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MATERIAL ASSIMILATION IN A SHALLOW DIAPIRIC FORCEFUL INTRUSION: EVIDENCE FROM MICROSTRUCTURES AND CSD ANALYSIS IN A PORPHYRITIC INTRUSIVE BODY, "LA LÍNEA" TUNNEL, CENTRAL CORDILLERA, COLOMBIA

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Abstract

The contact between the unit Porphyry Andesite and the Cajamarca Group is observed in the "Túnel de la Linea" section. The integration of petrographic, geochemical and textural (crystal size distribution, CSD) analysis allows description of physical and chemical processes that took place in the contact zone in order to propose a model for the intrusion. Material assimilation produced quartz enrichment towards pluton's boundaries associated to a simple process of melt injection. The difference between host rock and hot melt rheologies caused shear stress that produced crystal breaking, folding and foliation rotation.

Keywords: Cajamarca Complex, Cordillera Central, CSD, Igneous and metamorphic petrology, Andesite-Dacite porphyry, La Línea Tunnel.

Resumen

El contacto entre la unidad Porfido Andesitico y el Complejo Cajamarca es observado en la sección del "Tunel de la Linea". La integración de análisis petrograficos, geoquímicos y texturales (distribución de tamaño de cristales, CSD) permiten la caracterización de los procesos físicos y químicos que se dan en la zona de contacto y que sirven como base para proponer un modelo de intrusión. La asimilación de material produjo enriquecimiento de cuarzo hacia los limites del pluton y esta asociada a un proceso simple de inyección de fundido. La diferencia de reología entre la roca encajante y el fundido caliente ocasionó cizallamiento que resultó en rompimiento de cristales, plegamiento y rotación de la foliación.

Palabras clave: Complejo Cajamarca, Cordillera Central, CSD, Petrología metamorfica e ignea, Porfido Andesitico.

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Introduction

The Colombian Andes is a result of the interaction of several tectonic plates that have interacted since the Paleozoic; because of this, the orogen is an important record of all tectonic processes that have taken place in South America northwest corner from the Paleozoic to the present. The Central Cordillera is one of the most prominent geomorphologic features in the Colombian Andes and its central section consists of a set of metapelitic and metavolcanic rocks of Early Paleozoic age (Restrepo-Pace 1992), association that was intruded by Mesozoic and Cenozoic plutons probably related to subduction of oceanic lithosphere below the Colombian Andes (Aspden & McCourt 1986). In the axial zone of the Central Cordillera, between Calarca and Cajamarca towns, the digging of "La Linea" Tunnel (by "Instituto Nacional de Vias - INVIAS"), in both sides of the cordillera (Fig. 1), provided an excellent opportunity to have access to fresh rocks of the lithologic units present in the area.

This paper presents the study of the emplacement of an igneous body that involves juxtaposition of a hot and viscous liquid in movement against a cold and stationary solid of a different composition in the section cut by "La Linea" Tunnel. The conjugation of contrasting material properties and relative movement produced characteristic structures and textures related to chemical and mechanical interactions in the contact zone as reported in similar diapiric intrusions (e.g., deflection of regional markers and evidence of stoping; see for example Miller and Patterson, 1999; Tikoff *et al.,* 1999). The study presented here aims to a better understanding of the emplacement process of a small interpreted diapiric forceful intrusion at shallow crustal levels. With this purpose in mind, the use of traditional geochemical and petrographic techniques is complemented with a textural analysis of the porphyritic body to relate nucleation and growing rates with the emplacement process.

Geological setting

The eastern flank of the Central Cordillera, located inside the Central Andean Terrane (Restrepo & Toussaint 1988, Restrepo-Pace 1992), Chibcha Terrane (Toussaint 1993), or Cajamarca Terrane (Etayo-Serna *et al.*, 1983), consists of polymetamorphic, low to medium pressure, metapelitic and metavolcanic rocks of continental and marine origin. The terrane is limited at the east by the Otú-Pericos Fault and at the west by the Romeral Fault System.

The area was first described by Botero (1946), but the work of Nelson (1962) was the first to identify that the area is characterized by igneous bodies mostly in tectonic contact wit metamorphic rocks, both lithologies covered by recent volcanic (Fig. 1). Metamorphic rocks are grouped into a unit known as Cajamarca Complex (Núñez 2001), and are characterized by a sequence of amphibole and graphite schist metamorphosed under the greenschist to amphibolite-epidote facies (Restrepo-Pace 1992). Mayor and trace element geochemistry indicates that the protolith were rocks related to an intraoceanic island arc and a continental margin (Restrepo-Pace 1992). Radiometric dating gives a wide spectrum of ages that range from Paleozoic to Paleogene (315± 15 Ma to 63±2.3 Ma), where the oldest ages could reflect the age of the protolith (Restrepo-Pace 1992), and the youngest may reflect isotopic resetting caused by overprinting of dynamothermal events. The protolith could be even older than the oldest age obtained by radiometric dating according to Silva *et al.* (2005) who argues a Neoproterozoic – Early Cambrian age based on C and O stable isotope analysis.

The metamorphic association was intruded by Mesozoic-Cenozoic plutons (e.g., Ibagué Batholith, Payandé and Dolores Stocks and minor associated intrusions); these rocks are predominantly of quartz-diorite composition (Nelson 1962, Alvarez 1979). Mojica & Kammer (1995) associated the smaller intrusions to discrete mesozone and epizone plutons intruded during Early and Middle Jurassic and associated with contact metamorphic aureoles, skarn zones, and copper and gold mineralizations. Small, porphyritic bodies are thought to be related to nearby intrusives of batholithic dimensions because most of the small bodies intrude the batholiths (Sillitoe *et al.*, 1982).

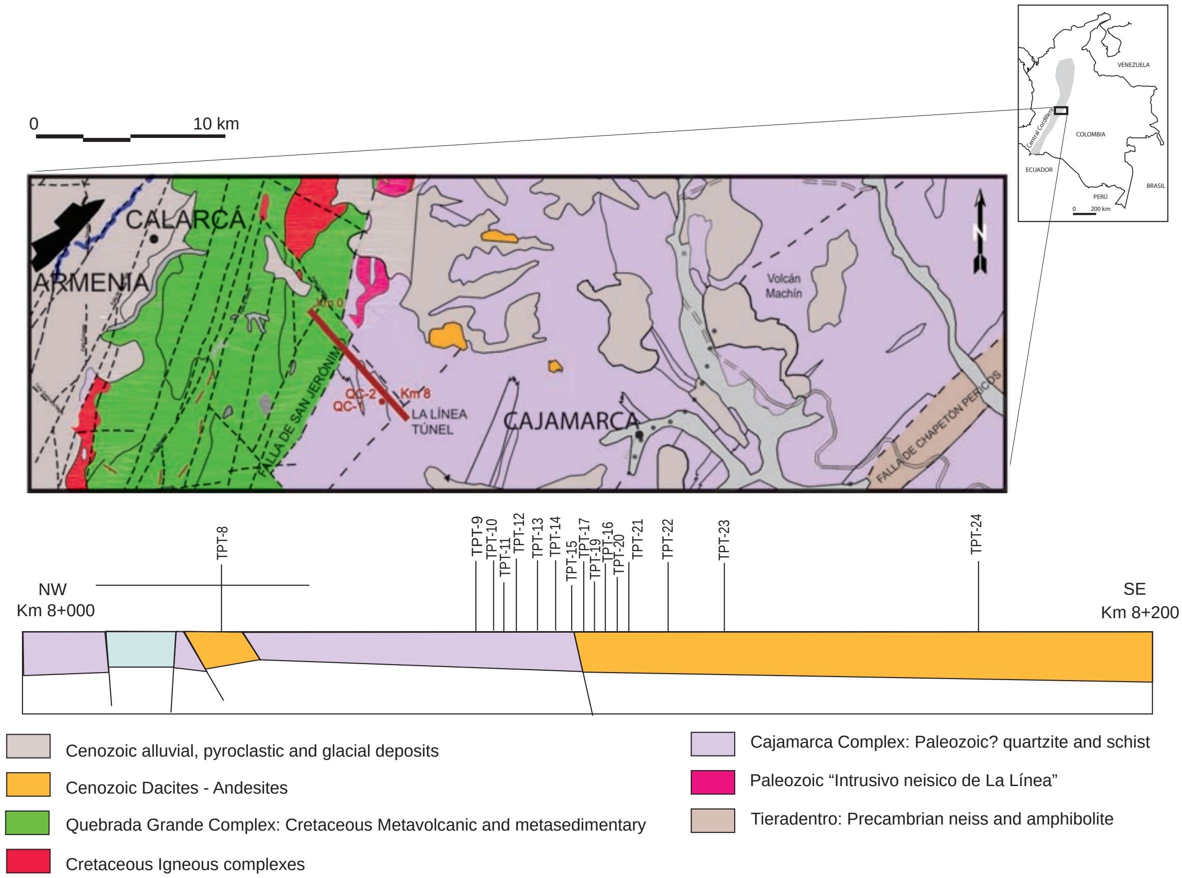


Figure 1. Regional geologic map from the area around "La Línea" Tunnel (Central Cordillera, Colombia). The tunnel is located towards the centre of the figure and cross mainly Paleozoic metamorphics (Cajamarca Complex) and Cretaceous metasedimentary and metavolcanic rocks (Quebrada Grande Complex). The map was redrawn from generalized geologic maps of Quindio and Tolima (Rodiguez & Nuñez 2001, Mosquera 2000). The schematic section below the map show sample localities in the tunnel between abscissa K8+000 and K8+200 (samples TPT-8 to TPT-24, represent by numbers 8, 10, 22, etc. without the prefix TPT).

Cause of magmatism is also a contentious issue, one view relates magmatism to evolution of a convergent margin where oceanic lithosphere is subducted below the Andes (Alvarez 1979, Aspden & McCourt 1986, Núñez 1986, 2001, Bayona *et al.* 1994); an alternative explanation is that magmatism is associated with distensive tectonics (rifting) caused by gradual continental separation across a paleorift (Mojica & Kammer 1995).

Structural styles in the region have a typical character of high angle inverse faults; seismic data indicates that these structures feed into a 20 km deep west-dipping décollement (Butler & Schamel 1988). Two of the most prominent faults of the region, the Chapetón-Pericos Fault and the Palestina Fault, separate different deformational styles. Between the two mentioned faults, the style is marked by isoclinals folds in all scales, while west of the Palestina fault and east of a third fault, the Aranzazu-Manizales Fault (La Soledad zone fault), a superimposed S-C fabric characterized the deformation style (Restrepo-Pace 1992). The Romeral Fault system is the main structure near La Linea Tunnel and it is also the main source of earthquakes; however, the 1999 Armenia's earthquake, showed the presence of NNW faults with recent activity (Monsalve & Vargas 2002). Additionally, there are several E-W systems that generate differential horizontal displacements and segment NNW faults (Vargas *et al.* 2008).

Methodology

Sample rocks were collected by a systematic way along the tunnel depending on the tunnel's walls covering. The contact zone between the metamorphic and the porphyritic body (abscissa K8+081 to K8+108, Fig. 1) was sampled with 2 m separation between samples to allow a detailed characterization of the zone. Beyond the contact zone, samples were taken with a separation of 10 m, 50 m and 200 m approximately. Sampling was accompanied by detailed structural characterization including data collection from joints, foliation, folds, cleavage and veins. A second auxiliary section was sampled in the surface in order to collect more information from the contact zone between the Cajamarca schist and the andesite porphyry. Nearly 200 structural data and 27 rock samples were collected (TPT-1 to TPT-24, QC-1 and QC-2). Thin sections of each one of the samples were obtained and three selected sections were polished for microprobe analysis. The petrographic characterization of the samples consisted of mineral identification, microstructure description and modal analysis (counting of 300 to 400 points). Rock microstructure descriptions include: grade of crystallinity, grain size, grain shape and crystal spatial relations. A FEI QUANTA 2000 scanning electron microscope, hosted at Universidad Nacional de Colombia – Bogotá, was used to obtained point analysis and backscattered electron images (BEI) of polished thin sections coated with a mix of Au-Pd (1:1 anode). Bulk rock chemical analysis were obtained from glass discs with the Universidad Nacional de Colombia – Bogotá MagixPro PW-2440 Philips X ray fluorescence spectrometer, fitted with a Rh tube, maximum power of 4 kW, and calibrated with international standards (MBH and NIST).

