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Petrogenetic and Compositional Features of Rare Metal Pan-African Post-Collisional Pegmatites of Southwestern Nigeria; A Status Review

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Abstract

This research reviews the geology, petrogenesis, compositional trends and geochronology of the rare-metal pegmatite of southwestern Nigeria. The source of these pegmatites is still presently debated which have been explained as either product of highly fractionated molten material or anatexis of the local crust. However, published works of past authors have been compiled to give a detailed understanding of the formation of the mineral deposits.

The basement complex of southwestern Nigeria comprises of Precambrian rocks of amphibolite, the hornblende gneiss and the granite gneisses which were formed as a result of the opening and closing of the ensialic basin with significant, extensive subduction during the Pan-African orogeny. The pegmatites in this region have shown internal zoning and a high degree of evolution from the border zone to the core zone during the crystallization and solidification of the felsic granite to pegmatite melt.

The rare-metal pegmatites have distinct chemical compositions and mineralogy, containing quartz, biotite, muscovite, microcline, garnet with localized tourmaline, tantalite and columbite. These pegmatites vary significantly by their bulk-rock and mineral chemistry which indicates a more peraluminous attribute and enrichments of lithophile elements of Rb, Cs, Ta and Ba. Previous K/Ar isotopic ages (502.8±13.0 Ma and 514.5±13.2 Ma) suggest that the pegmatites are related to the post-collisional phase of intensive metasomatism. Adopted from previous studies, a five-stage conceptual model of evolution which is widely accepted have been proposed for the origin of the pegmatites.

Key words: rare-metal; petrogenesis; pegmatites; granite; southwestern Nigeria

Introduction

Granitic pegmatites have in the past and present attracted interest as a vital source of rare-metals, such as Ta, Nb, Cs, Li, Sn and the rare earth elements (REE) as well as colourful gemstones (beryl, tourmaline). These minerals have gained increased applications in new and green technologies such as lithium is used for batteries in electric vehicles and energy storage, the REE are needed for high-strength magnets used in wind turbines and electric vehicle motors. In pegmatite research, debate explaining their origins and classification has become a challenge, and this has created intense research by geoscientists for well over decades. There has been much past work on pegmatites which are summarized by London (2008). Different hypotheses have been used to classify pegmatites such as descriptive or genetics, simple or complex, barren or rare-metal, and the generalized zoning sequence (Landes, 1933; Černý, 1991a; Ginsburg, 1984; London 1995, 2005b; Černý and Ercit, 2005), but the simplest classification is the division into barren and rare-metal pegmatites. London, (2014) described the rare-metal pegmatite as host to a substantial amount of lithium aluminosilicates, beryl with the occurrence of phosphates, magnetite, ilmenite, and other rare minerals.

Irrespective of the diversity of geological environments and complexities in their internal textural features and phase composition, the processes responsible for the formation of these pegmatites are primarily defined by the composition and initial volume of parent material from which the host is derived, regardless of the introduction of external material to the system (Novak et al., 2012). The proportion of rare-metals in such pegmatites is an indication of the level of fractionation achieved in the final stages of granitic differentiation (Černý, 1991a). These pegmatites can be categorically divided into two geochemical families, which correspond to the most distinctive enrichment of elements produced by fractionation abbreviated as LCT-lithium, caesium and tantalum, which are more abundant and enriched in Be, B, F, P, Mn, Ga, Rb, Nb, Sn and Hf. They are associated with S-type quartz-rich granites, peraluminous in nature due to the occurrence of muscovite, tourmaline, topaz and andalusite (Shelley, 1993; Audetat et al., 2000; Černý and Ercit, 2005; London, 2005b; Černý et al., 2012a) and NYF-niobium, yttrium and fluorine which have strong compositional affinity with alkaline A-type granites and in addition, enriched in heavy rare-earth elements (HREE), Be, Ti, Sc and Zr (Martin and De Vito, 2005; Martin et al., 2008). They typically possess most of the same elemental enrichments found in association with syenite-carbonatite magmatism (Sokolov, 2002). Most rare-metal pegmatites may contain significant tantalum mineralization. In accordance with the classification developed by (Beus, 1960; Rudenko et al., 1975; Černý, 1988), the pertinent pegmatite types and subtypes can be categorized for characterizing rare-metal mineralization as follows; (1) beryl-type, with beryl-columbite-phosphate subtypes, (2) complex-type, including spodumene, pentalite and amblygonite subtypes, (3) complex-type, lepidolite subtype, (4) albite-spodumene type, and (5) albite-type.

At present, there are two hypotheses that define the processes responsible for the formation of pegmatite melts: (1) extended fractional crystallization of a granitic magma at the scale of a pluton (Leake, 1990; London, 2005; Martin and De Vito, 2005), and (2) direct formation by low degree partial melting of crustal rocks in the middle to deep levels of Earth’s continental crust influenced by the presence of fluids (Romer and Kroner, 2016; Shaw et al., 2016; Muller et al., 2017; Lv et al., 2018). Several examples of rare-metal pegmatites formed by fractionation of a granitic melt are typical in the Superior province of Ontario, Canada (Selway, 2005), Yichun, China (Belkasmi et al., 2000) and the Adola belt, southern Ethiopia (Mohammed, 2017).

The rare-metal pegmatites associated with peraluminous plutons and post-collisional, (Goodenough et al., 2014) Pan-African granitoids in Nigeria have been shown to post-date the main phase of peraluminous

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magmatism by at least 90Ma, creating a 'pegmatite conundrum'. These pegmatites are associated with rare-metal (Sn-Ta) granitic pegmatites, most of which have been mined by artisans (Matheis and Caen-Vachette, 1983; Kuster, 1990; Adekoya, 2003; Garba, 2003; Okunlola and Ogedengbe, 2003; Akintola, 2004; Okunlola, 2005; Okunlola and Somorin, 2005; Okunlola and Jimba, 2006; Adetunji and Ocan, 2010). The rare-metal pegmatites trend in a SW-NE direction extending from Ife to Jos and appears to cross-cut the geological boundary between the eastern and western Nigerian terranes (Kinnaird, 1984; Woakes et al., 1987). Recently, (Okunlola, 2005) defined the metallogeny of the rare-metal pegmatites of Nigeria (Fig.1) outlining into seven broad fields; Ibadan-Osogbo, Ijero-Aramoko, Kabba-Isanlu, Kushaka-Birni Gwari, Lema-Share, Nasarawa-Keffi, and Oke-Ogun which have varied sizes, internal zoning, geochemistry and mineralogy.

This work reviews the geology, petrogenesis and compositional styles as well as temporal and spatial relationships between the rare-metal mineralization and associated granitic pegmatite in the south-west part of Nigeria using published works of past authors to further constraint the formation of the deposits within the framework of the regional geological and tectonic setting.

