UNIVERSIDADE DE BRASÍLIA
INSTITUTO DE GEOCIÊNCIAS

GEOCRONOLOGIA DE COMPLEXOS MÁFICO-ULTRAMÁFICOS: EXEMPLO DA SÉRIE SUPERIOR DO COMPLEXO DE NIQUELÂNDIA, BRASIL, E DO COMPLEXO KUNENE, ANGOLA

Osmar Samir Serrão Baxe

Dissertação de Mestrado

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Aos meus pais e amigos Helena e Baxe:

"Todo ponto de vista é apenas a vista de um ponto".

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Índice

Capítulo 3 45

Mesoproterozoic Magmatic ages of the Kunene Anorthosite Complex, SW Angola: ID-TIMS U–Pb and Sm-Nd isotopic evidence

Capítulo 4

Índice de Figuras e Tabelas

Capítulo 1

Capítulo 2

Capítulo 3

RESUMO

Esta dissertação reúne um conjunto de dados petrográficos, geoquímicos e geocronólogicos ID-TIMS U–Pb em zircão e de Sm-Nd em rochas da Série Acamadada Superior do complexo de Niquelândia no Brasil, bem como da Suíte Plutônica Kunene (SPK), no SW de Angola e NW da Namíbia. A similaridade de idades de cristalização Série Acamadada Superior do Complexo de Niquelândia de 1248 ± 23 Ma para (Pimentel et al. 2004) e da Suíte Plutônica Kunene com 1371 ± 2.5 Ma para (Mayer et al. 2004), bem como a similaridade litológica, gabro, troctolito, leucotroctolito e anortosito que caracterizam estes complexos motivaram esta pesquisa. Contudo, constatou-se que estes complexos são de natureza distinta e foram formados em ambientes distintos. A Série Acamadada Superior foi formada em um ambiente de crosta oceânica, similar ao N e T-MORB, enquanto que a Suite Plutonica Kunene foi formada a partir da coalêscencia de diversos pulsos magmáticos em ambiente extensional, anarogênico e intracontinental.

O Complexo de Niquelândia é constituído por duas intrusões distintas conhecidas como Série Acamadada Inferior (800 Ma) e Série Acamadada Superior datada neste estudo por ID-TIMS U–Pb em zircão de gabronorito em 1245 ± 4 Ma e 780 Ma constatado em titanita metamórfica de meta-anortosito. Os valores positivos de ε_{Nd} (T) indicam que a Série Acamadada Superior deriva de magma depletado e assinatura geoquímica similar ao N e T-MORB, sugerindo que a mesma foi formada em crosta oceânica. Estes novos dados contrastam com os apresentados para a Série Inferior de 800 Ma que apresenta valores de ε_{Nd} (T) negativos, indicando que a mesma foi fortemente contaminada por material crustal mais antigo.

Por outro lado, a Suíte Plutônica Kunene (SPK) no SW de Angola constituída essencialmente por uma suíte plutônica básica, caracterizada por intrusões gabro - anortosíticas e por uma suíte ácida constituída por “Granitos Vermelhos”.

Novos dados de ID-TIMS U–Pb em zircão de 1434 ± 2 Ma para leucogabro da intrusão Uanguembela, e 1403 ± 7 Ma para uma intrusão mangerítica ao sul de Otchindjau indicam que a suite básica é relativamente mais antiga que a suite ácida. Os valores negativos de ε_{Nd} (T) das rochas básicas (-0.30 to -12.42) e ácidas (-0.67 to -11.02) indicam que a SPK foi submetida a diferentes graus de contaminação crustal. Contudo, alguns plutons máficos apresentaram ε_{Nd} (T) positivo entre +0.67 to +1.12, sugerindo que estes magmas derivam de uma depletada.

A suíte plutônica ácida é constituída por granitóides tipo – A, conhecidos genericamente como “Granitos Vermelhos”, sugerindo que a Suite Kunene foi gerada em um ambiente intracontinental. A Suíte Plutônica Kunene é semelhante à Suíte Plutônica Nain (Labrador, Canadá) e apresenta potencial para hospedar depósitos magmáticos de Ni-Cu-PGE e Fe-Ti-V.

