards the Q-Or join. During H^+ ion metasomatism there is a reduction in both Ab and Or components. The plotting position on the Q-Ab-Or diagram depends on the intensity of earlier processes, thus samples which have been albitized and subsequently greisenized will plot towards the Q pole on the Ab-Q side of the diagram. In contrast, samples which have been microclinized and then greisenized will plot towards the Q pole but on the Or-Q side of the diagram. Those samples which have been subjected to all three processes will plot close to the vertical Q + (Or = Ab).

Structural Setting and Styles of Mineralization

The hydrothermal processes mainly affect biotite granites. Where these processes have been extensive, disseminated and vein deposits of Sn, Zn, W and Nb with Cu, Fe, Bi, U and REE are developed in and around the roof and marginal zones of medium or fine grained granite cupolas, with veins extending up to 2 km out into the country rock. Different styles of mineralization can be recognized:

(i) pegmatite pods with quartz, topaz, beryl and feldspar;
(ii) pervasive metasomatic disseminated mineralization with columbite or pyrochlore ± cassiterite;
(iii) prejoint and postjoint pegmatitic pods and lenses with albite or microcline, genthelvite, uraninite, columbite and thorite;
(iv) quartz rafts, stockworks, sheeted veins and altered wall rock with cassiterite, wolframite and sulphidcs;
(v) fissure-filling veins or lodes with cassiterite, wolframite and sulphides;
(vi) irregularly shaped replacement bodies with cassiterite and sulphides;
(vii) quartz veins with wolframite or scheelite, bismuth minerals, sometimes abundant cassiterite and/or sulphides;
(viii) mineralized ring-dyke with cassiterite and sulphides;
(ix) alluvial and eluvial deposits of columbite, cassiterite, zircon, etc.

The different processes of alteration and associated mineralization are characteristic of different parts of a granite pluton. These different structural environments of deposition can be regarded as five separate zones.

Environmental Zones of Deposition

The roof zone: The roof zone of an intrusion is characterized by disseminated mineralization related to sodic or potassic metasomatism, quartz rafts (sheeted vein systems), pegmatite pods and veinlets, irregularly shaped replacement bodies and fissure-filling veins in the apical region, e.g. at Ririwai-Ginshi Hill adit area and at Banke-Baban Damu.

The marginal zone: The marginal zone: of the intrusion may extend over a horizontal distance of 200–500 m inside the granite contact. It is characterized by stockworks, sheeted veins, associated wall rock alteration and pegmatitic pods, containing a complex paragenesis of oxide and sulphides associated with greisenization and silicification, e.g. at Rishi, in the Saiya Shokobo complex.

The contact area: The contact area occupies a zone of ca 200 in on either side of the granite contact. The zone is characterized by stockworks, fissure-filling veins and intense alteration. If the country rock is basement, chloritic alteration is often very intense and massive sulphide deposits may be deposited. Beneath a volcanic cover, pegmatitic quartz, feldspar and genthelvite may occur.

The country rock: Where the country rock is basement, mineralization occurs in quartz veins and stringers, or sometimes in marginal greisens. The quartz veins are wolframite- or scheelite-bearing with occasional bismuth minerals and sometimes abundant cassiterite or sulphides. Tile country rock may consist of an ignimbritic pile which is poorly jointed. Mineralization is restricted to thin stringers with cassiterite and sulphides. If the country rock consists of intrusions of earlier granites, thinsheeted vein systems may occur where individual veins are of the order of 2 mm–1 cm wide. Often these veins are unmineralized, greisenized granite, although occasionally they contain cassiterite and sulphides.

Ring-dykes: Circular, elliptical or polygonal porphyritic ring-dykes characterize many of the ring complexes. Mineralization may occur as disseminations within the porphyry ground mass or along joint planes. The mineralization, which is always sporadic and economically insignificant, is characterized by a sulphide assemblage of ores dominated by sphalerite, chalcopyrite and galena.