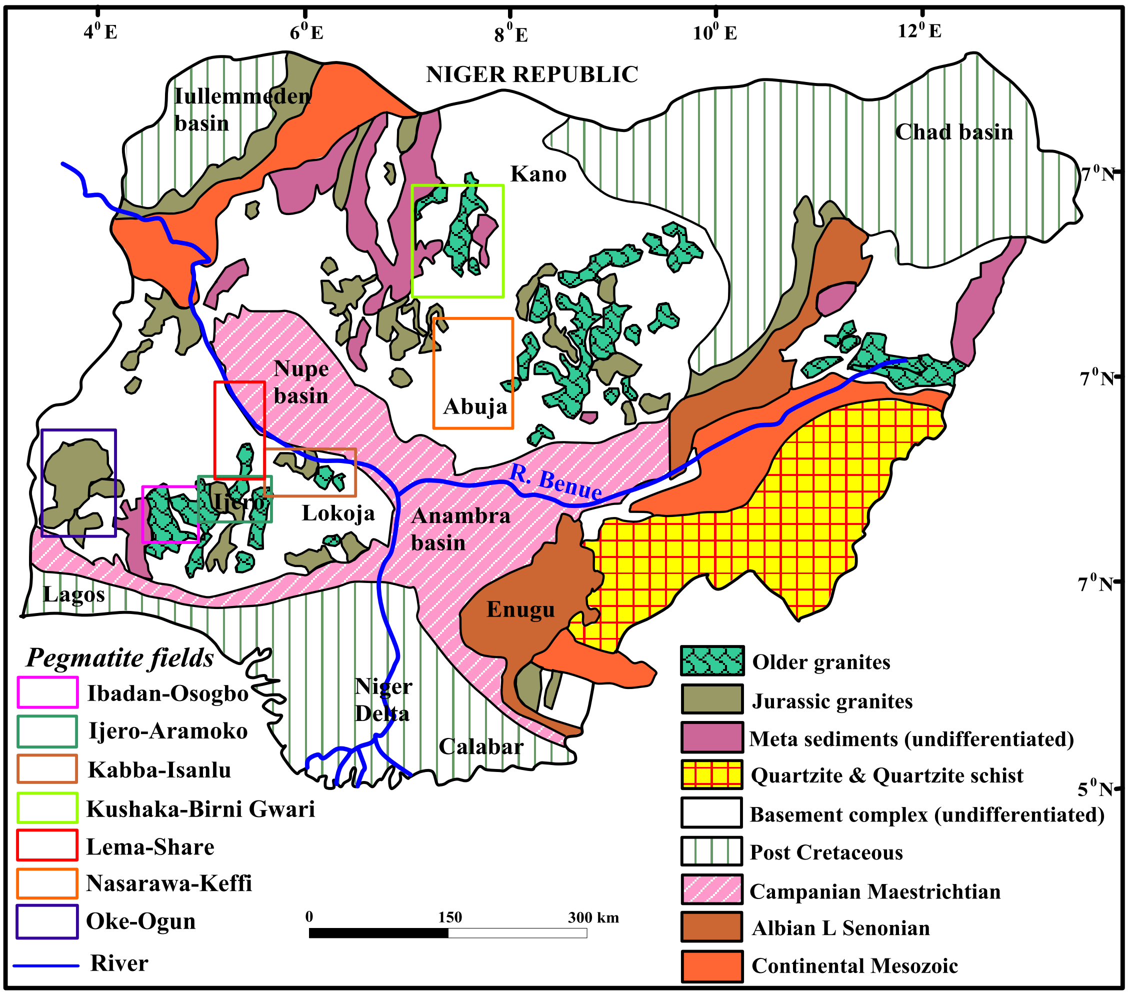

Fig.1. Simplified map of the geology of Nigeria, redrawn after Okunlola, (2005). Colored-edge boxes indicate the metallogeny of the rare-metal pegmatites of Nigeria.

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Geological setting: The Basement complex of southwestern Nigeria

The basement complex is one of the three major litho-petrological components that make up the geology of southwestern Nigeria (Rahaman and Ocan, 1978). The basement complex forms a part of the Pan-African mobile belt and lies between the West African and Congo Cratons and south of the Tuareg Shield (Black, 1980). It is intruded by the Mesozoic calc-alkaline ring complexes (Younger Granites) of the Jos Plateau and is unconformably overlain by Cretaceous and younger sediments. The southwestern Nigeria basement was affected by the 600 Ma Pan-African orogeny (Tubosun, 1983) and it occupies the reactivated region which resulted from plate collision between the passive continental margin of the West African craton and the active Pharusian continental margin (Burke and Dewey, 1972; Dada, 2006). The basement rocks are believed to be the results of at least four major orogenic cycles of deformation, metamorphism and remobilization corresponding to the Liberian (2,700 Ma), the Eburnean (2,000 Ma), the Kibaran (1,100 Ma), and the Pan-African cycles (600 Ma). The first three sequences were characterized by intense deformation and isoclinal folding accompanied by regional metamorphism, which was further followed by extensive migmatization. The Pan-African deformation was accompanied by regional metamorphism, migmatization and extensive granitization and gneissification which produced syntectonic granites and homogeneous gneisses (Abaa, 1983). Late tectonic emplacement of granites and granodiorites and associated contact metamorphism accompanied the end stages of this last deformation (Ferré and Caby, 2006; Dada, 2008). The end of the orogeny was marked by faulting and fracturing (Gandu et al., 1986; Olayinka, 1992). Within the basement complex of Nigeria four major petro-lithological units are distinguishable, namely; (1) The Migmatite – Gneiss Complex (Rahaman, 1988; Dada, 2006), (2) The Schist Belt (Metasedimentary and Metavolcanic rocks) (Grant, 1978; Olade and Elueze, 1979; Rahaman, 1981; Holt, 1982; Egbuniwe, 1982; Turner, 1983), (3) The Older Granites (Pan African granitoids) (Falconer, 1911; Rahaman, 1981; Rahaman, 1988; Dada, 2006) and (4) Undeformed Acid and Basic Dykes (Grant, 1970; Matheis and Caen-Vachette, 1983; Dada, 2006). The main lithologies in this region include the amphibolites, migmatite gneisses, granites and pegmatites. Other important rock units are the schists, made up of biotite schist, quartzite schist talc-tremolite schist, and the muscovite schists. The crystalline rocks intruded into these schistose rocks.

Paragenetic associations and mineralization of the rare-metals

The ore deposit of the magmatic stage which is the first stage of mineralization show complex internal zoning and series of an alternating paragenetic sequence. The magmatic stage is dominated by biotite-quartz-orthoclase-microcline pegmatite zones. The second stage is the albitization stage which is dominated by quartz-muscovite-microcline-albite pegmatites associated with albitized and greisenized lateral units (Fig. 2). The late stage (druse filling stage) is the most fractionated pegmatite dominated by large graphic quartz, crystalline white quartz, spodumene, microcline, muscovite and other opaque minerals. This stage is dominated by hydrothermally metasomatized minerals that range from coarse-flaky pink lithium-rich muscovites to lepidolites-quartz and albite-quartz-muscovite associations. Tourmaline, fluorite, epidote and axinite are associated with the succeeding stage of the druse filling.

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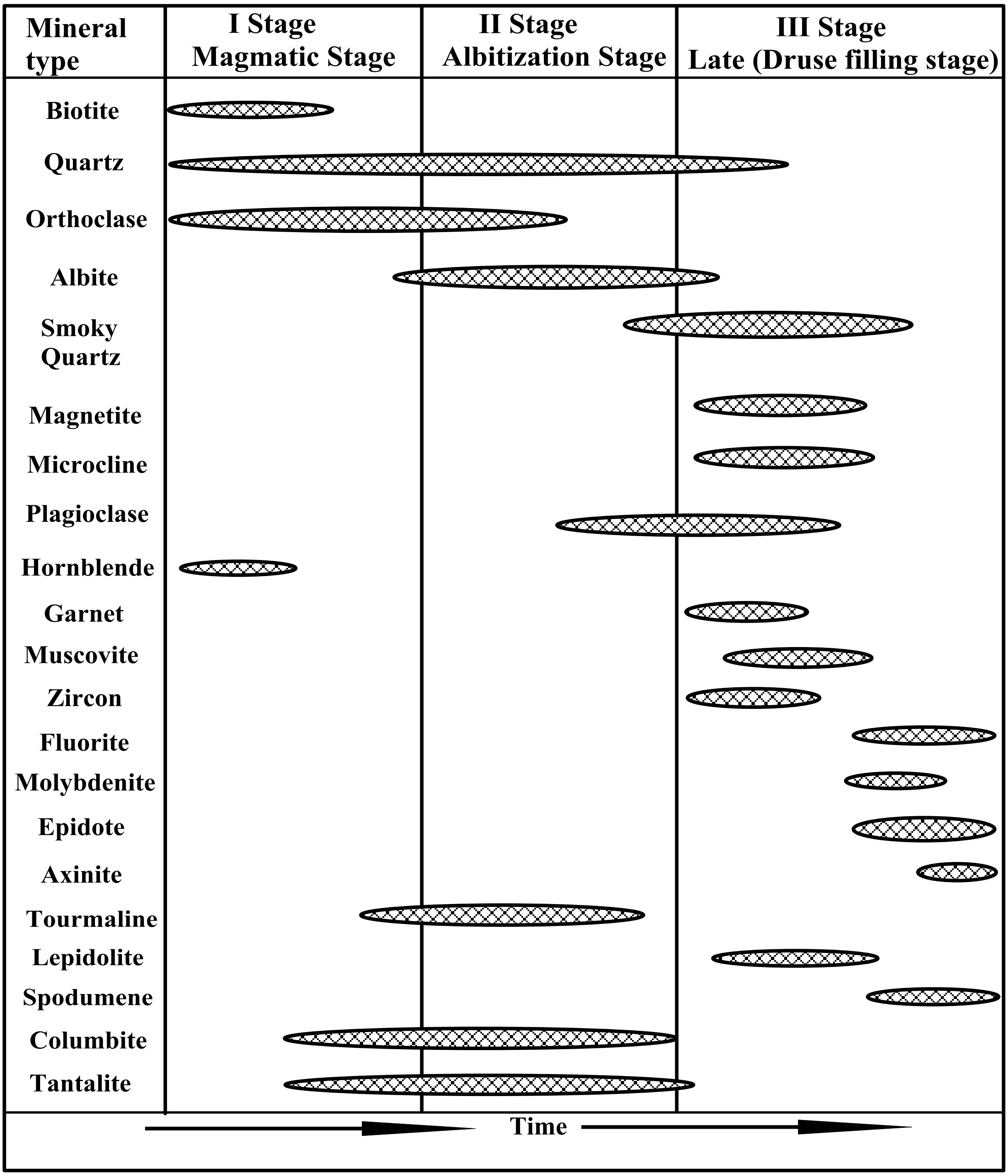