ABSTRACT

This work presents petrographic, geochemistry and geochronologic data ID-TIMS U–Pb in zircon and Sm-Nd isotopic data of the Niquelandia complex Upper Series in Brazil, and of Kunene Plutonic Suite (KPS) located in SW Angola and NW Namibia. The similarities of U-Pb ages between the Niquelandia complex Upper Series with 1248 ± 23 Ma (Pimentel et al. 2004) and Kunene Plutonic Suite with 1371 ± 2.5 Ma (Mayer et al. 2004) and also the litologic similarities, both composed mainly by gabbro, troctolite, leucotroctolite and anorthosite rocks were the main reasons for this research investigations to find any relationship between them. However, this study found out that these Niquelandia complex Upper Series are quite different from Kunene Plutonic Suite.

The age and tectonic significance of the Barro Alto, Niquelândia, and Cana Brava layered mafic–ultramafic complexes in Goias, central Brazil, have been a matter of debate and controversy during the last two decades. In many models, they have been considered to be representative of Paleoproterozoic intrusions metamorphosed during the Neoproterozoic, at approximately 0.79–0.76 Ga. In particular, the Niquelandia Complex has been described as formed by two different intrusions known as the Lower Series with 800 Ma and the Upper Series, of disputed age. New ID-TIMS U–Pb zircon data and Sm–Nd data presented in this study suggest that the Upper Series of Niquelandia Complex crystallized at 1245 ± 4 Ma and was metamorphosed around 780 Ma. The positive value of ε_{Nd} (T) indicates that the original magma of the Upper Series derived from a strongly depleted mantle. Anorthositic rocks have positive Eu anomaly and gabbroic rocks have REE patterns similar to MORB. These new data reinforce the idea that the Upper Series of the Niquelandia Complex are of oceanic nature and, therefore, considerably different from the Lower Series which present negative ε_{Nd} (T) values and trace element characteristics indicating extensive contamination with continental crust.

The Kunene Plutonic Suite (KPS) in SW Angola and NW Namibia is one of the largest anorthositic complexes in the world, underlying an area of approximately 18.000 km^2. It comprises a basic plutonic suite and an acid plutonic suite. The basic suite is mainly formed by gabbro-anorthositic intrusions and layered mafic bodies of different sizes. The acid suite includes mainly A-type "red granites". This study presents new ID-TIMS U-Pb and Sm-Nd data as well as geochemistry and petrologic data for gabbroic, anorthositic and granitic rocks of the KPS. One sample of a layered gabbroic intrusion (Uanguembela) of the Otchinjau-Oncócua region was dated at 1434 ± 2 Ma. A mangeritic intrusion exposed to the east of the Otchindjau layered mafic intrusion yielded the U-Pb age of 1403 ± 7 Ma. These ages are slightly older than the age of ca. 1.37 Ga reported previously in the literature, suggesting that the Kunene Complex is formed by various plutons with different ages, indicating the existence of distinct magmas which underwent distinct cooling histories and crustal assimilation in multi-pulse gabbroic and anorthositic intrusions.

The dominantly negative ε_{Nd} (T) values of the basic (-0.30 to -12.42) and acid rocks (-0.67 to -11.02) indicate that the KPS original mafic magmas has been contaminated by crustal material. However, some mafic plutons yielded positive ε_{Nd} (T) between +0.67 to +1.12 which indicates that the magma of some mafic intrusions within the KPS derived from depleted mantle. The emplacement of the Kunene Complex requires an extensional setting and a significant thermal anomaly at the margin of the Congo Craton during the Mesoproterozoic. The Kunene Plutonic Suite resembles the large Proterozoic anorthosite plutonic suites such as the Nain Plutonic Suite (Labrador, Canada) and is, therefore, of great potential for Ni-Cu-PGE and Fe-Ti-V economic magmatic deposits.