Crystal Size Distribution analysis was done for three pluton samples (TPT-16, TPT-20 and QC-2) at different scales, covering an average area of 2x3.5 cm^2. Photomicrographs, taken in 6 to 10 fields in each sample, and scanned thin sections (1000 dpi resolution) were processed with a drawing program to trace the maximum length of each crystal. The minimum and maximum number of crystals measured in all sections was 317 and 1678, for a total of 4793 analyzed crystals. The data was then analyzed with the software CSD Correction 1.37 (Higgins 2002).

Porphyry andesite

The body is exposed in an area of approximately 5 km^2, has an elongated N-NE shape geometry and its age is uncertain. It was probably originated by Neogene plutonism (see for example Aspden *et al.*, 1987), but could also belong to the porphyry mineralized bodies associated to a Jurassic calc-alkaline suite described by McCourt *et al. (*1984). The main constituents are plagioclase, amphibole and quartz, with minor biotite, apatite, pyrite, chalcopyrite, sphene and ilmenite and chlorite, sericite, epidote and carbonates as alteration minerals. In the QAPF modal classification of volcanic rocks (Le Maitre *et al.,* 2003) samples from this body felt in the basalt – andesite field (Fig. 2) and the rock is classified as a porphyry hornblende andesite. The quartz content increases towards the pluton´s boundary (most quartz-rich samples are located towards the pluton boundary) suggesting assimilation of material from the country rock.

The rock has prophyritic microstructure, is holocrystalline and contains phenocrysts of plagioclase up to 6 mm in diameter and hornblende from 0.5 mm to 2.5 mm in diameter. Micro-phenocrysts of plagioclase, hornblende and quartz with diameters of less than 0.4 mm are also present. The matrix (24 to 36%) is criptocrystaline; however, microlites of quartz and plagioclase were suspected under the petrographic microscope and confirmed by electron microscopy analysis. In general, crystals are subhedral to euhedral, but in some cases are highly fragmented due to deformation related to the intrusive process (e.g., TPT-21B; Fig. 3). Some samples

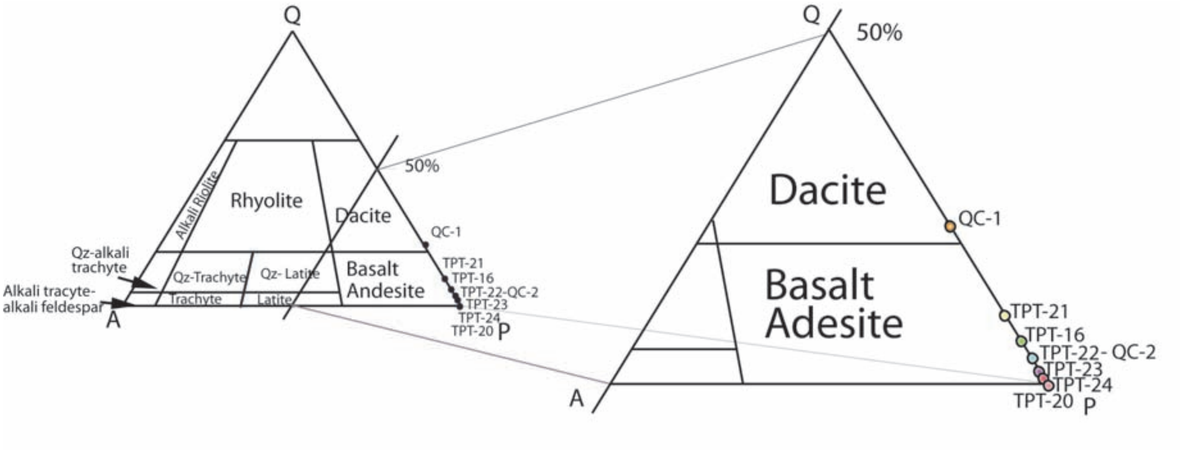


Figure 2. Diagram showing compositional variations of samples from the porphyritic intrusive body in the “La Linea” tunnel section. Note that most samples are within the basalt – andesite field (only sample QC-1 with a higher quartz content felt within the dacite field). The observed trend of increasing quartz content in the triangle corresponds with an increasing trend of quartz towards the contact between the intrusive and the metamorphics. QAPF modal classification of volcanic rocks (Le Maitre *et al.*, 2003).

show also microfaulting originated by post-emplacement processes as the microfractures also cut the country rock (Fig. 3).

Euhedral tabular plagioclase is the primary constituent of the rock (40 to 60%). Plagioclase composition ranges from andesine to oligoclase, phenocrysts range in composition from An_{26} to An_{43} and microphenocrysts range from An_{28} to An_{39} while matrix plagioclase has a composition of An_{31}. Phenocrysts have inclusions of pyrite and amphibole and are partially or totally replaced by sericite (12 to 43%). Epidote and calcite are also present as secondary minerals within plagioclase probably originated by action of hydrothermal fluids. The presence of euhedral Fe-rich epidote associated with plagioclase is restricted to the contact zone (samples TPT-21B and QC-1) suggesting schist partial melting and assimilation of the country rock material in the melt. Olive green brown to green yellow amphibole (13 to 55%) in euhedral, prismatic, rarely twinned crystals is the second most abundant constituent of the rock. It contains inclusions of plagioclase, ilmenite and pyrite and is incipiently zoned. This amphibole is Ca-rich with intermediate to low Si content and relatively high Al, whose compositional classification ranges between pargasitic hornblende to ferrous pargasitic hornblende and to edenitic hornblende and silicic edenite. Most hornblende crystals are altered to chlorite and biotite along cleavage planes and occasionally they are completely replaced. Anhedral quartz is present in less than 10% modal proportion. It usually has rounded edges with reaction and corrosion bays, reaction textures that suggest disequilibrium of this mineral with the melt. Opaque minerals (up to 18% modal proportion) include pyrite, chalcopyrite, rutile, and intergrown titanite – ilmenite. Accessories phases (<3%) include euhedral lath-shaped and locally kinked biotite (0.7 mm), euhedral apatite (0.1-0.2 mm), and euhedral zircon.

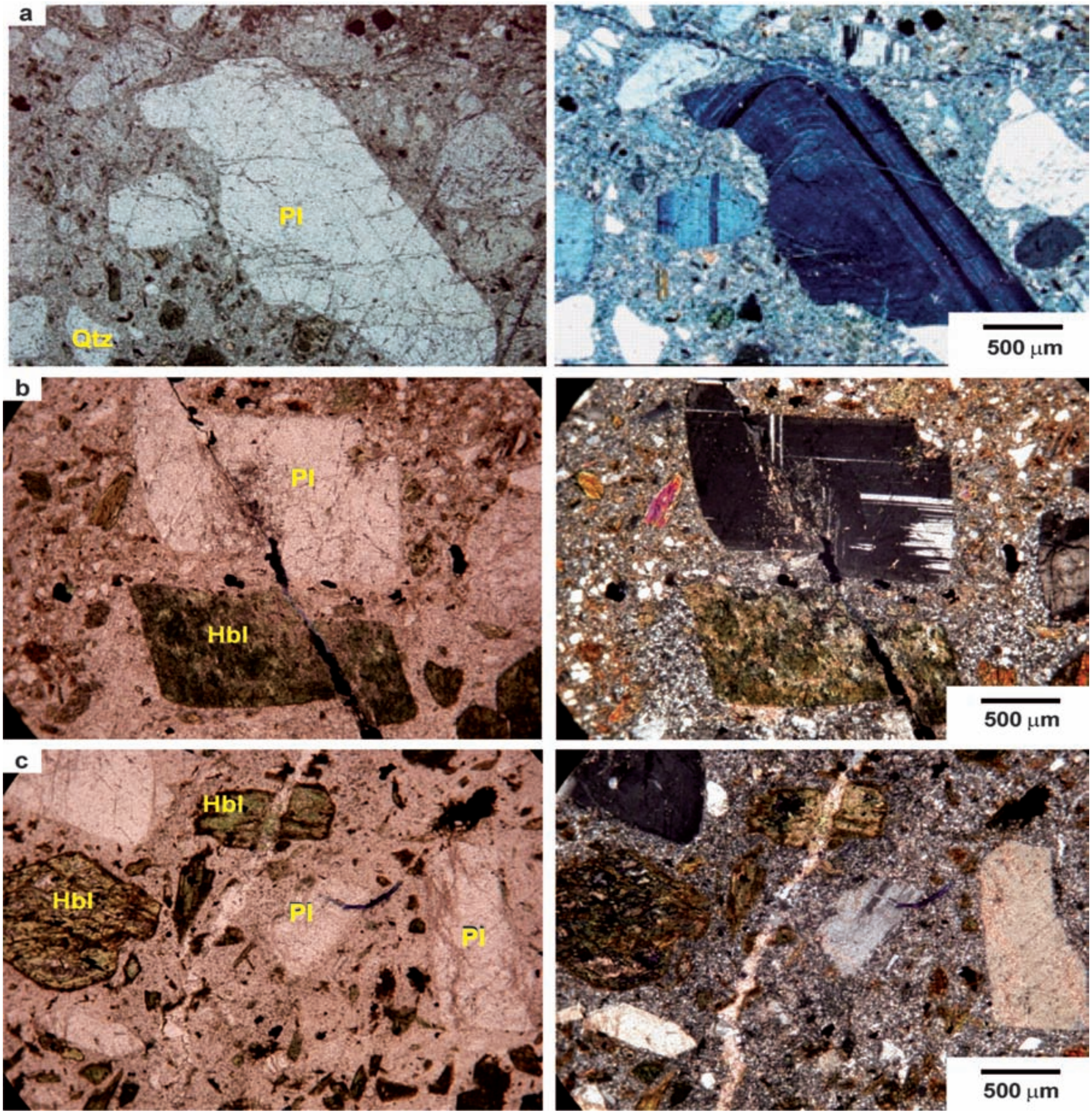
Cajamarca Complex (Pzc)

Quartz-biotite-graphite schist: They consist mostly of quartz (34 - 54%), graphite (1 - 23%), biotite (2 -34%), and muscovite (1 - 14%), with minor plagioclase, calcite, actinolite and chlorite (all <10%). Accessory minerals include apatite, monazite, pyrite, chalcopyrite, ilmenite, rutile and titanite. These rocks have schistose microstructure with folded microlithons of plagioclase and biotite-quartz-graphite-muscovite

(Fig. 3). The presence of biotite is indicative of the beginning of the Biotite Zone in the greenschist Facies. These rocks probably were originated from an impure psamitic to pelitic protolith consisting of thin interbeded sandstone and quartz claystone, very rich in organic matter, with some proportion of carbonates. The presence of multiple foliations indicates at least two deformative events.

Mica-quartz schist: They are composed mainly of quartz (45-70%), muscovite (10-25%), biotite (10%), minor plagioclase (7-11%), calcite (6-17%), chlorite (4-13 %), and graphite (3%), and accessory apatite, titanite, pyrite and chalcopyrite. The protolith was a psamitic sequence with quartz sandstone and small proportions of claystones and limestones. The parageneses of quartz-chlorite-muscovite suggests a regional metamorphism in the greenschist facies.