Fig.2. Paragenetic sequence of magmatic, albitization, and druse-filling stages of pegmatites in the southwestern part of Nigeria.

Distribution and occurrence of pegmatites of southwestern Nigeria

The pegmatite fields in the southwestern part of Nigeria mainly trend in the NW-SE direction. They occur as very coarse-grained dykes, dykelets and are extensive. They are typically comprised of medium-grained microcline-albite-quartz, blocky microcline-quartz, coarse-grained quartz and a core of coarse-grained muscovite-quartz and quartz (Okunlola, 2005). For this review, eight (8) pegmatite deposits and their geological

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characteristics will be discussed and summarized.

Ago-Iwoye barren pegmatite

The deposit is associated with coarse porphyritic granite, biotite-granite-gneiss, banded gneiss, quartzite and quartz schist, amphibolite schist, and intruding pegmatite (Akintola et al., 2012). The coarse porphyritic granite is mainly massive and composes of felsic minerals (quartz, microcline and muscovite). Observable phenocryst of feldspar is dominant on the outcrop, also contain some xenoliths or relicts. The pegmatite in this deposit is composed of minerals like microcline, quartz, plagioclase, micro perthite and dark brown biotite which occur as platy minerals within the samples.

Apomu barren pegmatite

The Apomu deposit consists of two main rock units, granite and pegmatite. The pegmatite occurs as near vertical dykes striking in the NNW-SSE direction and intrudes into the older rock unit of granite. Minerals associated with granite are microcline, biotite and quartz. The pegmatite veins are inequigranular, with a graphic appearance of quartz and interstitial mica plates. Petrographically, the dominant minerals in the pegmatite include microcline, quartz, biotite and plagioclase (Akintola et al., 2012).

Ijero/Oke-Asa deposit

The Ijero/Oke-Asa pegmatite is associated with granite, amphibolite schist, biotite schist, quartzite, calc gneiss, biotite gneiss, and migmatite gneiss (Okunlola and Akinola, 2010, Akinola, 2014). These rocks are evenly distributed across the land cover in the area. The pegmatite is highly coarse-grained dykes; they also occur as dykelets. The pegmatite is highly enriched in albite, microcline, quartz and most importantly lepidolite. The association of these minerals with lepidolite is an indication of a pneumatolytic source for the lepidolite formed at high temperature. It is known to host many valuable minerals such as tantalite, tin, niobium, and gemstones.

Awo deposit

The Awo deposit comprises of granite, banded gneiss, quartzite, quartz schist and pegmatite. Minerals associated with the Awo deposit are mainly plagioclase, muscovite, quartz, microcline, biotite and opaque minerals (tourmaline, garnet, cassiterite and tantalocolumbite). (Akintola et al., 2011). It is known to host valuable minerals such as tantalite, niobium, and gemstones.

Igbeti deposit

The Igbeti deposit primarily consists of biotite schist, granite, and pegmatite. Mineralogically, they are composed of quartz, biotite, muscovite, microcline and garnet. The porphyritic granite is extensive and highly weathered dominated by quartz, biotite and microcline (Okunlola and Oyedokun, 2009). The pegmatite trend mostly in the NNW-SSE direction and are mostly leucocratic. Mineral assemblage of the pegmatite includes albite, quartz, microcline, muscovite and tourmaline with less abundance of rutile and magnetite. It is known to host valuable minerals such as tantalite, tin, niobium, and gemstones.

Komu deposit

The Komu deposit is the largest and most productive pegmatite occurrence in southwest Nigeria (Akintola et al., 2012). It is known to host many valuable minerals such as tantalite, tin, niobium, and gemstones associated with granite gneiss, amphibolite and pelitic schist. Mineralization is limited to the pegmatites which mainly contain quartz, muscovite, mica-plagioclase and microcline with a minor amount of beryl and tourmaline.

Sepeteri deposit

The Sepeteri pegmatite mainly strikes in the NNE-SSW direction with an average dip of

60^0E intruding into older lithology of amphibole schist. The mineral assemblages of the amphibole schist include quartz, plagioclase, microcline, biotite and hornblende with a minor amount of zircon, apatite and sphene (Okunlola and Akintola, 2007). The coarse pegmatite appears as inequigranular veins and mineralogically consist of graphic quartz, microline, albite, muscovite and lesser amount of biotite. It is known to host many valuable minerals such as tantalite, tin, niobium, and gemstones.

Oro deposit

The Oro deposit is underlain by quartz-mica schists and granite gneisses, all intruded by pegmatites. The rocks are very sparse in the area, and most of those mapped are already fairly weathered. The schists often occur as layered relicts, lensoidal or pools of pods with quartz and muscovite mica are the major minerals and occur as elongated fibrous platelets often interlayered with subordinate fine quartz, the quartz is sometimes poikilitic within the micaceous rich layers (Oyebamiji, 2014). The main mineral assemblages are albite, microcline, quartz, muscovite, sericite, black tourmaline (shorl), columbite-tantalite. Albite is the most abundant of these minerals and forms coarse crystalline graphic intergrowth with quartz. They are sometimes perthitic with microcline as patchy and feathery perthites. These may indicate local metasomatic replacement. It is known to host valuable minerals such as tantalite, tin, niobium, and gemstones.

Discussion

Geochemistry

The rare-metal pegmatites of the southwestern Nigeria are mostly known to host minerals such as columbite, tantalite, tin, niobium, beryl and gemstones. Several authors (Okunlola and Akintola, 2007**;** Akintola et al., 2011, 2012; Okunlola and Oyedokun, 2009; Okunlola and Akinola, 2010) have worked on the whole-rock geochemistry of drill core samples, muscovite extracts, alluvial soils around the emplacement (Oyebamiji, 2014) and lepidolite samples (Akinola, 2014). The results are summarized in (Table 1). All the data shows internal zoning and a high degree of evolution from the border to the core zones during crystallization and solidification of the felsic granitic to pegmatitic melt (Okunlola, 2005).

Bulk-rock chemistry

Due to the textural characteristics and heterogeneity of the individual rare-metal pegmatite, the chemical compositions vary significantly from one deposit to the other. Moreover, the bulk of the whole rock samples across the southwestern part of Nigeria are granitic in composition and have SiO_2 greater than 65 wt. % (Fig.3). Albeit, some of the samples have lower SiO_2 content and plot in the gabbro, monzonite, diorite, syenite and granodiorite fields of a total alkali-silica diagram (Fig.3). MnO, MgO and TiO_2 are typically low (< 1 wt. % in all the deposits) while Na_2O, CaO and Fe_2O_3 are more variable. Generally, K_2O is the dominant alkali in all the pegmatite of southwestern Nigeria.