Capítulo 1

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1. Introdução

1.1. Objetivos

A presente dissertação aborda e discute dados petrológicos, geoquímicos e geocronológicos obtidos em rochas da Série Acamadada Superior do Complexo de Niquelândia, no Brasil central, e em rochas do Complexo Kunene, localizado no sudoeste de Angola e NW da Namíbia.

O Complexo de Niquelândia faz parte de um conjunto de três grandes intrusões máfica-ultramáficas no estado de Goiás, Brasil central, nomeadamente os complexos de Barro Alto e Canabrava formando um cinturão de 350 km de extensão na direção NNE. Os complexos foram metamorfizados em fácies granulito para anfibolito (Ferreira Filho e Naldrett, 1993). Os mesmos estão geologicamente inseridos na Faixa Brasília, da Província Tocantins. O Complexo de Niquelândia é formado por duas intrusões distintas, a Série Acamadada Inferior (SAI) constituída por rochas máfica-ultramáficas, e pela Série Acamadada Superior (SAS) constituída essencialmente por gabro e anortosito, separadas entre si por milonitos ao longo da falha subvertical (NNE) e teriam sido tectonicamente justapostas no final da orogênese Brasiliana (Ferreira Filho et al., 1995, 1998b).

Uma importante descontinuidade gravimétrica separa um alto gravimétrico à oeste e um baixo gravimétrico à leste paralelo aos três complexos (Marangoni et al. 1995).

O Complexo Kunene é um dos maiores complexos gabro-anortosíticos do planeta, localizado na região SW de Angola e NW da Namíbia, e cobre uma área de aproximadamente 18.000 km^2. Geologicamente está inserido na margem sul do Cráton do Congo sendo formado por distintas intrusões gabro-anortosíticas associadas com corpos graníticos, em menor escala (Carvalho e Alves, 1990).

O presente trabalho teve como principal objetivo investigar a Série Acamadada Superior (SAS) do Complexo de Niquelândia, no Brasil, e do Complexo Kunene, em Angola a fim de caracterizar suas idades de cristalização por meio de análises ID-TIMS U-Pb, a origem, evolução e nível de contaminação crustal das mesmas partir de dados isotópicos de Sm-Nd, diagnosticar a natureza geoquímica e petrográfica, definir o ambiente tectônico em que os mesmos foram formados e finalmente propor um modelo evolutivo para o magmatismo destes complexos.

1.2. Justificativa do tema

A génese dos complexos anortosíticos e a razão pela qual foram gerados predominantemente durante o Proterozóico são questões pertinentes e interessantes na Geologia. Vários estudos referem-se a essas questões como "o problema dos anortositos". As dúvidas a respeito de sua formação referem-se ao fracionamento, alojamento e cristalização dos magmas, bem como ao regime tectônico geral nos quais esses processos ocorreram.

O Complexo de Niquelândia tem sido alvo de vários estudos, intenso debate científico e controvérsias durante as duas últimas décadas. O mesmo apresenta extrema importância geotectónica, como também pelo potencial económico com depósitos de Ni-Cu-PGE. Segundo Girardi et al. (1986) o Complexo de Niquelândia representaria uma única intrusão na Faixa Brasília. Ferreira Filho et al. (1994), Suita et al. (1994), Correia et al., (1996, 1997, 1999) apresentaram idades U-Pb e Re-Os entre 1.6 e 2.0 Ga para os complexos de Niquelândia e Barro Alto. Brito Neves et al. (1995) interpretaram os mesmos como parte de um sistema de rifte continental paleoproterozóico. Correia et al. (1996) obtiveram idades de SHRIMP em núcleos de zircão datados em 1.99 Ga, e análises de Re-Os em rocha total de 2.07 Ga. Posteriormente, Correia et al. (1997, 1999) apresentam idades U-Pb e Sm-Nd de 1.26-1.3 Ga para as rochas da Série Superior do Complexo de Niquelândia. Contudo, Ferreira Filho e Pimentel (2000) e Pimentel et al., (2004) mostram que o Complexo de Niquelândia constitui-se de dois sistemas magmáticos distintos e tectonicamente justapostos no final da orogênese Brasiliana, sendo a Série Acamadada Superior (US) mais antiga com 1.35 Ga, e a Série Acamadada Inferior (LS) mais recente datada em 800 Ma e intrudiu na crosta continental e foi fortemente contaminada por material siálico mais antigo (εNd(T) de -5.8, e grãos zircão herdados com idades entre 1.0 e 1.9 Ga).