Amphibole-epidote schist: It consists of hornblende (40-60%), epidote (9-67%), plagioclase (2-18%), and minor calcite, chlorite, titanite, zircon



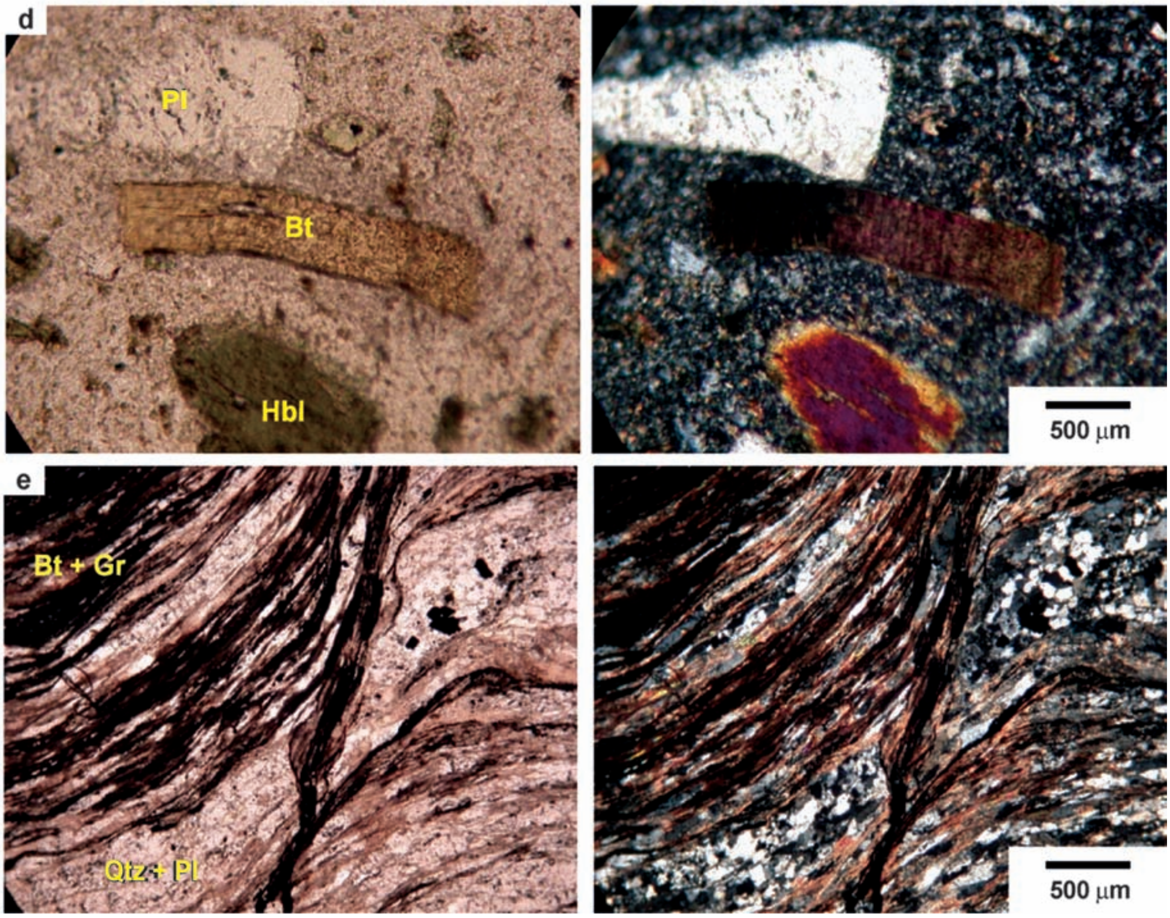


Figure 3. Thin section photomicrographs of samples from the tunnel showing evidence of fragile and ductile deformation, left: PPL, right: XPL. a. sample TPT-21, microfaults in apatite and biotite crystals, b. sample TPT-21B, plagioclase broken crystals, c. sample TPT-22, fractures in plagioclase filled with quartz, d. sample TPT-21B, bended biotite crystals, e. sample TPT-19, microshear zones. Mineral abbreviations after Kretz (1983).

and opaques (<10%). They have a schistose microstructure marked by preferred orientation of hornblende and epidote. The parageneses talc-epidote-calcite indicates that these rocks were metamorphosed under regional metamorphism in the greenschist facies.

Quantitative analysis of Crystal Size Distribution (CSD)

Quantitative CSD analysis complements results from petrography and from chemical analysis to reveal the magmatic processes that affect the evolution of the body. This technique is based on textural analysis of rocks and considers the crystal content as a function of size, shape and orientation (Marsh 1998; Higgins 2002). Crystallization is mainly controlled by the rate of heat removal from the system, which results from interactions between kinetics, time and temperature; for example, high temperatures and large diffusion rates favored a few large crystals (Vernón 2004). The size of crystals is primarily the result of heterogeneous nucleation, where material is rapidly and continuous added to a crystal boundary (growing rate) during all stages of crystallization (Marsh 1998). The subsequent states of nucleation not only depend on the cooling rate but also in the process of growth of the nuclei initially formed. Therefore, changes in the rates of nucleation (N) and growth (G) are the result of the interplay of various factors such as temperature diffusion and time and are reflected in the crystal size population. The most important part of the CSD curves is their shape and not the absolute values in the graphs (Marsh 1998). A linear logarithmic CSD is basically originated from an exponential change of nucleation rate over time; thus, changes in the slope reflect changes in the relative rate of nucleation. Under stable conditions, the maximum size of crystals should increase systematically with the increase of crystallinity, so that a curved CSD clearly reflects the addition of natural crystals. For example, if a CSD suggests multiple states, then nucleation can be interpreted as induced by different thermal regimes. CSD is a statistical method and the frequency depends on the size of the crystals; thus, the analyzed samples must be large enough to get a statistically valid analysis, a minimum of 200 crystals must be measured to get a reasonably valid CSD (Mock and Jerram 2005). That is why samples selected for this study have a population of at least 317 measurements obtained at two different scales.

Results

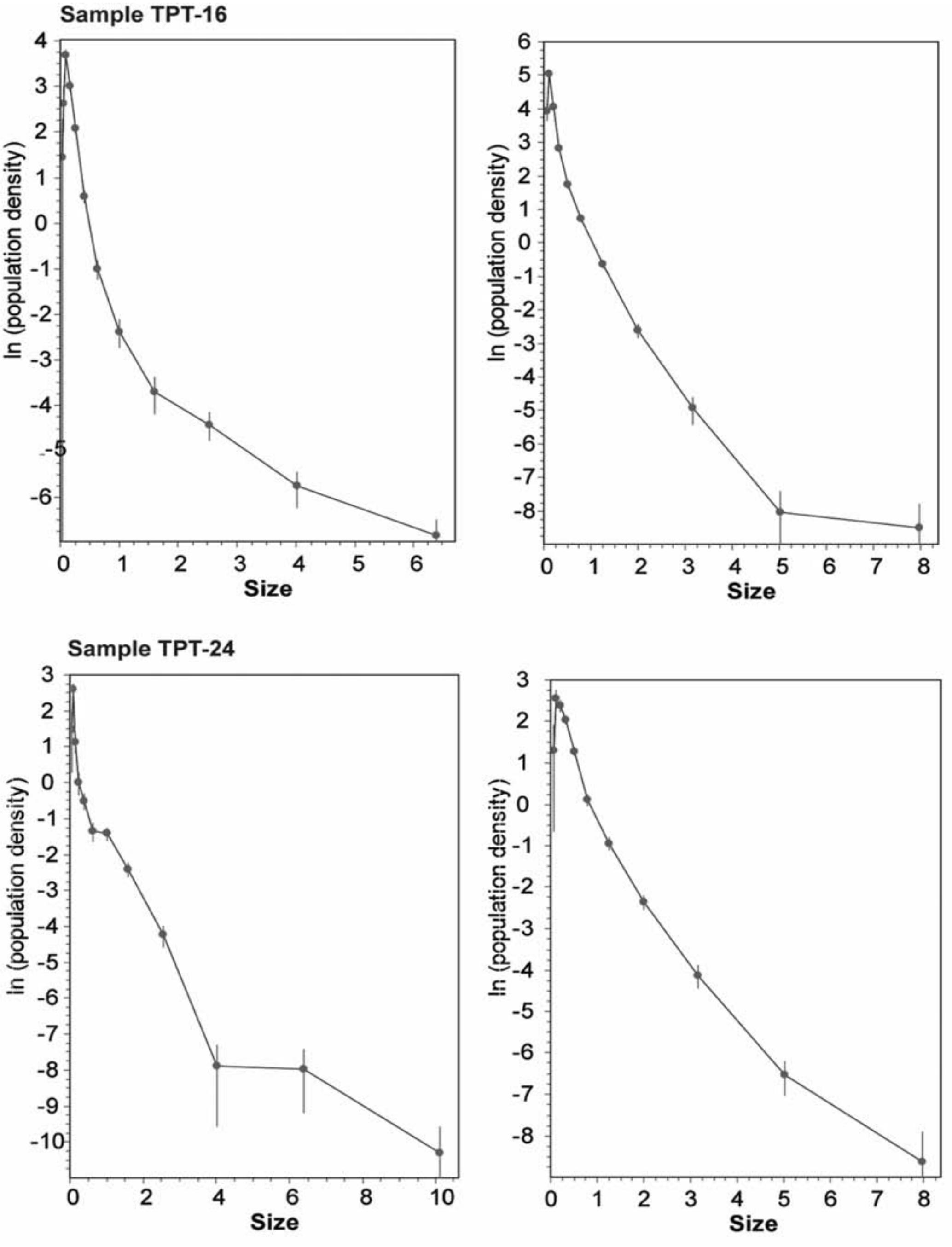
CSD graphs for two crystalline phases (plagioclase-hornblende) show a variable slope and concave shape (Fig. 4). The abnormal changes of the slope are interpreted as measurement errors and fall within the error bars that indicates wide dispersion of the data. The CSD curvature can be explained in two different ways. First, the shape could reflect two nucleation events (ΔN) with a super exponential increase in its final part that explains the higher frequency of small crystals. This increase in nucleation rate could be interpreted as a product of addition of country rock material, in agreement with variations in the slope of the CSD away from the edges of the intrusive, which becomes more linear, and with the interpretation of quartz and mica assimilation supported by rock compositional variations. Second, the shape of the curves could be caused by a growth rate dependent or proportional to size (ΔG) (Eberl *et al.* 2002), this is in discrepancy with mineral analysis that shows an overlap in the compositional range of phenocrysts, microphenocrysts and matrix crystals indicating that these may have nucleated simultaneously. However, an alternative explanation is that some nuclei may have begun to grow more rapidly than others, the larger crystals have lower surface energy and growth more at expenses of the smaller ones (Ostwald ripening) favoring the emergence of phenocrysts and the greater number of small crystals is favored by selective and concentrated growth of the larger crystals.

Discussion and conclusions

Since relationship between country rock and type of intruding magma is the governing factor for the type of generated contact, the characterization of the host rock is important to determine the effects of the approximating heat source in the pressure and temperature regime. For example, a type of relationship in forceful intrusions develops when magmatic fluids move into fractures opened in the country rock. These fracturing is created or enhanced by a momentum generated by the intrusive itself. In the case here, petrographic characterization and field evidence (Fig. 5) suggest that the contact between the Porphyry andesite and Cajamarca Group is intrusive, this contact was later affected by a deformation event causing a faulted contact in some parts of the intrusive (N to NNW predominant direction).

The suggested forceful intrusion is also characterized by assimilation of quartz in the igneous body and hydrothermal fluid exchange between country rock and the igneous body. The presence of Fe-rich epidote restricted to the contact zone support the interpretation of partial melting of the schist country rock and assimilation of that material into the melt and/or hydrothermal fluid exchange. CSD curves show an increase in nucleation rate that is interpreted here as a product of addition of country rock material, it is possible that the shape of the CSD was influenced by nucleation and growth, however geochemical evidence of country rock assimilation is in agreement with the interpretation of CSD affected by rock assimilation.