Tantalum mineralization in all the deposits are zoned mostly in the columbite (-Fe) and tapiolite fields, less zoned in the columbite (-Mn) and tantalite (-Mn) fields. The columbite-tantalite group minerals (CGM) compositions from south-west Nigeria follow a trend from columbite (-Fe) to tantalite (-Mn) (Fig.4). The trend of the compositional variation in the CGM diagram has a direct relationship with the degree of fractionation. Most pegmatites which plot in the field of ferrocolumbite have been interpreted as a primitive and moderately promising source of Ta ores. The Igbeti and Komu rare-metal pegmatites plot in the field of tapiolite and wodginite, hence the reason for high values in Ta, Cs and Rb (Table 2). In general, the whole-rock geochemical signature of the rare-metal pegmatites of southwestern

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Nigeria corresponds to a peraluminous, highly silicic felsic granite, strongly enriched in lithophile elements of Rb, Cs, Ta and Ba. They are products of strongly differentiated felsic granites with high values of Rb and low Sr content related to magmatic differentiation. The Rb-Ba-Sr ternary plot (Fig.5) of some granitic rocks associated with rare-metal pegmatites of southwest Nigeria indicates a granitic trend typically of strongly differentiated granites with Rb enrichment, lesser Ba enrichment and low Sr contents for the whole rock samples.

The rare earth elements (REE) exhibit a complex geochemical behaviour because they can adopt different valences at natural geological conditions. As magmas evolve toward silicic or felsic compositions, the alkali feldspar hosts some REE, but the diminishing REE content of the magmas is partitioned increasingly into the accessory phases (Schwab and Johnston, 2001; Johnston and Schwab, 2004; Gaetani, 2004; Keshav, 2004). The total earth element (TREE) abundance increases with increasing alkalinity and decreasing silica content of the melt phase (Ercit, 2005). Hence, the REE abundances become very low in peraluminous granites and pegmatites associated with the LCT family, regardless of changes in LREE/HREE. The total earth element (TREE) concentrations in all the samples analyzed from the various deposits are

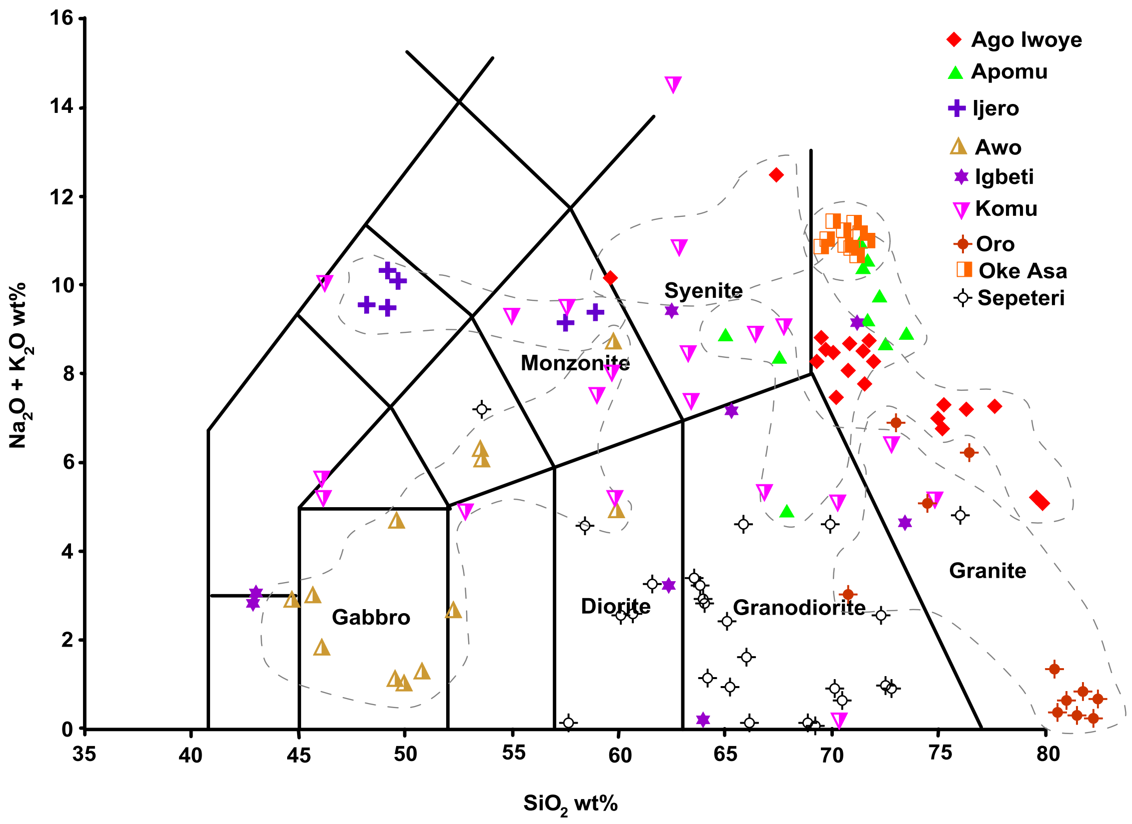

Fig.3. Total alkali versus silica diagram for all analysed whole rock samples from southwestern Nigeria. Ago Iwoye (Akintola et al., 2011), Apomu (Akintola et al., 2011), Awo (Akintola et al., 2011), Igbeti (Okunlola and Oyedokun, 2009), Ijero (Akinola, 2014), Komu (Akintola et al., 2012), Oke-Asa (Okunlola and Akinola, 2010), Oro (Oyebamiji, 2014), and Sepeteri (Okunlola and Akintola, 2007).

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Tab.1. Summary of the major element compositions of bulk whole rock pegmatite samples in southwestern Nigeria

Deposit	N	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	Source
Ago Iwoye	Range (20)	61.23-81.13	11.57-17.63	0.75-2.79	0.004-0.081	0.02-0.78	0.09-3.91	2.18-6.91	1.09-9.65	0.02-0.38	0.03-2.62	Akintola et al., 2011
	Mean	73.74	14.68	1.49	0.04	0.16	0.78	4.46	3.52	0.08	0.20	
	SD (1σ)	4.44	2.02	0.65	0.02	0.17	0.81	1.28	2.11	0.09	0.57	
Apomu	Range (11)	46.03-75.54	7.84-16.25	0.26-13.67	0.01-0.23	0.03-3.47	0.19-5.12	0.14-4.52	0.05-8.24	0.01-0.69	0.02-0.23	Akintola et al., 2012
	Mean	69.35	14.35	2.61	0.05	0.78	1.63	3.31	4.80	0.18	0.08	
	SD (1σ)	8.24	2.31	3.94	0.06	1.07	1.49	1.22	2.72	0.21	0.07	
Ijero	Range (11)	49.43-58.81	22.85-28.37	0.14-0.41	0.08-0.37	0.15-0.35	0.033-0.23	0.2-3.65	5.73-10.25	0.01-0.03	0.02-0.09	Akinola, 2014
	Mean	52.70	26.39	0.25	0.20	0.26	0.11	1.42	8.42	0.018	0.05	
	SD (1σ)	4.40	2.60	0.10	0.13	0.10	0.08	1.62	2.01	0.01	0.03	
Awo	Range (15)	44.79-70.37	14.7-33.51	0.25-7.22	0.008-8.41	0.01-0.14	0.03-1.74	0.09-4.82	1.47-6.95	0.01-0.199	0.016-0.41	Akintola et al., 2011
	Mean	54.95	25.77	2.45	1.61	0.06	0.30	1.28	3.74	0.06	0.14	
	SD (1σ)	8.45	7.62	1.98	2.85	0.04	0.45	1.73	2.07	0.06	0.13	
Igbeti	Range (8)	42.92-74.69	14.74-37.42	0.04-6.56	0.01-0.74	0.01-2.99	0.01-4.92	0.64-7.47	0.09-6.54	0.01-0.76	0.13-2.70	Okunlola and Oyedokun, 2009
	Mean	61.31	21.86	2.09	0.30	0.77	1.77	3.23	1.98	0.21	0.78	
	SD (1σ)	12.14	9.73	2.46	0.29	1.24	1.92	2.39	2.02	0.33	1.00	
Oke Asa	Range (10)	71.12-73.44	13.69-14.21	1.25-1.69	0.11-0.13	0.01-0.04	0.72-1.41	2.02-2.14	8.61-9.02	0-0.03	0.24-0.3	Okunlola and Akinola, 2010
	Mean	72.04	13.90	1.49	0.12	0.03	1.12	2.08	8.77	0.01	0.26	
	SD (1σ)	0.74	0.18	0.13	0.01	0.01	0.23	0.04	0.15	0.01	0.02	
Sepeteri	Range (25)	54.05-77.64	14.18-31.37	0.77-18.31	0.01-0.7	0.09-1.09	0.03-1.97	0.04-4.14	0.27-4.47	0.18-2.65	0.03-24.28	Okunlola and Akintola, 2007
	Mean	66.17	25.51	3.91	0.19	0.37	0.35	1.19	1.16	0.73	1.17	
	SD (1σ)	5.50	4.27	3.31	0.24	0.26	0.58	1.40	1.26	0.60	4.82	
Komu	Range (20)	46.32-76.71	11.92-29.75	0.47-10.26	0.023-2.31	0.01-3.19	0.02-0.75	0.16-9.92	0.11-11.28	0.015-1.23	0.01-0.48	Akintola et al., 2012
	Mean	62.08	21.24	3.91	0.63	0.67	0.30	4.22	3.17	0.27	0.08	
	SD (1σ)	9.00	5.24	2.97	0.67	0.96	0.20	2.82	3.51	0.39	0.10	
Oro	Range (10)	71.49-97.77	0.73-15.2	0.45-6.09	0.01-0.04	0.01-1.32	0.01-0.65	0.02-6.82	0.09-0.99	0.02-0.87	0.01-0.18	Oyebamiji, 2014
	Mean	86.43	6.86	2.05	0.03	0.23	0.22	2.09	0.44	0.31	0.08	
	SD (1σ)	10.43	6.21	1.70	0.01	0.42	0.27	2.80	0.36	0.31	0.07	