Styles of Mineralization

Pegmatitic pods with quartz ± beryl + feldspar. Generally the margins of the granites are not characterized by pegmatitic development. Where this does occur the resultant pods are sporadic and usually only of the order of a few centimetres or less. The pegmatite pods may be composed of clear or smoky quartz with long prism faces, alkali feldspar sometimes twinned, blue-green beryl, often of gem quality, aquamarine and colourless to pale blue topaz, also often gem quality. Crystals rarely exceed 8 cm in size but crystals of topaz and beryl are commonly 5 cm.

Pervasive metasomatic disseminated mineralization: The most important phase of disseminated mineralization is related to sodic metasomatism since disseminated potash metasomatism is not a widespread process and fracturing and fissuring of granites during late stage cooling usually channels late stage fluids into distinct tabular zones. During sodic metasomatism of the peralkaline albite arfvedsonite granites, the dispersed mineralization is dominated by pyrochlore which forms distinct irregularly- distributed, honey-coloured octahedra in six localities. At each of these, the albitized peralkaline facies covers only a small area. The pyrochlore may contain up to 5% Uranium, but despite localized high concentrations, the heterogeneous dispersed nature of mineralization over such small areas have proved to be too difficult and expensive to attract mining interest so far. During sodic metasomatism of biotite granites a series of oxide ores, principally columbite and cassiterite, is disseminated throughout the apical zone. Subsequent unroofing by erosion of these ore-rich apical zones has resulted in the formation of economically important alluvial and eluvial ore deposits. Many of the alkali biotite granites in Nigeria show slight sodic metasomatism. However, the most intense albitization and highest primary enrichment occurs in localized parts of the Jos- Bukuru complex and Udegi area of the Afu complex. In these areas the granite has been decomposed to the consistency of clay by late stage argillic alteration. This allows the extraction of the ore minerals by the use of monitor and gravel pumps. At Jantar, 12 km south of Bukuru, the white granite forms sills and irregularly branching dykes feathering out upwards into small white veinlets cutting the dark coloured schistose basement. There is a very large variation in columbite content from <30 to >2,200 ppm Nb_20_5. At Harwell, 5 km NE of Bukuru, the columbite-rich facies also contains abundant thorite, xenotime and monazite with traces of ilmenite, magnetite and zircon. The zircon which forms brown, almost opaque crystals contains up to 5% Hf. There is a substantial enrichment in heavy rare-earth elements and also uranium in the ores, particularly in the thorite, xenotime, monazite and zircon. In the Udegi area, the fine grained, columbite-rich albite zinnwaldite granite forms an elliptical plug into the surrounding pink perthite granite. It is approximately 3,000 m long and 1,400 m wide trending NE-SW with the greatest decomposition and columbite enrichment along the northern and southern margins. The average grade described by Jones (1953) is equivalent to 1,200 ppm, with an average Nb_20_5 : Ta_2O_5 ratio of 13: 1. This grade has decreased with depth of working.

Pegmatite pods and lenses with albite or microcline: The pegmatites are sporadically distributed and unimportant in economic terms. They are <1.5 m in width and traceable as lenses over 100 m. They are characterized by abundant feldspar with two types depending on the dominant feldspar. At Harwell, both types of pegmatites are found cutting the decomposed columbite-bearing albite zinnwaldite granite in a disused mining paddock. The earlier of the two types, the albite pegmatite, is commonly sinuous in form and < 1.5 m in width. It contains occasional patches of genthelvite, associated protolithionite and accessory thorite and columbite. The later pegmatites are strongly tabular in form, commonly only a few centimetres wide and are characterized by green amazonite as a major constituent with some quartz, protolithionite, genthelvite and microlite. A uraninite-bearing albite pegmatite with quartz and genthelvite occurs in the Saiya Shokobo complex. Uraninite forms as small black crystals approximately 1 mm in size, clustered on the feldspar crystals. The pegmatite is associated with greisens that have developed along both horizontal and vertical joints. A similar relationship between pegmatite and greisen occurs in the Baban Damu area of the Banke complex, 5 km WNW of Banke School. Here, sinuous quartz, albite, green-mica pegmatites, containing knots of blue-green aquamarine, lie approximately parallel to horizontal greisens which are interlinked by vertical greisens.