Structural data also support the interpretation of a forceful intrusion. The country rock near the contact has a different foliation orientation than the regional trend suggesting rotation of foliation that could be originated by the emplacement of the pluton (Fig. 6). The two lithologies have contrasting mechanical behavior, while the Cajamarca Group schist



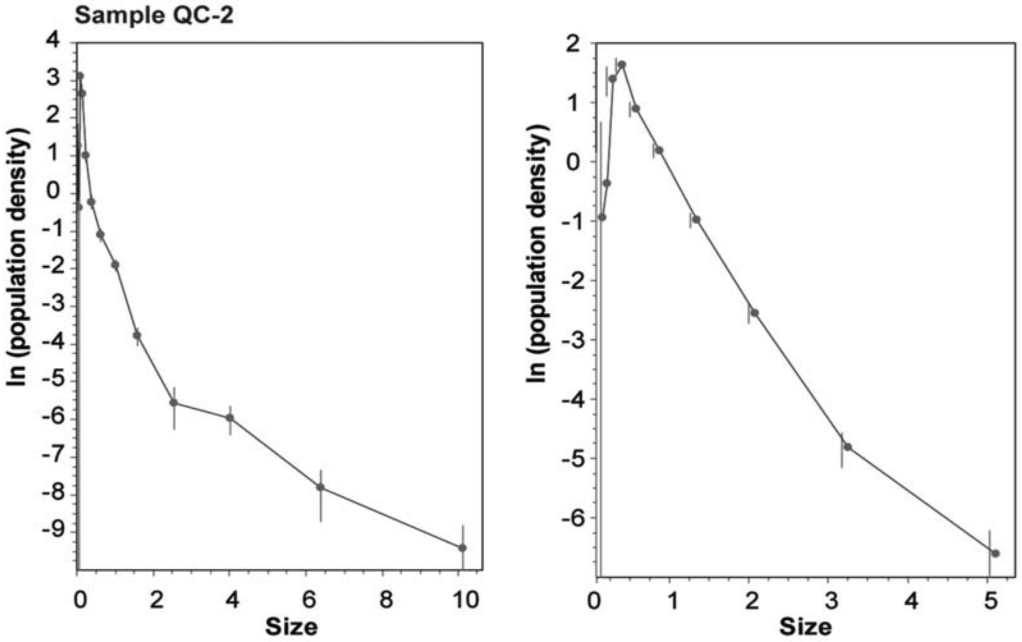


Figure 4. CSD Diagrams, samples TPT-16 (top), QC-2 (middle), and TPT-24 (bottom). The diagrams illustrate the crystal size distribution for plagioclase (left) and hornblende (right). Size of the crystals, given in mm, plotted as a function of the natural log of population density.

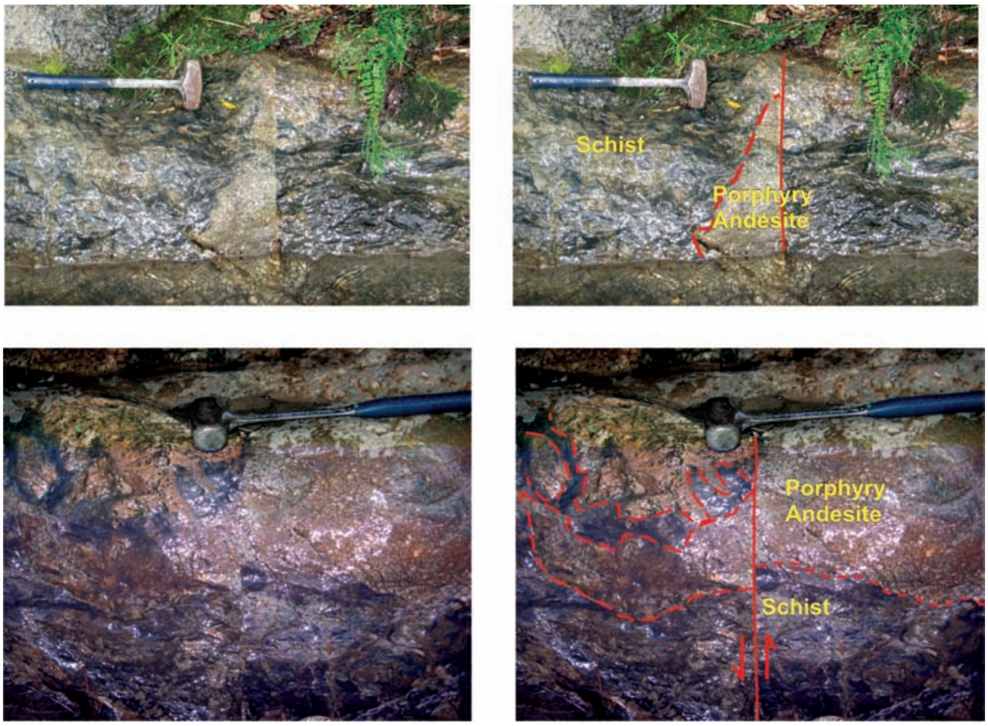


Figure 5. Field intrusive evidence of the porphyry (top) and subsequent faulting affecting the intrusive contact (bottom).

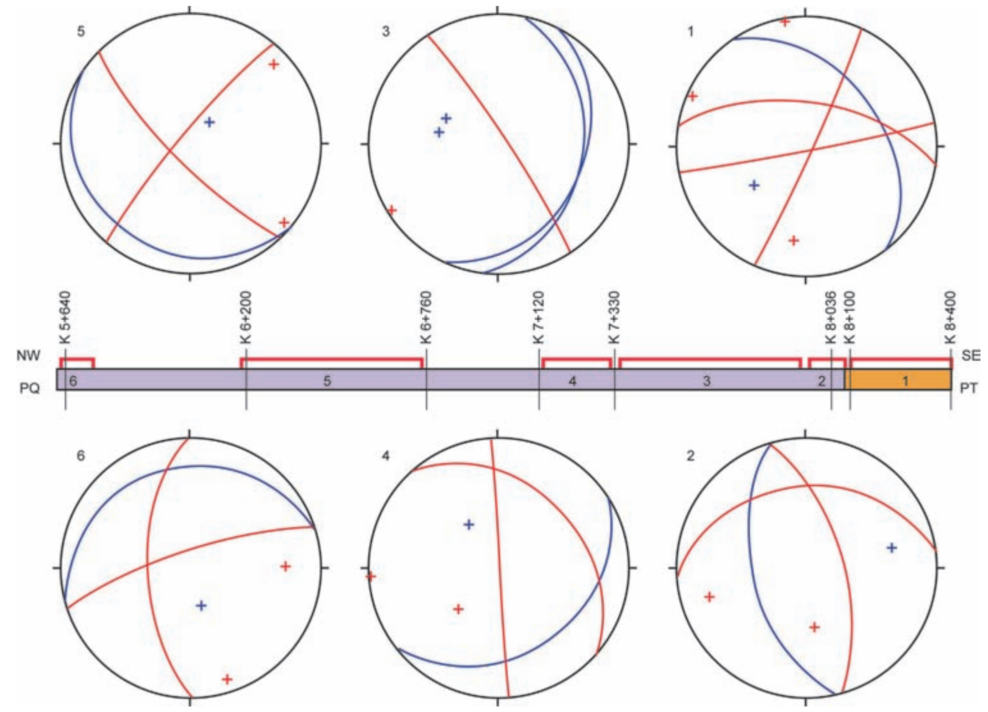


Figure 6. Stereograms of structural data between Km. 5+640 and Km. 8+400. The section runs from the NW to the SE (PQ = "Portal Quindio", PT = "Portal Tolima"). Blue lines represent foliation and red lines represent joints. Note the change in foliation orientation near the contact between the intrusive and the metamorphics (sector 2).

and quartzite have ductile behavior that is expressed in tight folds developed in two orientations (0/72 and 162/60) the intrusive body is affected by faults and microfaults (fragile deformation, Figs. 3 and 5) that also cut the country metamorphic rock suggesting a post-emplacement fragile deformation event. Additionally, crenulation cleavage that affects the foliation in several directions (Fig. 3e) and quartz, carbonate and sulfurs veins that cut in different directions the foliation suggests that other processes affect the rock after peak metamorphism.

We suggest that the magma formed a gradational contact zone in a simple injection process, where fragments of the country rock were trapped into the magma and some of the fragments were not completely melted and formed xenoliths (see Fig. 5). However, a faulted contact between the intrusive and the country rock is observed in the area (Fig. 5), this faulted contact has a trend of N to NNE consistent with the regional trend of the structures such as the Otú Pericos Fault and Romeral Fault System. There is not field evidence in the form of dikes or sills that suggest pervasive invasion of melt, this is because of the characteristics of the country rock (quartz-rich schist) that acted as an impermeable unit.

Acknowledgments

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MINERALIZATION CONTROLS AND PETROGENESIS OF THE RARE METAL PEGMATITES OF NASARAWA AREA, CENTRAL NIGERIA

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Abstract

The pegmatites of Nasarawa area occur in the central part of Nigeria. They are mainly hosted by phyllonites in a NNE-SSW trending shear zone lying east of some foliated Pan-African and West of Jurassic Afu Complex Younger Granites. A geological mapping of the area was followed by petrographic and mineralogical studies of selected rock and mineral samples. A total of 72 samples consisting of 25 rocks, 22 feldspars and 25 white micas were analyzed for various elements.

The pegmatites are peraluminous and are genetically linked to the late Pan-African leucogranite with the shear zone. The Pan-African granites have very low REE abundances and non-chondritic ratios of Zr/Hf and Y/Ho and low Nb/Ta ratios indicating crystallization from a liquid-rich melt. Barren pegmatites are closely associated with the primitive hornblende biotite Pan-African synorogenic granites while Sn- Nb – Ta mineralized granites are correspondingly enriched in pegmatites spatially associated with Pan-African synorogenic granites with enhanced values of rare lithophile elements such as Rb, Cs, Mn, Sn and Nb-Ta. The primary control of rare metal mineralization in the pegmatites is the composition of the source rock since the Ta-Nb-Sn-Li-Be-W mineralized pegmatites crystallized from fluid (H_2O-B-P-F) rich melts.

It is hereby proposed that the late Pan-African tectonic granite which is parental to the highly mineralized pegmatites in this area originated from anatexis of undepleted mica-rich metasediments at depth, followed by a magmatic fractionation of the fluid rich melt as it ascended through reactivated ancient fractures. The heat for the partial melting might have been supplied mainly by the reactivation of ancient fractures, which controlled the emplacement of the fertile granites and the related pegmatites.

Keywords: Pegmatites, Nasarawa, shear zones, mineralization, anatexis, magmatic fractionation, Nigeria.

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Resumen

Las pegmatitas del área de Nasarawa se dan en la parte central de Nigeria. Ellas están principalmente emplazadas en filonitas de una zona de cizalla con una tendencia NNE, SSW reposando al E de algunos complejos graníticos como el Pan Africano joven y al W el Complejo Jurasico AFU. Un mapa geológico del área fue seguido mediante estudios petrográficos y mineralógicos de rocas seleccionadas y muestras minerales. Se realizó un análisis de varios elementos sobre un total de 72 muestras compuestas por 25 rocas, 22 feldespatos y 25 micas blancas.