Tab.2. Summary of the rare-element compositions of pegmatite samples in southwestern Nigeria

Deposit	N	Ta	Cs	Rb	Sn	Nb	Sr	Y	Ba	Ti	Source
Ago Iwoye	Range (20)	1-33.8	0.5-15.5	24-251	1-17	4-44	9-925	1.3-112	10-3646	0.1-1.5	Akintola et al., 2011
	Mean	6.54	4.57	106.85	3.90	22.09	89.43	16.15	396.75	0.47	
	SD (1σ)	7.36	3.79	54.16	4.00	10.46	219.35	25.86	969.11	0.37	
Ijero	Range (11)	0.02-1	182-269	520-678	12.5-19.5	2.6-3.9	0.5-1.9	0.12-1.4	7.17-13.8	0.05-0.4	Akinola, 2014
	Mean	0.37	224.33	577.50	15.21	3.34	1.26	0.77	10.02	0.15	
	SD (1σ)	0.36	31.92	57.92	2.81	0.51	0.57	0.52	2.33	0.14	
Awo	Range (15)	1-365	2.5-526	58-1000	2-244	4-390	22-278.9	1-10	29-442	0.1-22.6	Akintola et al., 2011
	Mean	92.35	147.41	566.82	109.40	92.35	45.98	5.16	79.67	5.69	
	SD (1σ)	106.57	137.36	355.53	81.17	91.03	64.65	3.01	101.84	7.64	
Igbeti	Range (8)	135-500	12.4-1000	52-1000	0.5-25	13-150	34-575	1.5-28	13-148	0.7-60.8	Okunlola and Oyedokun, 2009
	Mean	274.38	380.50	679.13	7.06	56.75	194.75	8.25	67.38	21.61	
	SD (1σ)	141.91	404.46	436.31	8.01	53.94	196.61	11.04	45.21	24.97	
Oke Asa	Range (10)	17.5-51.8	19.7-25	536-600	5-14	18-53	54-90	28-43	203-221	0-0.02	Okunlola and Akinola, 2010
	Mean	28.09	21.69	570.60	8.30	28.40	73.70	34.80	210.80	0.01	
	SD (1σ)	10.25	1.68	21.59	3.02	10.63	12.05	4.44	5.65	0.00	
Sepeteri	Range (25)	0.1-253	4.2-381.3	24.3-5782.2	11.2-279	21.8-91.8	13-445	0.8-20.9	48-511	0.11-1.59	Okunlola and Akintola, 2007
	Mean	33.09	70.68	548.90	50.41	36.73	87.52	6.52	236.60	0.43	
	SD (1σ)	50.99	95.72	1279.40	60.21	13.63	110.88	4.83	148.57	0.36	
Komu	Range (20)	9.9-500	14.4-1798	24-10000	1-150	16-1393	3-34	0.8-177	5-213	0.1-34.9	Akintola et al., 2012
	Mean	183.22	306.98	1425.37	42.65	361.19	14.22	33.09	49.50	7.67	
	SD (1σ)	166.73	495.10	2978.33	42.44	397.41	9.00	46.62	74.19	11.99	
Oro	Range (10)	0.21-200.21	0.1-7.1	4.1-383.6	1.06-14.89	1.15-99.65	3.8-156.3	0.7-18.9	19-143	0.1-0.2	Oyebamiji, 2014
	Mean	23.48	2.90	73.92	6.06	29.30	31.03	7.71	59.00	0.13	
	SD (1σ)	62.23	2.64	115.39	4.96	29.89	47.21	6.61	37.60	0.05	

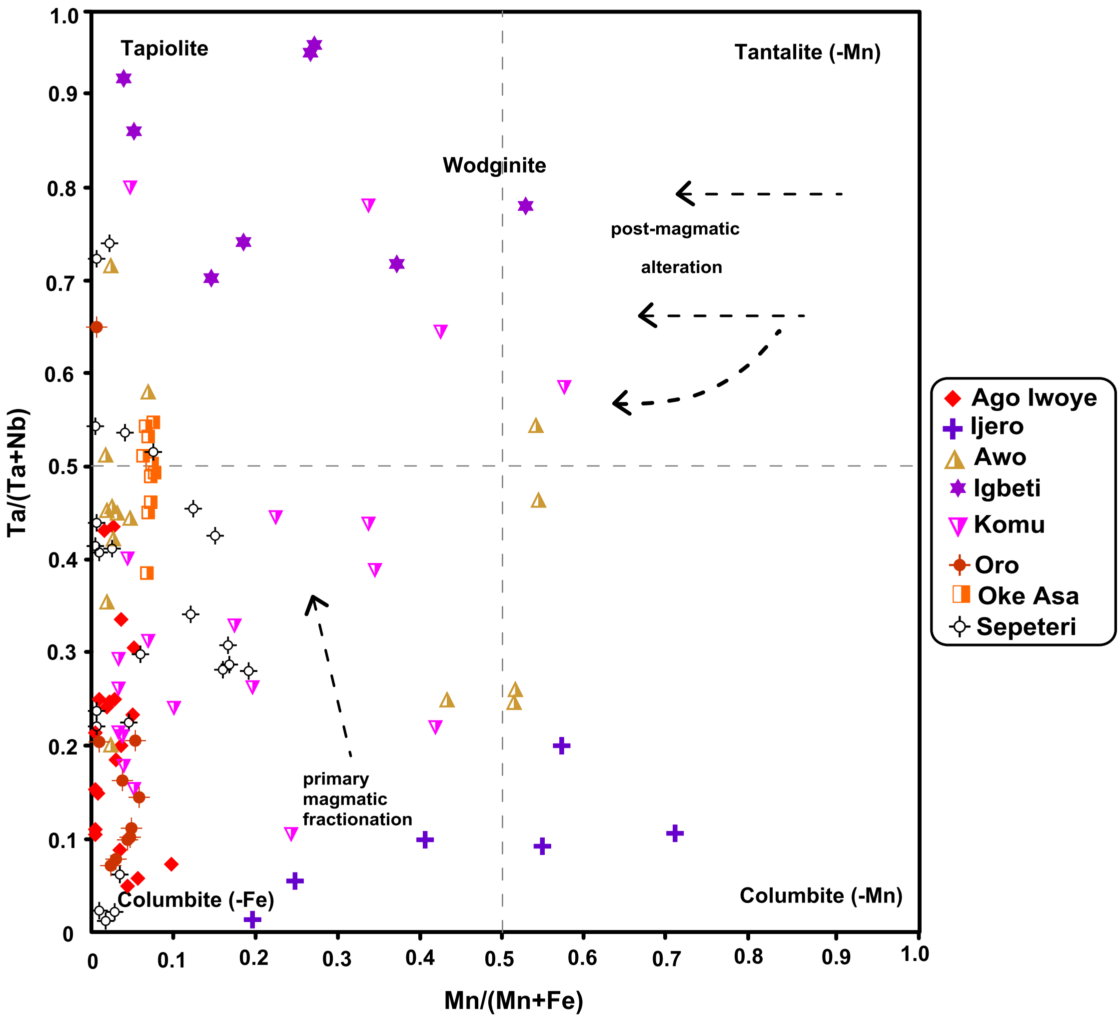

Fig.4. Columbite-tantalite group (CGM) variation diagram of (Mn/Mn+Fe) and (Ta/Ta+Nb) of the pegmatites of the southwestern Nigeria (after Breaks et al., 1999). The arrow represents magmatic fractionation trend from primitive columbite (-Fe) to evolved tantalite (-Mn). Ago Iwoye (Akintola et al., 2011), Awo (Akintola et al., 2011), Igbeti (Okunlola and Oyedokun, 2009), Ijero (Akinola, 2014), Komu (Akintola et al., 2012), Oke-Asa (Okunlola and Akinola, 2010), Oro (Oyebamiji, 2014), and Sepeteri (Okunlola and Akintola, 2007).