Quartz rafts, sheeted veins attd stockworks. Quartz rafts characterize the roof zone of a biotite granite cupola. They occur at the contact zone between the granite and the overlying volcanic pile where the volcanics have not fractured to allow fluid escape. They are not common throughout the province possibly because the right erosional level is exposed in so few complexes. Nor are they richly mineralized, although there does seem to be an enrichment in ore minerals beneath the rafts. The best developed is at Uwar Gida near Ginshi Hill, Ririwai. Here the pink medium grained biotite perthite granite becomes a quartz feldspar porphyry and then immediately beneath the volcanics becomes a genthelvite-rich microgranite. Between this and the banded volcanics lies a zone of pure massive, milky quartz up to 2 m thick. Although the quartz is only slightly mineralized, the underlying stockwork within the top 30 m of the granite roof is richly mineralized and has been worked by trenching and adits, mainly for cassiterite. The sulphides, which have not been worked, appear to be disseminated below the main cassiterite horizon. Sheeted veins and stockworks characterize the marginal and contact zone of a biotite granite. Sheeted veins consist of a series of thin, subparallel veins. They are found in many complexes but are particularly well-developed in the Ladini area of the Saiya Shokobo complex and in the Banke complex. The sheeted veins may be subhorizontal as at Banke, or steeply dipping as at Saiya Shokobo. Individual veins may vary from 1 mm to 0.5 m and usually consist of a greisen assemblage of quartz-siderophyllite, occasionally with a thin central stringer of quartz. The stockworks are similar to the sheeted veins except that they do not occur as parallel veins but as a series of anastomosing ramifications within the marginal or contact zone of a granite intrusion. Mineralogically the veins systems are characterized by quartz, pale or green coloured Li-AI or Li-Fe mica usually with abundant topaz and some fluorite, cassiterite or, more rarely, traces of sulphides. Both stockworks and sheeted vein systems differ from fissure-filling lode systems in terms of size and complexity, they are much smaller and have a much simpler paragenesis.

Fissure filling lodes: Only two major lodes have been noted in Nigeria and occur in the adjacent complexes of Tibchi and Ririwai: In both these complexes it appears that the earliest igneous activity was violent and eruptive culminating in the formation of a central shield volcano built on an updomed terrain (Ike, 1983; Kinnaird et al., 1985). The lodes are aligned along fractures formed during the updoming of the underlying central biotite granite. In the Tibchi complex the elliptical intrusion has a long axis orientated north-west–south-east whereas in Ririwai the axis of the ellipsoid intrusion lies east-west with an east-west orientation to the lode. In both complexes the lodes are the product of several alteration processes with fluids channelled in enlarged steeply dipping tectonic master joints. In the Tibchi complex the mineralized veins extend out into the basement which overlies the biotite granite, but in both complexes the lode system is confined within the outer ring-dyke. The lodes are rich in cassiterite and wolframite and have been surface mined on a small scale for many years. About 50 tonnes of wolframite were extracted from the Ririwai lode during Second World War (Jones, 1953). In both complexes sphalerite is the major ore mineral. In Ririwai this is about 1.5%, followed by cassiterite with 0.5%. It is estimated as at 1986 that when in production the mine wouldl produce 1,600 tonnes of tin metal a year and 6,000 tonnes of zinc metal. The Ririwai lode was opened up as an underground mine and was undergoing assessessment at the time for future production of primary cassiterite as alluvial ores were being depleted.