Las pegmatitas son peraluminosas y están relacionadas genéticamente con el leucogranito Pan Africano tardío y con la zona de cizalla. Los granitos Pan Africanos tienen muy bajos contenidos REE y proporciones no condríticas de Zr/Hf y Y/Ho y las bajas relaciones de Nb/Ta indican cristalización a partir de un fundido rico en líquido. Las pegmatitas Barren están muy relacionadas con la biotitas y orblendas primitivas de los granitos sinorogénicos Pan Africanos, mientras que los granitos mineralizados con Sn-Nb-Ta son correspondientes con las pegmatitas enriquecidas espacialmente relacionadas con los granitos sinorogénicos Pan Africanos con valores altos de elementos litófilos raros tales como_: Rb, Cs, Mn, Sn y Nb-Ta. El control primario de la mineralización de metales raros en las pegmatitas es la composición de la roca fuente a partir de las pegmatitas mineralizadas en Ta,-Nb-Sn-Li-Be-W cristalizadas a partir de un fundido rico en fluidos (H2O-B-P-F).

Aquí se propone que el granito tectónico Pan Africano tardío, el cual es padre de las pegmatitas altamente mineralizadas en esta área se originó a partir de la anatexia de metasedimentos no empobrecidos en micas, seguido por un fraccionamiento magmático del fundido rico en fluidos que ascendió a través de fracturas antiguas reactivadas, las cuales controlaron el emplazamiento de granitos fértiles y las pegmatitas relacionadas.

Palabras clave: Pegmatitas, Nasarawa, zonas de cizalla, mineralización, anatexia, fraccionamiento magmático, Nigeria.

Introduction

The pegmatite field belongs to the pegmatites related to syn to late Pan-African tectonic granites occurring in the Pan-African Mobile Belt east of the West African Craton. The field occurs in an area bounded by $7^0 35^1$E – 7^0 05^1E, $8^0 08^1$N – $8^0 30^1$N covering an area of 531 km^2 (Fig. 1). Nb-Ta-Sn-Be-Li- W primary mineralization is hosted in quartz-feldspar-muscovite pegmatites. Intrusion of the Older Granites into the reactivated Archean to Lower Proterozoic crust of central and southwestern Nigeria have been shown by Rb-Sr whole rock and U-Pb zircon age determinations) to have lasted at least 630 to 530Ma. Pegmatites in the same area have been dated 562-534 Ma (Matheis and Caen-Vachette, (1983) indicating that the pegmatite emplacement occurred at the end of Pan-African magmatic activity.

The Nasarawa pegmatite field is also in close spatial relationship with the granites of Afu Complex, which is the southernmost occurrence of the 1250 km-long belt of ring complexes extending across Niger and Nigeria. Rb/Sr age decreases from Ordovician in Northern Niger to Late Jurassic (141 Ma) of the Afu Complex in Nigeria. The Younger Granites as this later suite of rocks are called, are notably mineralized in Sn and Nb. The two geochemically distinct and economically important types of primary Sn-Nb-Ta mineralization were already recognized by Raeburn (1924).

In Wamba area, Kuster (1990) has shown that the emplacement of late Pan African granites with similar geochemical characteristics with the mineralized pegmatites was fracture-controlled and mylonitized along a conjugate set of NE-SW and NW-SE to NNW-SSE- striking faults. In more recent times, new rare-metal pegmatite fields have been discovered both within a NE-SW belt recognized by the earlier workers, Jacobson and Webb (1946) and Wright (1970) as well as other areas already known for gold mineralization northwest of the pegmatite province especially the Kushaka schist belt, the Magami and Maradun areas of northwestern Nigeria, Garba (2003).

All the rare metal and gold mineralizations are associated with prominent regional faults in the Basement Complex of Nigeria. This paper discusses the geology and geochemistry of the Nasarawa area in relation to the source and controls of mineralization of rare metal pegmatites in the Nasarawa area.

Regional Geology

Nigeria lies within the zone of Pan-African reactivation (ca.550 Ma) to the east of the West African Craton, which has been stable since approximately 1600Ma. This mobile belt extends from Algeria across the Southern Sahara into Nigeria, Benin and Cameroon. Rocks of the Nigerian Basement Complex which is part of the Pan African Mobile Belt are intruded by Mesozoic ring complexes of Jos area and overlain unconformably by Cretaceous to Quaternary sediments forming the sedimentary basins. Three broad lithological groups have been distinguished in the Nigeria Basement Complex: A polymetamorphic Migmatite-Gneiss Complex with ages ranging from Liberian (ca. 2800 Ma) to Pan-African (ca. 600Ma). Ages >3000Ma have lately been obtained from some of the rocks (Dada, 2006). Metamorphism is generally in the amphibolite to granulite facies grade. Younger members of this group are N-S to NNE-SSW trending belts of low grade (greenschist to amphibolite facies) metasedimentary and minor metavolcanic supracrustals of Late Proterozoic age. The schist belts which are concentrated in the western half of Nigeria are seldomly found east of 8^0 E longitude, (Ajibade and Wright, 1989). The schist

Figure 1. Geological Sketch map of central and south-west Nigeria showing the location of the Nasarawa pegmatite field (study area) and the distribution and ages of Pan-African Older Granites and pegmatites (underlined). Geochronogical data sources are van Breemen *et. al.* (1977), Rahaman *et. al.* (1983), Matheis and Caen-Vachette (1984), Tubosun *et. al.* (1984), Dada *et. al.* (1987).

belt rocks host the gold and rare metal mineralized pegmatites and veins, which are associated with prominent regional fractures. The Older Granites, which are Pan-African orogeny-related, range from syn- through late to postorogenic granitoids of upper Proterozoic to Lower Paleozoic age (ca. 873-500 Ma). They intrude both the Schist Belts and Migmatite-Gneiss Complex rocks and comprise diorites, tonalites, granodiorites, granites, syenites, gabbros and charnockites.

The end of the Pan-African tectonic event is marked by a conjugate fracture system of strike-slip faults (Ball, 1980). Fault directions have a consistent trend and sense of displacement; i.e. a NNE-SSW trending system having a dextral sense of movement and a NW-SE trending system with a sinistral sense (McCurry, 1971; Ball, 1980). Both sets crosscut all the main Pan-African structures, including older N-S trending shear zones (mylonites) (Ball, 1980; Ajibade and Wright 1989, Kuster 1990, Garba 1996). Other parallel Pan-African fracture systems with structural trends (N30^{0}E and N60^{0}E) appear to have been precursors to the development of the Cretaceous Benue Trough and its associated volcanics. The pattern of these fracture systems was probably established during the Pan-African orogeny (McCurry, 1971), and the main transcurrent movement probably occurred then – but may well represent lineament of much greater age. Wright (1970) was of the opinion that the regional faults had some influence on the direction of migration of hot spots within the mantle that culminated in the formation of the Mesozoic ring complexes.

Late Pan-African granites parental to rare metal pegmatites and gold-bearing veins are closely associated with the fractures in the Pan African mobile belts (Kuster, 1990; Ekwueme and Matheis, 1995; Garba, 2002; Okunlola, 2005). The pegmatites, both rare metal mineralized and non-mineralized, are associated with the Older Granites. The pegmatites were initially thought to be concentrated in a NE-SW zone extending from Ago-Iwoye in the southwest through Wamba-Jema'a to Bauchi area in the north- east. However, other pegmatite fields have more recently

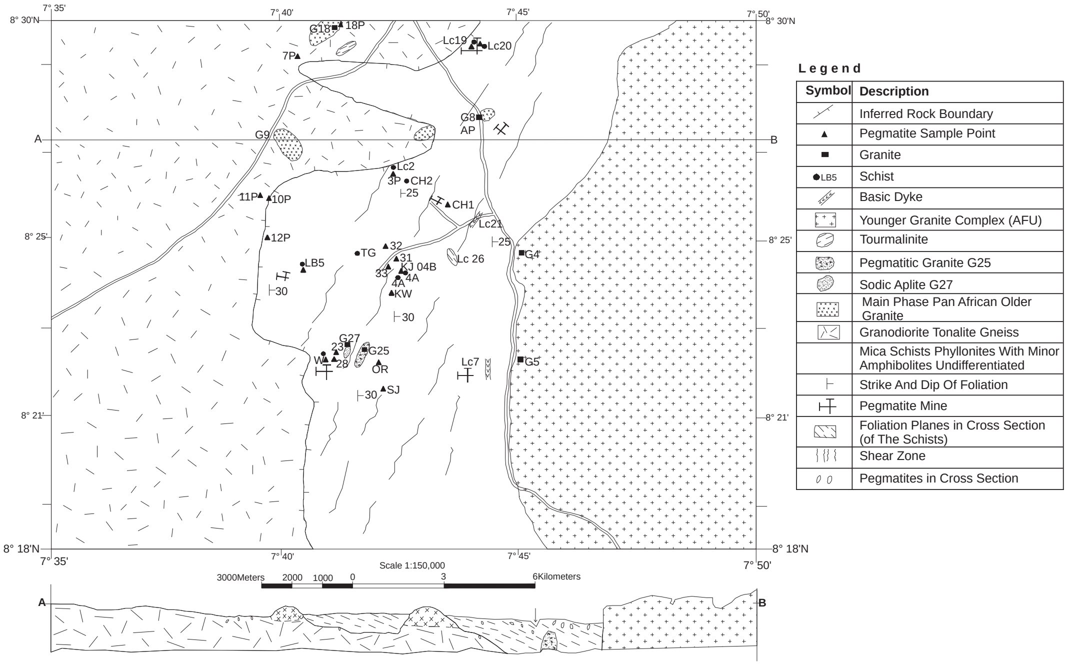

Figure 2. Geological Map of Nasarawa Tantalite Field (Sheet 229 Northwest Udegi).

been known around Zuru-Gusau in the northwest (Garba, 2002 and Okunlola, 2005), and Obudu area in the southeast of Nigeria (Ekwueme and Matheis, 1995).

"Younger Granites"- a 1250km-long belt of ring complexes extending across Niger and Nigeria, with the Rb/Sr age decreasing from Ordovician in northern Niger to Late Jurassic in Central Nigeria. These are high level anorogenic volcanic-plutonic ring complexes (Jacobson, Snelling et al, 1964) intruded into the older Precambrian to Paleozoic Basement Complex rocks. Granites overwhelmingly predominate in the province, but in some complexes their emplacement was preceded by basic and intermediate intrusions, ranging from olivine-gabbro to quartz-monzonite and syenite. The basic, intermediate and porphyritic members of the Younger Granites carry Pb-Zn-Cu-Fe sulphide mineralization. The granitic members are mainly peralkaline arfvedsonite granites and the metaluminous to peraluminous biotite granites: These are the commonest and carry most of the Sn-Nb mineralization.

Chemical analysis

Geological maping of the area was followed by petrographic and mineralogical studies of the rocks. Whole rocks chemical analysis of selected representative samples of the granites and the simple graphic quartz-feldspar pegmatites was done using Phillips 1404 automatic X-ray fluorescence (XRP) spectrometer on their powder pellets and glass discs in the Geochimistry Laboratories of the Technical University of Berlin. ICP-MS measurements of Ta, Nb and REEs were performed for 14 samples in Geoforschungs Zentrum Potsdam, using an ELAN 5000A quadrupole ICP mass spectrometer (Perkin- Elmer/SCIEZ), Canada. Details of laboratory procedures used in analyzing some of the samples by ICP-MS are as published by Dulski (2001) in Geostandars Newsletter. Few samples with peculiar assays were analyzed by the XRD method to determine their mineralogy. The framed powder samples using Phillips PW 1820 diffractometer in the Technical University of Berlin X-rays were generated at 50kv, 30mA. Analitycal condition for each sample were: 0.02° 2Ø/step, 2.5 seconds per step with analysis completed from 3-80°2 Ø.