slightly above 100 ppm. The rare earth trends typically show a slight enrichment in light (LREE- La, Ce, Pr, Nd) and medium (MREE- Sm, Eu, Gd, Y, Tb, Dy) compared to the heavy rare earth elements (HREE- Ho, Er, Tm, Yb, Lu). There is negative Eu anomaly in the REE pattern of whole rock pegmatites suggests the early fractionation of alkali-rich feldspar, possibly containing a small proportion of the anorthite component (Fig.6). These signatures are likely inherited from the sources of these melts, and they will depend wholly on the specifics of the melting reactions and the extent of melting in their respective sources. The REE fractionation patterns reverse where the REE-selective phases become major contributors to the melting reaction, as opposed to the crystalline residuum.

The relationship between the rare metal composition is revealed by the ternary plots of Ti-Sn-(Nb+Ta) (Fig.7a-h), these plots show the high degree of enrichment and its indicate a significant difference between the mineralized and barren pegmatites (Kuster, 1990; Okunlola and King, 2003). The dominance of Ta, Nb and Sn in the mining output is confirmed in the trace element composition of the various deposits. It seems therefore likely that the

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metasomatic replacement and mineralization processes have been generated from residual fluids of the pegmatite melts themselves and not by external fluid injections.

Tectonic setting

Considering the plots of Y+Nb against Rb (not plotted in this review), the whole rock rare-metal pegmatites of most of the deposits of southwestern Nigeria have been interpreted as Volcanic Arc Granite (VAG), Syn-Collisional Granite (SCG) while some are interpreted as Within Plate Granite (WPG) using the whole rock geochemical analysis. This is an indication that the pegmatites are products of (i) extreme fractionation of syn- to late-tectonic granites (London, 2005) or (ii) anatexis process or partial melting of the metasedimentary rocks present in the region. Hundreds of streams of individual pegmatites have been mapped through ground mapping and aerial photographs reconnaissance survey (Okunlola, 2005). The pegmatites have been classified as either "simple" or "complex" according to their degree of chemical evolution. Trace element compositions of the simple pegmatites are consistent with their derivation by fractional crystallization of the host granites while the complex pegmatites originated from partial melting of a geochemically more fertile source. However, these complex pegmatites of most of the productive mines (Komu, Oro and Sepeteri) contain the assemblages of spodumene+quartz.

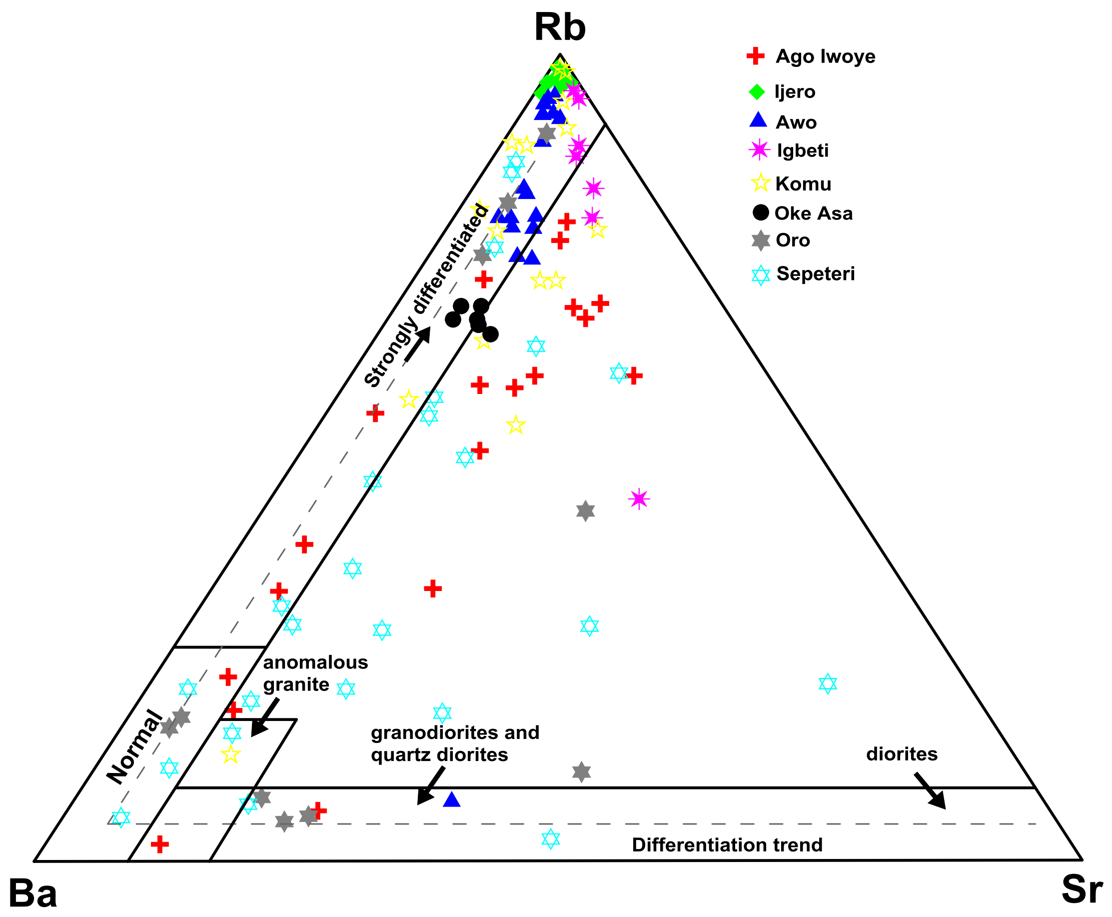

Fig.5. Rb-Ba-Sr ternary plot of some granitic rocks in southwestern Nigeria. It indicates a granitic trend typically of strong differentiated granites with Rb enrichment, lesser Ba enrichment and low Sr contents for the whole rock analysis of samples. Ago Iwoye (Akintola et al., 2011), Awo (Akintola et al., 2011), Igbeti (Okunlola and Oyedokun, 2009), Ijero (Akinola, 2014), Komu (Akintola et al., 2012), Oke-Asa (Okunlola and Akinola, 2010), Oro (Oyebamiji, 2014), and Sepeteri (Okunlola and Akintola, 2007).