The Ririwai lode has been described in detail by Kinnaird et al. (1985*).* It extends for a distance of 5 km in an east-west direction and to over 400 m depth and dips to the south at 85°. The maximum surface width of the lode system is 8 m. The lode, which is extensively mineralized, consists of a series of parallel to subparallel or braided quartz veins enclosed by zones of grey greisen grading outwards into reddened wall rock and occasionally through a narrow buff-coloured zone out into the pale pink equigranular biotite perthite granite. Hydrothermal alteration began with potash metasomatism and perthitic feldspar adjacent to the fissure was microclinized. Early monazite, zircon and ilmenite deposition was followed by the formation of cassiterite, wolframite and rutile and finally by the introduction of molybdenite (Kinnaird et al., 1985). During subsequent hydrogen ion metasomatism the microcline was altered. Greisen was formed, consisting of green coloured lithium siderophyllite or grey zinnwaldite and quartz. Localized concentrations of ore are associated with clusters of mica. The sequence of oxide ore deposition, beginning with early monazite, is similar to that associated with potash metasomatism. However, sphalerite with stannite, pyrite and marcasite and finally chalcopyrite follows molybdenite. During silica metasomatism, in addition to the deposition of quartz into vugs created by earlier processes major fissure-filling quartz veins up to 75 cm are formed. Cassiterite is the first ore to be deposited at this stage followed by a major deposition of sphalerite, traces of stannite, pyrite and marcasite, abundant chalcopyrite, and other minor copper and bismuth ores as exsolution blebs in the main sulphides. Abundant galena is the last major ore. Large cavities (30–100 cm in size) occur within the quartz veins and are infilled with kaolinite. Supergene alteration of the ore minerals is limited.

The Tibchi biotite granite has long been recognized as one of the most intensely mineralized in the province (Falconer and Raeburn, 1923). Within the granite, there are two lode systems forming a letter Y. One orientated N–S, between 3 and 15 m wide and strike length of at least 1 km, the other is orientated NW–SE, with similar dimensions and a strike length of over 2 km. This is believed to be the earlier of the two systems since it does not cross the N–S lode (Bowden, 1982). The north–south lode consists in the south of reddened quartz veins rich in cassiterite and wolframite with an almost complete absence of sulphides. In the north it is poorly mineralized and is often characterized by the development of mica-rich pods. The NW–SE lode follows the main axis of the elliptical biotite perthite granite. It is similar to Ririwai with a reddened microcline-rich outer facies grading through a greenish grey greisen to fissure-filling quartz, which is sometimes massive and milky, sometimes well crystallized (Ike, 1979). Early albitization of the biotite granite preceded a weak vein-controlled microclinization which was followed by greisenization and silicification. Oxides dominated by cassiterite are disseminated through the greisen and red quartz-microcline wall rock. Sphalerite and chalcopyrite accompanied by pyrite, molybdenite, arsenopyrite and galena with traces of stannite and other minor sulphides were thought to be probably related to silicification (Bowden, 1985). The lode is well exposed on Kogo Hill which rises 100 m above the surrounding biotite granite.

In both the Tibchi and Ririwai complexes therefore, it is apparent that there are several phases of deposition of the major ore minerals and that mineralization was repeatedly emplaced in the same lode system. Wall rock alteration may occur marginal to the quartz veins or the veins may infill fissures in a lode system with mineralized greisen, as at Tibchi and Ririwai. Also the quartz veins may cut the granite or country rock without any marginal alteration. The quartz veins that occur in the basement are generally characterized by wolframite of ferberite composition. The wolframite occurs sporadically as bladed crystals, at the margin or vein centre, orientated parallel or perpendicular to the strike of the vein. The wolframite is accompanied by some cassiterite and minor sulphides and often by bismuth minerals. The wolframite-rich quartz veins of the Dagga Allah area occur at a greater distance from the Younger Granites than is usual. It seems likely that they are related to Younger Granites which may exist at shallow depth within the Dagga Allah ring-dykes. Geophysical prospecting supports this possibility (Ajakaiye, 1983). The quartz veins within the Younger Granites, such as in the Ririwai lode, may contain a wider spectrum of ore minerals than those of the basement.