Results

Geology and petrology of the area

The Nasarawa area comprises metasedimentary rocks (mainly mica schists and sericitized/chloritized phyllonites) intruded by a Pan-African granodiorite/granite batholith (ca. 600Ma), fracture controlled elongate Late Pan-African granite and pegmatites (Fig.2). Abutting the mica schist southeast of the area is the Afu Complex of Late Jurassic (ca. 141Ma) composed mainly of biotite granites with minor quartz porphyry. There is a shear zone that trends north-north east in the area within which the rocks are mylonitized. Below is the detailed description of the geology of the area and Figure 2 is the geological map of the area. The schists occur as relics and xenoliths in the Older Granites and pegmatites with thick successions in a north-south trending low-lying area that lies between the Older Granite and granodiorite/tonalite gneisses rock suite in the west and the Jurassic Younger Granite (Afu) Complex in the east (see Figure 2). The schists generally have measurable north-south trending foliations that dip to the east at low angles (25^0-30^0). The north-south foliations are interpreted as Pan-African structures superimposed on earlier tectonite fabrics, which sometimes give contorted appearances to the schists.

Compositionally, the rocks range between metamorphosed pelitic to semi-pelitic and psammitic rocks with biotite, quartz and minor muscovite, as the major minerals. Compositional changes related to pegmatites' intrusion are noticeable at the contacts of the pegmatites and the schist. Towards the south of the area, the schist becomes gneissic with appearance of feldspars and pale amphiboles. Accessory minerals found in the schist include opaques (ilmenite and magnetite), sphene and garnet. Tourmalines and apatites are common accessory minerals in the schist at contact zones with pegmatites and in some cases may constitute more than 20% of the rock The tourmalines in the pegmatites' exocontact zones in the schist are usually zoned which shows that they crystallized from highly fluid-rich melts (London and Manning, 1995). Radiogenic haloes are formed around inclusions of radioactive minerals (monazite and zircon) in biotites. The schists as well as other rocks within the shear zone are mylonitized. The mylonitized mica schist-phyllonite is composed of porphyroclasts of biotite and chlorite in a matrix of fine-grained groundmass of muscovite and quartz.

Within the schist at the center of the area, and in proximity to the schist at the northern part of the area are tourmalinites, which are essentially composed of tourmalines and quartz with accessory to minor apatites. Within the schist are fragments of foliated amphibolites that are too small in dimensions to be represented as discrete bodies on the map. The mineral assemblages of biotite, muscovite, and garnet in the schists as well as amphiboles and feldspar porphyroblasts indicate that the rocks must have reached amphibolite grade of regional (Barrovian-type) metamorphism, during the Pan African orogenic cycle. The greenschist facies minerals such as chlorite and green biotite, recrystallized fine-grained muscovite and quartz within the shear zone are products of retrograde metamorphism of the rocks by the post-tectonic processes of shearing/mylonitization that probably accompanied the emplacement of the pegmatites. Coincidentally, the boundary of the shear zone marks the boundary of the zone of occurrences of the mineralized pegmatites within the schists.

The mylonitic micro-textures of these rocks within the shear zone provide evidence of fracturing/shearing of the rocks. This phenomenon is observable in the leucogranitic samples and schistose samples in which porphyroclasts of biotite, chlorite and quartz are set in a groundmass of recrystallized fine grained muscovite and quartz. The shear zone is occupied by schistose metapelites/metapsammites in a north-northeast belt. Within this belt are also the leucocratic pegmatitic granite. Ocan and Okunlola (2001) have also observed zones of mylonitization in the rocks (granite and schist) associated with the mineralized pegmatites at Angwan Doka, north-east of this area. Similarly at Wamba, about 100kilometers northeast of this area (Kuster, 1990), there are elongated granitic plutons that are partly affected by deformation (mylonitization) along a conjugate set of strike-slip (transcurrent) faults. The emplacement of these granites appears to be fault-controlled and the directions of relative movements are dextral along NE-SW striking faults and sinistral along NW-SE to NNW – SSE striking- faults. It thus appears that there is a regional northeast trending shear/fracture-zone characterized by mylonitization of the rocks coinciding with the zone of mineralized pegmatites, and movement along the faults must have been active before and after the emplacement of the granites and the related pegmatites. Older Granites of batholitic dimensions intrude these schists, which range in composition from hornblende-biotite granodiorite/tonalite gneiss to biotite granites at higher elevations. This suite of rocks appears to represent the first major episode of granite plutonism in the area. While the granodiorite/tonalite gneiss occupies the western part of the area, the biotite granites, which outcrop as inselbergs, occur in the northwestern part of the area. The granodiorites are strongly foliated with the quartzo-feldspathic phenocrysts developed into porphyroblasts or augen structures.

In thin sections, the granodiorite/tonalite gneiss consists of quartz, plagioclase, bluish and brownish amphiboles, biotites with accessory titanite (sphene) and apatite. Feldspar and quartz sometimes form wart-like intergrowths –myrmekites. In the biotite granite, quartz, biotite, microcline and plagioclase feldspar are the essential minerals. There may be minor or no hornblende. At the northernmost part of the area, the biotite granite is fluid-rich. Some plagioclase shows some sericitisation and pegmatites close to this granite have enhancement of the rare lithophile elements compared with pegmatites close to a less fluid-rich granite. Granites at the south-central part of the area are smaller bodies than the main phase granites and have some distinct characteristics in their mode of occurrence in the field. The pegmatitic granite in thin section consists of phenocrysts of quartz in a groundmass of felsic quartz, alkali feldspar and white mica, with very little biotite. The quartz phenocrysts are strongly deformed showing wavy/undulose extinction in cross-polarized light; and in some cases, they are recrystallized due to shear movement. The rock is however not foliated and the elongated mode of emplacement is obviously controlled by a northeast-southwest trending fault. Some mineralized pegmatites are close to this pegmatitic granite.

Simple pegmatites with mineral assemblage of microcline-quartz and minor plagioclase (albiteoligoclase) with accessory garnet, tourmaline (schorl), biotite and magnetite intruded the biotite granites-granodiorite suites. Within the schists, the pegmatites become richer in muscovites and the rare metal minerals. There is a tendency towards the arrangement of the pegmatites in sub-parallel groups akin to an en-echelon emplacement, and in some cases there are two or more intersecting sets of dykes. A rose diagram plot of the pegmatites indicate two major directions, viz:east-west and north to north north-east. Many of the richly mineralized pegmatites occur as sill-like bodies. The swellings are generally loci of intense albitization and mineralization. While majority of the pegmatites in the study area strike north-east/south-west, some have north-west-south-east and east-west strike directions. Strike and dip may change even in one dyke, following planes of weakness (joints, fractures and foliation planes) in the country rock. Majority of the pegmatites generally cut across the foliation of the host schists and gneisses. Many of the complex pegmatites display a textural and mineralogical zonation parallel with the walls of the intrusion. A zone of tourmalinization (black tourmalines) within the host rock at the contact with the pegmatites is followed by a prominent zone of quartz-mica margins of the dykes. In the complex pegmatites the marginal facies may be up to two feet or more in thickness and as observed in the Liberia pegmatite with a paragenesis of cloudy (and in some rare cases smoky) quartz, mica, microcline, albite and accessory large crystals of alkali enriched (blue-green) tourmalines and fluorapatite. The mica is coarse-grained and oriented at right angles to the contacts. Within the quartz-mica marginal zone is the quartz-microcline-albite-muscovite-beryl zone. This is followed by a quartz-muscovite-albite- tourmaline-amblygonite-montebrasite zone. At the inner zone, there is albite-fine grained muscovite-quartz (clear and colourless). In Liberia pegmatite, an albite-rich footwall zone with finely disseminated Nb-Ta mineralization was observed. From the outer to the inner zones there is enrichment in Ta, Li and Cs and their ores, and the toumalines become albite with increasing contents of Na and attractive colours. Most of these zones are observable in the complex pegmatites with some minor variations due to variations in their bulk chemistry; at Kilimanjaro, hydrated lithium-aluminosilicates (cookeite) were crystallized (no lithium aluminophosphates was sampled from this pegmatite) with albite, mica and quartz in the inner zone.

Pegmatite-country rock relationships (sharp contacts, unfractured wall rocks, variations in strike, dip and thickness of the dykes) suggest an emplacement level transitional between ductile to brittle host-rock behaviour (Kuster, 1990). Xenoliths of the foliated host rock, quartz-biotite schist, are present in some pegmatites, suggesting that the pegmatites are younger than the schists. The barren simple quartz-feldspar pegmatites found in proximity to the biotite Older Granites at the western part of the area are composed essentially of quartz, microcline-microperthite and minor plagioclase (albite-oligoclase). The minor plagioclase appears to be replacing the perthite with sericite by-product. Garnet, magnetite and tourmaline are accessory minerals observed in the simple pegmatites.

The more complex and mineralized pegmatite deposits occurring in the area show a more pervasive albitization. Some pegmatites show subparallel micro cracks with a large perthite crystal, which are filled with albite and sericite. Such cracks provide the channel ways by which the soda-rich late stage mineralizing fluids deposit the ores of Nb-Ta-Sn-Li-Be. In a favourable environment especially in the middle to inner zones (close to the quartz cores of the mineralized, complex and zoned pegmatites), replacement of microcline by albite is complete, giving rise to the formation of secondary feathery albites and fine-grained muscovite- “gilbertile”. East of the

Table 1: Trace elements of the microcline, microperthites (K-feldspars) of the pegmatites

Trace Elements of pegmatitic K-feldspars											
Sample	**l3**	**l6**	**l7**	**l10a**	**luz**	**lu**	**ls**	**s2**	**k1**	**k3**	**w2a**
P (ppm)	2400	2461	2662	2579	2130	4774	5398	6642	2854	2138	3024
F	0	0	0	0	0	0	326	0	0	0	0
Ba	44	35	34	67	10	30	53	36	69	91	39
Bi	20	10	17	15	17	15	10	13	12	10	21
Cd	13	7	9	5	6	bdl	bdl	bdl	bdl	bdl	16
Ce	40	32	32	12	52	21	0	19	35	0	69
Co	16	33	18	28	20	28	31	25	23	31	18
Cr	10	13	9	14	2	15	35	11	6	1	6
Cs	1722	1487	1540	1226	1482	602	111	160	844	692	3489
Cu	7	7	14	9	0	13	13	8	4	19	16
Ga	18	15	17	15	17	16	44	19	18	14	17
La	95	73	74	58	84	27	2	16	38	31	166
Nb	8	5	9	7	9	22	39	8	4	8	8
Ni	20	0	31	28	0	0	0	0	0	0	27
Pb	70	57	81	79	69	46	0	35	125	140	93
Pr	19	15	16	13	18	8	0	6	9	8	29
Rb	8546	6536	9534	8303	8420	5537	2593	3069	5440	4089	9474
Sn	21	13	187	15	14	28	24	28	9	8	24
Sr	38	144	58	44	51	22	30	183	64	70	32
Ta	b.d.l.	1	2	b.d.l.	b.d.l.	9	6	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Tl	49	38	57	49	49	30	12	16	39	30	73
W	155	241	137	187	176	203	195	154	143	204	160
V	10	0	0	14	18	0	0	0	0	0	20
Y	30	18	20	0	19	24	12	11	0	14	24
Zn	44	0	0	0	0	0	40	0	0	0	0
K/Ba	2521	2906	3492	1694	11058	3628	1696	2841	1571	1165	2916
K/Rb	13	16	12	14	13	20	35	33	20	26	12

Continuación Tabla 1

Trace Elements of pegmatitic K-feldspars											
Sample	**l3**	**l6**	**l7**	**l10a**	**luz**	**lu**	**ls**	**s2**	**k1**	**k3**	**w2a**
Na/K	0.10	0.17	0.06	0.08	0.09	0.12	0.20	0.16	0.12	0.12	0.06
K/Cs	64	68	77	93	75	181	811	639	128	153	33
K/Tl	2264	2676	2083	2316	2257	3628	7493	6393	2780	3534	1558
Rb/Tl	174	172	167	169	172	185	216	192	139	136	130

area is the western flank of the Afu Younger Granite Complex. The Complex is the southernmost occurrences of the Nigerian anorogenic ring complexes, which extend through Jos and northwards to the Arid region of Niger Republic. The Complex was dated 144± 2 Ma (Bowden *et al.*, 1976). It is elliptical in outline and about 50km in maximum diameter. It shows broad similarities (geochemical, mineralogical, etc.) to the other Younger Granite Complexes emplaced during the Early to Late Jurassic (Jacobson *et al.*, 1958 and Macleod *et al.*, 1971).