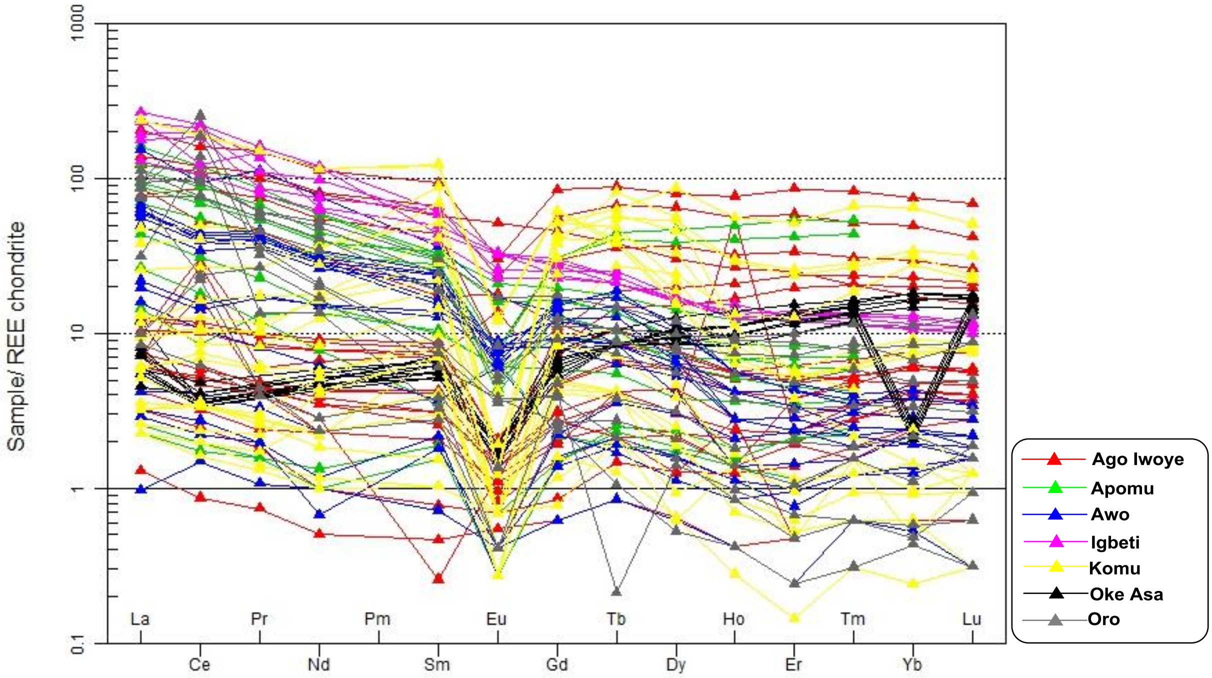

Fig.6. Chondrite normalized REE concentrations plot for some selected pegmatites from the southwestern Nigeria. Normalising factors from Boynton (1984). Ago Iwoye (Akintola et al., 2011), Apomu (Akintola et al., 2011), Awo (Akintola et al., 2011), Igbeti (Okunlola and Oyedokun, 2009), Komu (Akintola et al., 2012), Oke-Asa (Okunlola and Akinola, 2010) and Oro (Oyebamiji, 2014).

Age and emplacement of rare-metal pegmatites

The Precambrian rare-metal pegmatites of Nigeria lack documentation of geochronological data. Past work carried out by (Matheis and Caen-Vachette, 1983) using the Rb/Sr method to determine the cooling ages of Egbe and Ijero deposits was calculated to be 545±10 Ma and 537±12 Ma respectively. On the other hand, (Okunlola and Ofonime, 2010) determined the mineralization age for the pegmatites of Komu using the K/Ar isotopic method and agreed on a mineralization age ranging between 502.8±13.0 Ma and 514.5±13.2 Ma. These ages are close to the earlier ages documented by (Matheis and Caen-Vachette, 1983). This suggests that the rare-metal mineralization of the pegmatites of southwestern Nigeria may not be cogenetic with the main cooling phase of the Pan-African magmatism but temporally related to the post-collisional phase of intensive metasomatism (Melcher et al., 2015).

A conceptual model for the emplacement of the pegmatites

Pegmatites owe many of their trace elements characteristics to the partial melting of rocks in the middle to deep levels of the Earth's continental crust, to produce granitic magmas. Considering the different proposed models that simplify the formation and mineralization of pegmatites (a) the fractional crystallization of the melt and (b) interaction of the aqueous fluid with the liquefy are the two contending models. The concentration of fluxing segments and other incongruent components increase towards the middle point of the magma chamber as crystallization continues coming about expanding synthetic fractionation from the edge to the centre of the pegmatites. The crystallization of minerals, however, can be proved for the mixing of liquids and the unstiffen by soluble bases incongruent apportioning, for example, the fluid liquids enhanced in K, and the melt enriched in Na. Afterwards, the model of buoyant ascent has

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been proposed by to clarify the chemical fractionation of the pegmatites.

Two end-member models have been proposed for the development of pegmatites, i.e., continuous crystallization and fractional dissolving. Persistent crystallization of prior parental melts by fractional dissolving which homogenizes in an aggregate chamber produces an assortment of granitic magmas relying upon the level of partial crystallization. The shifting level of incomplete melting produces a wide compositional variety of magmas. Partial melting of compositionally distinct protoliths can likewise deliver a wide compositional spectrum of magmas with a similar degree of melting. This could emerge from the change mineralogy, trace element chemistry, mineral stability field of sheet silicates or frill minerals and their substance in the mineral/residuum stage and metasomatic adjustment of the source metasedimentary lithology (Shearer et al., 1992). Incomplete fractionation of mica-rich melts in collisional zones normally form LCT granitic pegmatites gives a high concentration of trace elements. Muscovite and biotite convey a large portion of the following components. Copious muscovite schist of marine sedimentary starting point responds broadly at the beginning of anatexis. The liquefying response of muscovite and biotite likewise produces K-feldspar with some amount of aluminosilicate and spinel under low H_2O immersion condition. The ratio of Li and Cs, which are compatible elements in K-feldspar, is elevated as compared to Rb during consecutive crystallization resulting rare-alkali enrichment.

A conceptual genetic model of origin is proposed for the evolution of the pegmatites as shown in Fig.8. A five-stage model is proposed, stage (a) represents basal heat flow regime at pressures greater than 12 kbar at the lower crust to 6-9 kbar at the middle crust. This stage is followed by decompression to ~ 3 kbar at near peak temperatures of ~ 750 ^{0}C. Stage (b) is the partial melting zone which transits between the pegmatites emplacement and the metamorphic peak. At this stage, the main melting zone would transit with energy-induced melt segregation, and the pegmatites intruded at sites where pegmatite fluid pressures are higher than the effects of normal and tensile force. The third stage (c) is the fractional crystallization stage associated with assimilation. The melts move upward through the conduits to reach a shallow crustal level before solidification. The fourth stage (d) involves the interaction or reaction between the pegmatite and the enclosing wall rock. The pegmatites are emplaced as they reach their point of crystallization. The pegmatites at this stage are still partially molten, but also volatile saturated, because of exocontact metasomatism is also evident (McKeough et al., 2013). Evolving of the pegmatite continue until the last stage (e) which is the hybridization reactions in the open system. There is infiltration of volatile phase through crystallized portions of the pegmatite and the host rocks. There is also diffusion of elements which would facilitate the metasomatic transfer and hence influence the melt viscosity.

Conclusion

Geological appraisal of the rare-metal pegmatites of the southwestern Nigeria indicates that most of the pegmatites (except Ago-Iwoye and Apomu deposits) are enriched in mineralization of rare-metals. The pegmatites occur mostly as steeply inclined intrusive bodies into the basement of coarse porphyritic granite, banded gneiss, biotite schist, migmatite gneiss, granite gneiss, amphibole schist and quartz-mica schist emplaced mainly in the NNE-SSW striking direction of the shear zone. The deposits are paragenetically associated with three stages of