Irregularly shaped replacement bodies: Irregularly shaped replacement zones containing massive or disseminated ore may occur in the roof and contact zones of biotite granite bodies. Generally they are composed of mica-rich greisens formed by hydrogen ion metasomatism of granite already altered by potash metasomatism. The best examples occur in the Rishi biotite granite and at Rafin Gabas in the Afu complex. At Rafin Gabas the host granite is coarse grained biotite perthite granite. In the mineralized zone, deposition of cassiterite and wolframite, accompanied by siderite, was followed by massive sphalerite and chalcopyrite, then pyrite and green fluorite formation. The dark iron sphalerite, with up to 17% Fe forms massive well twinned crystals <25 cm in size which are brecciated and recemented by late stage wolframite-bearing quartz veins. Brecciation probably took place during sphalerite formation as the chalcopyrite exsolution blebs within the sphalerite are elongated into rods. The sphalerite clasts often have a thin crust of quartz crystals. The ore bodies were first worked by opencast techniques and a block of cassiterite weighing 9 tonnes came from here. The area was also a major source of wolframite during the Second World War.

Quartz veins: The quartz veins are generally vertical and vary from massive milky veins 30 m wide to clear comb-textured veins 1 cm wide. Virtually all the granites of the province show late stage quartz-veining but only those granites which have disseminated mineralization have ores within the quartz veins.

Mineralized ring dykes. Ring-dykes of granite porphyry characterize many of the complexes. Fluids escaping along these steeply dipping fractures locally react with, and mineralize the porphyry. Where fluid interaction has occurred, the fine grained matrix has been largely altered to a greisen assemblage leaving the K-feldspar phenocrysts unaltered or partially transformed to microcline. Often these petrological changes are limited to narrow zones although the degree of reaction may be locally intense. The mineralization is characterized by a sulphide assemblage of ores dominated by sphalerite, chalcopyrite and galena, with pyrite, pyrrhotite, stannite, arsenopyrite and molybdenite. At Zarara quarry in the ring-dyke of the Banke complex Bowden (1982) noted that the porphyry has been brecciated and cemented by mineralizing fluids and late stage vein quartz. At Gindi Akwati in the Rop complex, the ring-dyke has brecciated, metamorphosed and permeated an earlier basic-dyke. The breccia has been cemented by pale coloured mineralized veins in which quartz or fluorite may be the main gangue.

Alluvial and eluvial mineralization: Uplift of the central part of Nigeria which began in Neogene (Kogbe, 1981b) led to the formation of an upstanding area known as the Jos Plateau, in the Jos-Bukuru area. The plateau, which rises $>$400 m above the surrounding basement plain, has an above average rainfall for this part of Nigeria, resulting in more rapid denudation of the granite cupolas. The plateau region forms a major watershed so the ore minerals eroded from the granites are widely distributed in the modern river systems and are readily worked due to the almost perpetual availability of water. During the Pleistocene, thick deposits of cassiterite-bearing alluvium were laid down in the broad shallow valleys of the central plateau. These deposits are the targets for the extensive mining activity on the Jos Plateau, especially in the Ngell River area, west of Sabon Gida. Large reserves of high grade placer deposits are still preserved beneath basalt where Quaternary to Recent basalt lava flows have filled the broad Pleistocene valleys. The concentration of mining in the Jos-Bukuru and Rop areas reflects the widespread secondary distribution of ore minerals and does not necessarily reflect the abundance of the primary source. More than 95% of Nigeria's tin export is produced from alluvial deposits. Between 1905 and 1971 about 630,000 tonnes of cassiterite was exported with maximum production in 1946 when 14,255 tonnes of concentrate containing between 72% and 74% tin was produced. In 1981 cassiterite production was 3,750 tonnes and has since fallen below 2,500 tonnes per year. Prior to 1965, 95% of the world's columbite consumption was supplied by Nigeria and peak production was in 1963 when 3,334 tonnes were exported (Kogbe and Obialo, 1976). Alluvial monazite, thorite, zircon, pyrochlore and xenotime have all been sold sporadically with annual combined export from zero to 1,000 tonnes.

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