The Afu Complex is composed mainly of biotite granites with minor quartz porphyry (Imeokparia, 1982). The biotite granites show a somewhat fractionation trend with an enrichment of Nb, Li, F, Sn, in the more evolved albitized granites with low biotite contents. Mineralogically, the biotite granites are composed of quartz, K-feldspar, albite, and biotite, with fluorite, zircon, cryolite, magnetite, hematite and less commonly cassiterite, columbite, thorite, apatite and monazite as accessory minerals.

Geochemistry

In the Older Granites G8, G9 and G18b on the one hand have similar geochemical characteristics, which differentiate them from G25 and G27 (see Table 1). G8, G9 and G18b are calc-alkali granites with higher contents of Ca and Mg. Their K/Rb ratios range between 155 and 261. The lowest value 155 in the range is that of G18b. Field evidence shows that these three granites belong to the main-phase Pan African Older Granites. Sample G18b with the lowest K/Rb ratio as well as Ce among these three samples has relatively enhanced values of Rb-254ppm, W 241ppm, Ta 2ppm, Mn 700ppm, Sn 32ppm, Cs 11ppm, and Nb 36ppm. The spatially associated pegmatites 18P and 18aP have enhaced concentrations of Rb, 917ppm and 1718ppm; Cs, 62ppm and 779ppm, low K/Rb ratios 73 and 40 and correspondingly enriched in the ore elements Sn, 13ppm and 17ppm; Nb, 65ppm and 80ppm; and Ta, 15ppm and 21ppm, respectively. On the other hand, the pegmatite 10P which is spatially associated with the less geochemically evolved Older Granite in the area has low concentrations of the rare elements Rb, 450ppm; Cs, 2ppm; Sn, 9ppm ; and Ta 3ppm and a high K/Rb of 155.

Major elements composition of SiO_2 73.16, 71.1; Fe_2O_3 1.54, 2.02; CaO 0.88, 1.75 and MgO 0.42, 0.5 respectively show that G25 and G27 are more leucocratic than the main phase Pan African Granites. However, trace elements' compositions of the two granites show a lot of differences and indicate different levels of fractionation and possibly origins for the two granites. G27 has very high Ba (1377ppm), Sr (677ppm), Ba/Rb (17.21), and very low K/Ba (22) and Rb/Sr (0.12), which may indicate a metamorphic origin of the rock. The G25 has enhanced Mn (600ppm), Rb (295ppm), Ta (13ppm), Nb (24ppm) low K/Rb, Al/Ga, Zr/Hf and Nb/Ta ratios of 134, 2486, 19.96 and 1.85, respectively. Such high values of lithophile rare elements and low K/Rb, Al/Ga, Zr/Hf and Nb/Ta ratios are characteristic of

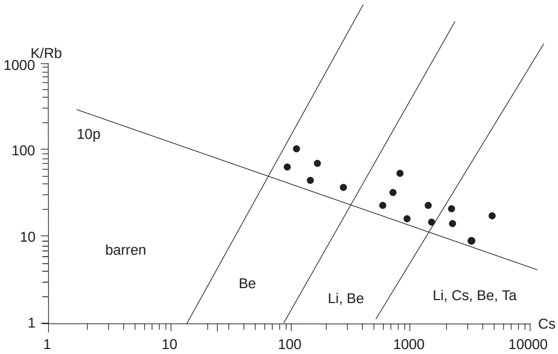

Figure 3. Classification of the pegmatites using the plots of K/Rb versus Cs of their K-feldspars according to Trueman and Cerny (1982).

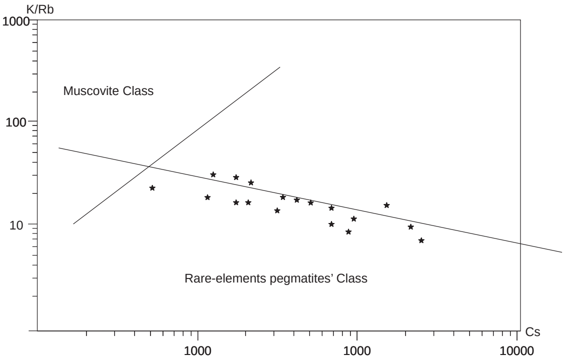

Figure 4. Plot of K/Rb versus Cs for the pegmatites'muscovites (After Cerny and Burt, 1984).

highly evolved granites parental to rare metal pegmatites (Raimbault *et al.*, 1995). Thus the major and trace element distribution in the sampled Older Granites show that samples G25 and G18 are more highly evolved with LCT geochemical affinities (Cerny, 1991c) than G8, G9 and G27. Both granites also have negative Ce anomaly which may be an indication of oxidizing conditions during rare-metal mineralization (Piper, 1974).

The sampled Afu Complex Younger Granites G4 and G5 are depleted in Ca, Mg and Sr; have high Fe/Mg, and are enriched in Nb, Y, F and Zr, thereby showing the characteristics of the NYF suites (Cerny, 1991c) compared with the Older Granites. They have lower ASI (aluminum saturation indices) and more alkaline. In both the Older and the Younger Granites, Mg, Ti, Ba and Zr are depleted in the granites with enhanced values of Rb and therefore amply depict the degree of magmatic fractionation within the suites (Figures 3 and 4). The granites with enhanced values of Rb are also enriched in Cs and the ore elements of Sn-Nb-Ta. In the Younger Granites, G5 is more leucocratic and coarser grained with less biotite than G4 It also has more enhanced values of the lithophile rare elements like Ta, Nb, F, P, Rb, Mn, Y,U, Cs, Th, Mo, W, and low K/Rb (104) and Al/Ga (2280) ratios. It however has a higher Nb/Ta ratio (4.65) when compared with that of 1.85 of G25.

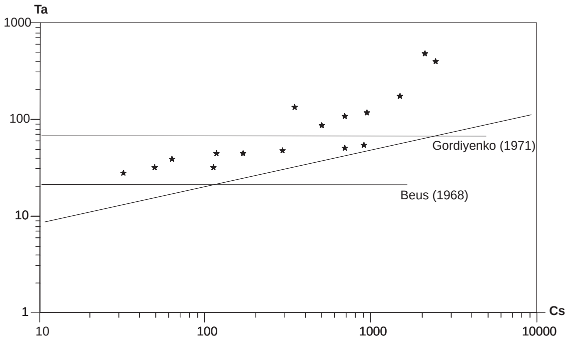

Figure 5. Plot of Ta Versus Cs For The Muscovites of Nasarawa Pegmatites. (After Beus (1968), Gordiyenko (1971)).

The Younger Granites have on the average, higher F content that the Older Granites while negative Ce anomaly (very low Ce content) is observed only in the mineralized Older Granites G25 and G18. Kinnaird (1984) and Barchelor (1987) have observed similarly distinct geochemical characteristics in the Older and Younger Granites of Nigeria. The REE concentration (Fig. 5) of pegmatites 10p and 11p show a decrease of an order of magnitude from those of the granite G25 while the REE in the pegmatitic white mica are the least (see Table 2). The REE generally have sub-horizontal to heavy rare earth element-depleted patterns; minerals with the lowest REE abundances have nearly horizontal patterns. REE contents of the granite, G25, which is highest in the samples analyzed, is very low (< 2x chondritic). Such

Table 2: Trace element contents of the albitic pegmatite phases

Sample	Albites					Cookeite	Phosphates		
							Fluorapatite	Amblygonites	
	lb6a	lb8	sj3	rNa	lc19	kj2fsp	lb9	lb10	ch1
P2O5 (%)	0.481	0.487	2.169	1.763	0.243	0.017	24.97	49.973	43.25
F (ppm)	1240	0	0	0	0	294	11637	13897	14203
As	0	0	7	8	6	1	0	0	0
Ba	19	51	37	26	102	56	31	33	61
Bi	14	11	11	16	12	12	38	1	8
Ce	14	12	22	14	0	0	443	0	7
Cd	7	bdl	bdl	bdl	bdl	bdl	27	bdl	bdl
Co	115	47	25	31	37	5	16	8	6
Cr	1	0	0	11	0	15	1	2	1
Cs	851	23	19	74	9	49	1	28	6
Cu	0	0	24	16	4	0	0	16	535
Ga	76	24	21	22	39	58	14	21	18
Hf	2	3	0	3	3	2	0	3	2
La	48	9	0	3	3	0	204	0	0
Mo	0	5	1	1	0	4	0	1	0
Nb	88	75	62	326	115	33	190	26	25
Nd	3	11	9	8	2	0	144	5	7
Ni	14	5	3	4	0	3	9	4	3
Pb	25	10	7	0	0	0	74	9	0
Pr	10	2	1	2	1	0	65	0	1
Rb	4829	69	347	252	31	444	46	290	62
Sc	0	0	9	0	4	0	0	0	5
Sm	1	3	2	2	1	1	66	1	1
Sn	565	659	14	174	35	54	28	231	67
Sr	263	52	1037	305	51	8	64	11	188
Ta	345	109	67	305	297	37	21	107	86
Th	0	0	0	0	0	3	2	1	4
Tl	23	bdl	bdl	bdl	bdl	5	bdl	bdl	bdl
U	0	3	0	10	0	1	216	0	7
V	5	1	4	15	6	5	16	4	8

Continuación Tabla 2

Sample	Albites					Cookeite	Phosphates		
							Fluorapatite	Amblygonites	
	lb6a	lb8	sj3	rNa	lc19	kj2fsp	lb9	lb10	ch1
W	502	346	201	247	298	64	46	89	124
Y	6	1	0	0	1	0	1391	1	0
Zn	229	63	26	187	12	39	62	26	119
Zr	17	12	17	68	18	5	17	54	7
H2O	2.42	0.43	1.1	0.82	0.36	8.8	0.51	5.27	7.54
SUM	98.71	98.24	97.67	99.4	99.79	98.01	98.12	102.94	86.53
K	33457	1577	11540	3321	1079	9132	1494	3487	664
K/Rb	7	23	33	13	35	21	32	12	11
Mg(hx)				13		139		7	23
Li(hx)				225		685		16400	20750
Li(fusion)				227		2900		13366	17882
Na/K	1.17	43.74	5.81	19.80	72.80	<1	21.80	4.23	n.d.
Nb/Ta	0.26	0.69	0.93	1.07	0.39	0.89	9.05	0.24	0.29

low REE abundances (mostly between 20x and 1x chondritic) with sub-horizontal to heavy rare earth element-depleted patterns are typical of rare metal granites and associated pegmatites, (Cerny, 1991c; Raimbault et al, 1995; and Morteani et al, 1995; Preinfalk *et al.*, 2000). Despite the low REE abundances in the rocks/minerals, evidence of magmatic fractionation is given by the negative Eu anomalies in the pegmatites and muscovites.

G25 shows a rather horizontal REE pattern and slight inflections with minima corresponding to Nd, Gd, and Ho, which indicate a fractionation reflecting the lanthanide tetrad effect (Bau, 1996). The tetrad effect is more noticeable in white micas and the pegmatitic samples with some showing the V-shaped pattern with strong negative Eu anomaly. According to Zhao and Cooper (1993), V-shaped patterns indicate an extensive crystal fractionation involving feldspar, biotite and accessory REE minerals such as monazite and Zircon. The extremely negative EU-anomalies also correlate positively with the rare-element accumulation (Matheis, 1991). The REE-depleted and Rb-enriched nature of the G25 is also characteristic of peraluminous LCT (enriched in Rb, Be, Ga, Sn, Mn, Li, Cs, Nb, and Ta) granite intrusions (Cerny, 1991c).