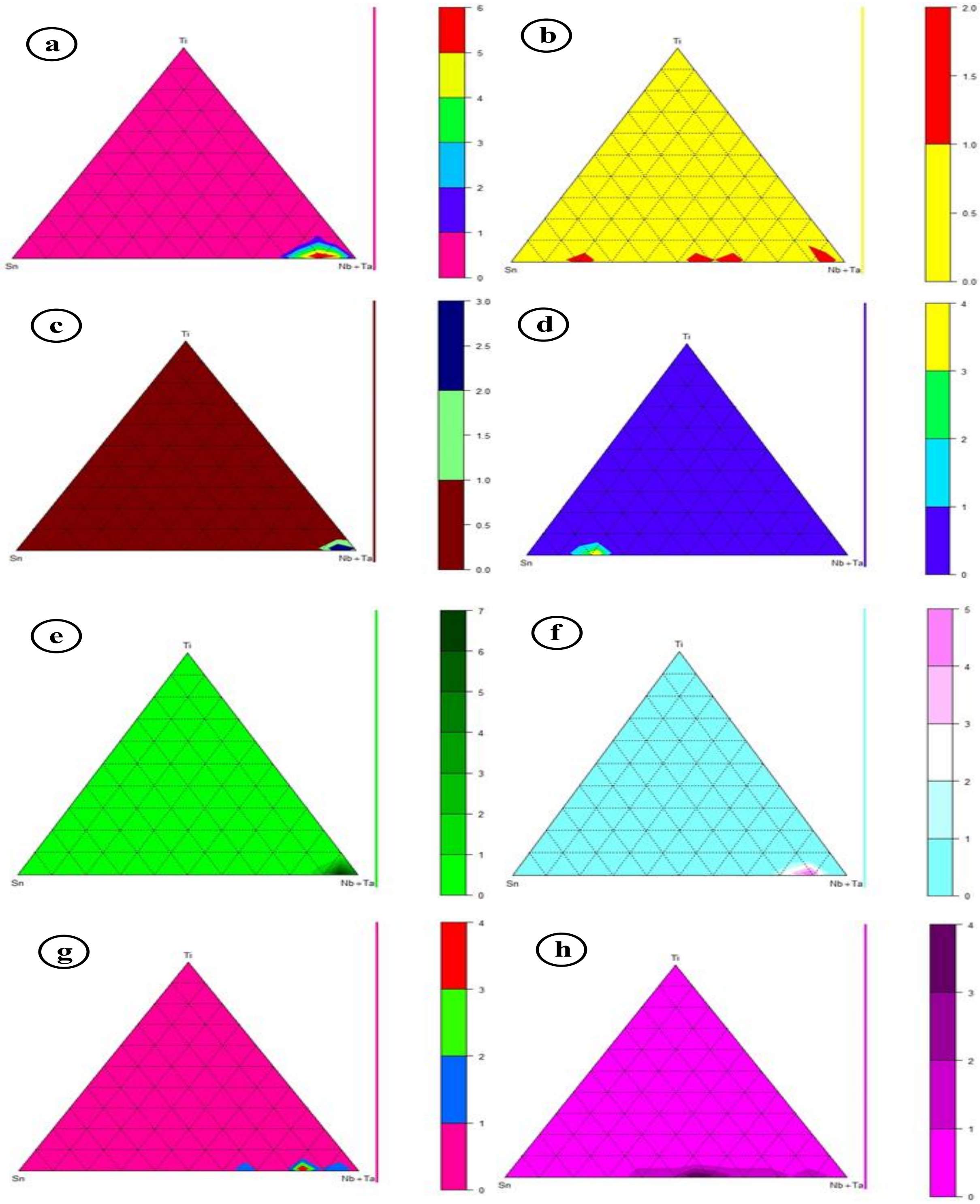

Fig.7. Triangular Ti-Sn-(Nb+Ta) plots for some pegmatite deposits in southwestern Nigeria (a) Ago Iwoye (Akintola et al., 2011), (b) Awo (Akintola et al., 2011), (c) Igbeti (Okunlola and Oyedokun, 2009), (d) Ijero (Akinola, 2014), (e) Komu (Akintola et al., 2012), (f) Oke-Asa (Okunlola and Akinola, 2010), (g) Oro (Oyebamiji, 2014), and (h) Sepeteri (Okunlola and Akintola, 2007). The peak of the contours indicates the relationship between Ti-Sn-Nb+Ta which occur within the samples analyzed in each deposit.

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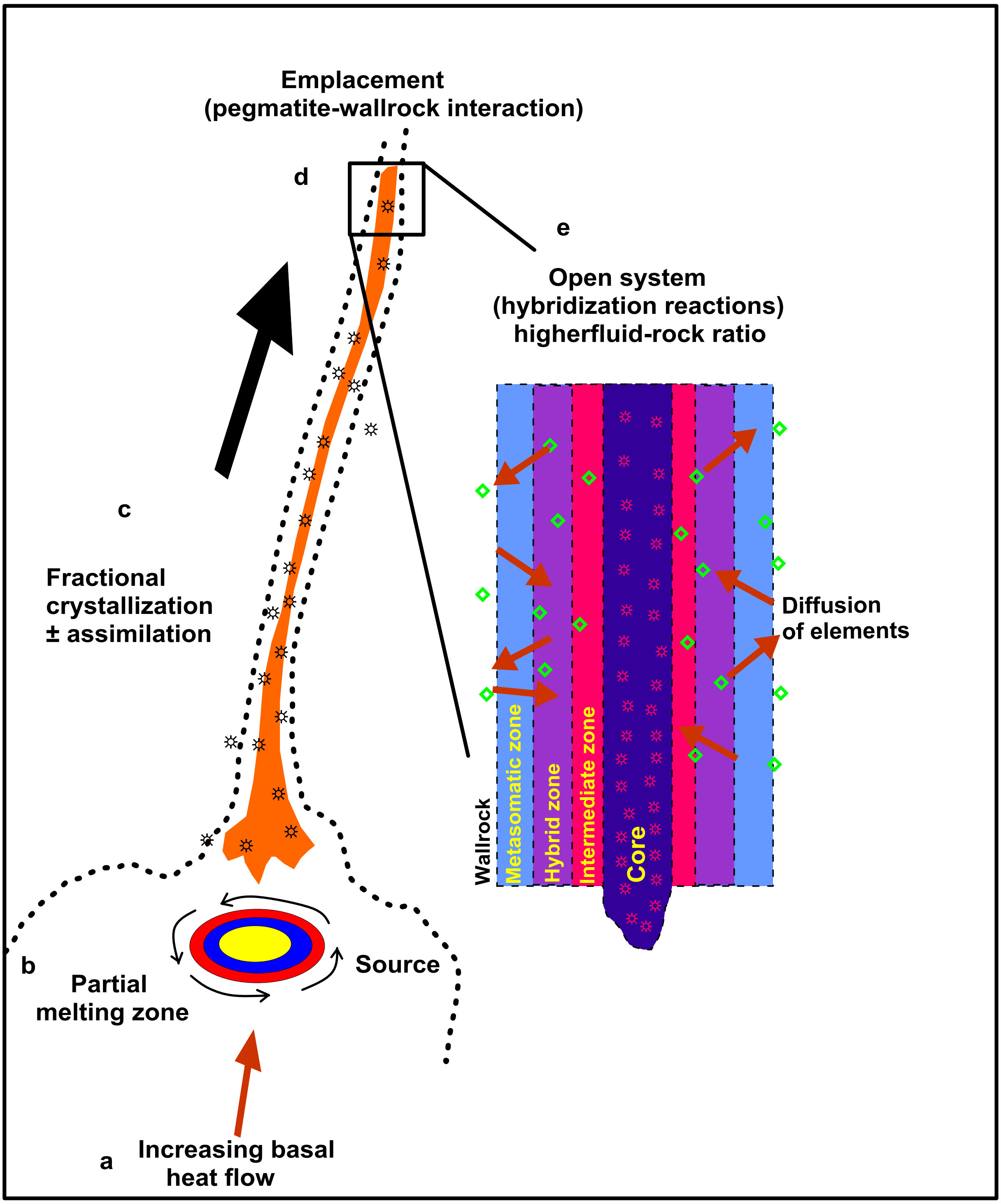

Fig.8. Conceptual model to illustrate the origin of pegmatites in southwestern Nigeria (modified after McKeough et al., 2013).

mineralization; magmatic, albitization and the druse filling stage. The analysed samples have shown internal zoning and a high degree of evolution from the border zone to the core zone during crystallization and solidification of the felsic granite to pegmatitic melt.

Considering the textural attribute and homogeneity of the individual rare-metal pegmatite, the chemical compositions vary significantly from one deposit to the other. Most of the pegmatite samples have SiO_2 content greater than 65 wt. % and have K_2O as the dominant alkali. Tantalum mineralization is zoned mostly in the columbite (-Fe) and tapiolite fields. The REE trends mostly show a slight enrichment in the LREE and MREE compared to the HREE. These deposits have been classified as either "simple or complex" according to their degree of chemical evolution. The tectonic setting of the southwestern Nigeria rare-metal pegmatites is in the Volcanic Arc Granite (VAG) and the Syn- Collisional Granite (SYG) suites. They are probably sourced from extreme fractionation of syn- to late-tectonic granites or partial melting of metasedimentary rocks. The mineralization age has been determined to range between 502.8± 13.0 Ma and 514.5± 13.2 Ma which suggests an involvement of the post-collisional phase of intensive metasomatism during the Pan-African orogeny.

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