Petrogenesis of the Rare Metal Pegmatites

The peraluminous pegmatite granites parental to the rare-metal pegmatites were formed by partial melting of mica-rich metasediments along the regional fracture zones as enunciated by Wright (1970), Matheis (1991) and Garba (2002). Although, the anatexis of the metasediments occurred at deeper levels below the currently exposed surface, evidence of shearing of the rocks at the earth's surface is provided by

Table 3: Trace elements in the pegmatite micas

Sample	unit	le7	le8	le14	le13	le18	l4	l10b	l8a	l9a	lz	lua	ls	7	Lc-19	lc20	lc20a	s1	k	ka	lc23	lc28	w	w2	r	lc30	lc31	lc32	lc33
F	ppm	2933	3197	3215	3220	2970	2745	3233	3131	2884	4351	2465	2106	617	1004	390	393	329	667	461	2841	2254	2616	2965	4751	940	1088	881	374
Ba	ppm	15	60	31	27	24	12	30	35	20	3	12	35	37	69	35	19	13	28	15	42	25	100	74	33	16	23	44	18
Bi	ppm	17	21	20	16	21	25	16	19	12	19	13	14	12	15	28	34	14	21	17	18	20	11	18	15	13	12	13	17
Ce	ppm	12	29	5	20	26	13	0	11	0	0	0	0	9	32	39	37	18	26	14	1	29	0	27	0	22	0	2	3
Cs	ppm	171	874	290	300	260	874	1008	1001	232	896	206	32	118	342	2120	2467	424	515	694	51	694	215	174	929	1499	63	116	346
Ga	ppm	167	163	163	153	167	168	158	164	162	174	155	203	200	166	156	164	159	141	176	174	197	154	145	162	97	147	161	138
La	ppm	0	57	15	20	23	54	44	45	10	36	9	0	0	47	98	108	17	14	36	0	40	32	0	49	71	0	2	15
Nb	ppm	181	116	178	165	182	131	119	113	185	144	178	218	256	187	75	55	146	151	160	211	143	193	200	127	64	223	190	135
Nd	ppm	9	17	4	14	10	6	0	7	2	0	2	0	1	9	12	7	7	13	2	1	7	0	11	0	9	4	5	7
Ni	ppm	7	27	17	18	21	23	24	24	21	23	13	8	9	18	27	31	18	21	16	11	20	10	6	17	11	16	18	24
Pb	ppm	18	47	23	21	30	46	45	45	19	44	17	6	4	25	47	64	18	26	22	7	33	10	9	33	27	9	18	19
Pr	ppm	3	15	6	8	8	14	12	12	6	11	6	1	3	11	19	22	6	6	9	2	11	7	3	11	13	2	4	5
Rb	ppm	4803	9410	5093	5578	5839	9139	9150	8803	5289	8873	4751	3133	2659	5638	7774	10182	4504	4941	5527	3471	7749	3284	2870	6803	4581	3645	4324	4248
Sn	ppm	217	471	275	336	357	525	533	597	274	681	239	61	266	397	681	649	295	364	394	87	437	139	118	902	539	147	271	219
Sr	ppm	15	50	41	18	19	24	27	25	17	24	16	11	13	18	25	32	16	18	19	11	23	15	12	21	15	17	17	16
Ta	ppm	44	58	45	50	63	53	59	71	71	71	41	27	46	72	502	425	75	85	115	31	51	62	64	120	183	39	31	140
Tl	ppm	22	43	24	27	26	40	39	39	25	40	21	17	15	31	52	64	24	29	28	16	35	18	17	36	33	18	21	25
W	ppm	71	51	65	71	237	39	33	28	38	77	25	84	65	40	86	89	34	36	48	56	52	40	49	91	56	114	32	61
Zn	ppm	421	1000	452	435	472	961	1023	911	416	800	379	231	131	217	111	123	142	242	142	187	341	249	163	453	47	161	177	112

mylonitization of the rocks within the fracture zone. High heat flow and shear movement along the regional fractures might have contributed significantly to the heat for the partial melting of the metasediments. An evolution of the magma as it ascends through the fractures would be toward an increase of the depolymerizing elements F, P and Al (Raimbault *et al.*, 1995). These elements would depress the liquidus of the magma, thereby reducing the viscosity of the melt while aiding both its flow along the fractures and the extreme fractionation of the elements. Roofward enrichment of rare elements (such as B, Li, Rb, Cs, Ti, Be, Mn, Sc, Y, H, REEs, Sn, Th, Mo, Ta>Nb, and W) can be expected (Cerny, 1991c) in the LCT granite-pegmatite suite. The magmatic evolution of the melts is towards an increase in the Al, Rb and Cs as documented in granites and pegmatites in the area while evolution from silicate-dominated melt to water-dominated B, F, Li and P-rich fluids is marked: petrologically by common accessory apatites and zoned tourmalines in the pegmatites' exocontact host schists, as well as deuteric alteration, sericitisation and albitization of feldspars in the granitic rocks parental to the mineralized pegmatites. The most complex of the pegmatites in this area belong to the amblygonite subtype of the classification of Cerny (1991b) enriched in P, F, Li, Rb, Cs, Be, Ta>Nb. Geochemically by low Mg, Ti, Ba, Zr and Ce, as well as low Ba/Rb, low K/Rb, Nb/Ta and K/Cs ratios in the pegmatites and the related granites as well as non-chondritic Y/Ho and Zr/Hf ratios, high negative Eu anomaly and lanthanide tetrad effect in the REE distribution patterns as documented in the pegmatitic granite G25.

As already noted by Bau (1996) the rare elements are transported as complexes in such fluid-rich melts. It is also clear from this area that there are two distinct rare metal generating events associated with the Pan African orogeny viz: Enrichment of the rare metals in the fluid-rich and deuterically altered main phase Pan African granite G18 and the spatially/genetically related pagmatites. This granite is the northernmost extension of Older Granites in this area and obviously represents marginal part of the batholith. It is characterized by a widespread strong alteration of plagioclase (a replacement of the plagioclase by perthite, and finally albitisation/sericitization). This deuteric alteration resulted from the late metasomatic fluids that mobilized the ore elements, Sn and Nb, and concentrated them in the granite. Such deuteric alteration is marked in the border zones and in the uppermost parts of granitic bodies (Pedrosa and Siga, 1987). Enhancement of the rare metals in the geochemically distinct G25 is fracture controlled and postdates the emplacement of the main phase Pan African granites.

The fact that the pegmatitic granite G25 was emplaced into fractures and again mylonitized after emplacement (see also Kuster, 1990), shows that these fractures were active before and after the emplacement and were probably reactivated during the emplacement of the Younger Granites during the Jurassic. Matheis and Caen Vachettee (1983) have documented biotite ages of 185/183Ma from south-western Nigeria. Basalt intrusions of 165Ma north of Zaria in northwestern Nigeria, which as inferred by Matheis and Caen Vachette (0p cit) indicate a regionally more extensive thermal event in association with the central Nigeria Younger Granites emplacement. The low P and F contents of the pegmatitic granite G25 (P_2O_5 0.068%, F35ppm Table 1) may be explained in that the elements which would have been concentrated at the roof of the granite, would at the current level of exposure of the granite have been lost to erosion. It appears, based on the low elevation of the G25 and the outcrop of NE-SW and NW-SE trending tourmalinites, which are most probably related to the pegmatitic granite intrusion in the area that some of the granites parental to the rare metal pegmatites are not yet exposed at the current erosional level (that is they are still lying buried). Similar views were very recently expressed by Garba (2002) who inferred from the studies of gold and rare-metal pegmatite occurrences in the Kushaka Schist belt of North-western Nigeria that the mineralizations are controlled by, postdates the Pan-African tectonism and related to NE-SW and NNE-SSW trending regional fractures. It is worth noting that Pan-African Sn-W bearing quartz-veins occur in the reactivated crust of the central Hoggar and are probably related to a 521Ma old peraluminous differentiated granitic plutons. Helba *et al.* (1996) also reported higher Ta/Nb ratios in the more differentiated albitized Eastern part of Nuweibi albite granite, in the Eastern Desert region of Egypt. ^{207}Pb/^{206}Pb ratios in zircon from the granite yielded 450 – 600Ma-a post-kinematic Pan-African age.

Discussion

Cerny (1991c) and Douce (1999) have observed that anatexis of mica-rich supracrustal sequences as well as ortho and para-lithologies of their basement in both the classical orogenic cycles and non-orogenic magmatic events give rise to peraluminous granites. These observations are corroborated by high intial ^{87}Sr / ^{86}Sr ratios (0.710 to 723) of the Pan African Older Granites as well as the post-kinematic intru- sives i.e. the Pan African Older Granites (Matheis and Caen-Vachette, 1983; Bertrand *et al.*, 1987), which strongly suggest crustal influence in the generation of the late Pan African peraluminous granites. Thus the Older Granites share some geochemical affinities with the LCT suites while the Younger Granites share geochemical affinities with the AYF suites as recognized by Cerny (1991c.)

Kuster (1990) observed that the late Pan African tectonic granites at Wamba (about 100km northeast of Nasarawa) are all subalkaline, peraluminous, and highly siliceous rocks with their peraluminosity more pronounced with increasing differentiation. The major elements Si, Al, K, and Na show only slight variations; only Na is enhanced toward the end of granite evolution. In the course of evolution from the biotite granites through biotite-muscovite granites, muscovite granites to the apogranites, there is a pronounced enrichment of Rb, Li, Cs, Sn, Nb, Mn, and P whereas B is only slightly enhanced. Strong depletion is evident for Ba, Sr, Zr, Y, La, and Ce together with Ti, Mg, Ca, and Fe. These results support the observation that the rare-metals are related to highly differentiated granitic magmas and represent strongly fractionated residual melts rich in silica, alumina, alkali elements, water and other volatiles, lithophile elements, and rare metals, (Cerny, 1991b and London, 1990).

Conclusions

It is conclude that anatexis of mica-rich supracrustal sequences as well as ortho and paralithogies of their basement give rise to peraluminous granites. These observation are corroborated by high initial ^{83} Sr /^{86}Sr, ratios (0.710 to 723) of the Pan African Older Granitesas well as the Younger Granites which strongly suggest crustal influence in the generation of the late Pan African peraluminous granites. Thus the Older Granites share some geochemical affinities with the LCT suite while the Younger Granites share geochemical affinities with the AYF suites.

In the course of evolution from the biotite granites through biotite-muscovite granites, muscovite granites to the apogranites, there is pronounced enrichment of Rb, Li, Sc, San, Nb, Mn and P whereas B is only slightly enhanced. Strong depletion is evident for Ba, Sr, Zr, Y, La, and Ce together with Ti, Mg, Ca, and Fe. These results support the observation that the rare metals are related to highly differentiated granitic magmas and represent strongly fractionated residual melts rich in silica, alumina, alkali elements, water and other volatiles, lithophile elements, and rare metals.

The NE-SW and NNE-SSW regional fractures controlling the mineralization are deep seated. Reactivation of the fractures in the Mesozoic probably influence the emplacement of the anorogenic Younger Granites and initiated the formation of Benue Trough in the Mesozoic period. The Benue Trough, which is parallel to the NE-SW trending belt of mineralized pegmatites hosts Pb-Zn-Cu-Fe sulphides, fluorites and barites.

The Afu Complex Younger Granites are more alkaline than the other granites as reflected in their lower A/N+K ratios; they have high Fe/Mg ratios and low TiO_2 contents which tend to agree with Lameyre and Bowden’s (1982) documentation of the Younger Granites of Nigeria as continental epeirogenic uplift granitoids (CEUG). Peraluminous granites are known, according to Cerny (1991c) to be parental to the granite-pegmatite suites. Trace element studies of the suites also show that extreme igneous fractionation aided by the fluids rich in B, P and F leads to the concentration of the rare metals in the residual melts that form the pegmatites.

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