Este estudo é um incremento ao debate de mais de duas décadas que tem sido alvo o Complexo de Niquelândia e a relação entre as Séries Acamadada Superior (US) e Inferior

(LS), reforçando o entendimento do magmatismo, cronologia e evolução tectônica deste complexo.

O Complexo Kunene ocorre na margem sul do Cráton do Congo, sendo constituído por predominantemente por rochas básicas de composição variando entre gabro, leucotroctolito e anortosito formando plutons maciços e corpos acamadados, associados a rochas ácidas denominadas genericamente de "granitos vermelhos". Contudo, existem várias questões em aberto quanto à cronologia e evolução magmática deste complexo.

Segundo Carvalho e Alves (1990; 1993) trata-se de um complexo acamadado de grande porte, semelhante ao Complexo Bushveld na África do Sul, onde estariam expostas principalmente as porções superiores e mais fraccionadas da câmara magmática. Trabalhos mais recentes de Mayer et al. (2004), Slejko et al. (2002) contudo, sugerem que o Complexo Kunene corresponde a um complexo anortosítico maciço. Druppel et al. (2007) obtiveram idades de U-Pb em zircão de 1385 ± 25 Ma obtidas em anortosito e de 1376 ± 2 Ma obtidas em rochas félsicas associadas, no extremo sul deste complexo, região de Zebra Mountains, NW da Namíbia, e sugerem que as duas suites são coevas. Características geoquímicas dos anortositos (alto Al2O3, CaO, Sr e Eu, intermediário até alto valores de Mg 0.37-0.74, e εNd (T) positivo +3.0 to +1.0, e razão Sr de 0.7028-0.7041) indicam que os mesmos derivam do fraccionamento de líquidos basáslticos.

A interpretação do Complexo Kunene como complexo acamadado ou anortosítico maciço é de grande importância, tanto para a avaliação do potencial metalogenético, quanto para o entendimento da evolução tectônica da região.

A similaridade entre as idades de cristalização dos magmas da Série Acamadada Superior do Complexo de Niquelândia com 1248 ± 23 Ma (Pimentel et al. 2004) e do Complexo Kunene com 1371 ± 2.5 Ma (Mayer et al. 2004), bem como a similaridade litológica, ambas apresentam relativa abundância de gabro, leucotroctolito e anortosito foram factores críticos que motivaram esta pesquisa, a fim de constatar alguma relação entre as mesmas.

1.3 Metodologia geral do trabalho

O trabalho foi dividido em várias etapas. Primeiramente realizou-se a compilação e revisão bibliográfica crítica das áreas de estudo. Posteriormente foram feitas campanhas de campo para reconhecimento e amostragem de rochas ígneas em ambos os complexos para análises laboratoriais. A amostragem foi devidamente georreferenciada com uso de GPS. Finalmente foram realizados o tratamento e a interpretação dos dados obtidos.

No Brasil, a campanha de campo foi realizada na Série Acamadada Superior do Complexo de Niquelândia. A amostragem foi feita na região da Serra dos Borges, entre as cidades de Niquelândia e Indaianópolis - GO.

Em Angola, a amostragem foi realizada nas porções centro e sul do Complexo Kunene, mais especificamente na região de Oncócua e Otchindjau.

As análises petrográficas foram realizadas no Instituto de Geociências da Universidade de Brasília, por intermédio do microscópio em lâminas delgadas, a fim de determinar a mineralogia e textura das rochas.

A partir do estudo petrográfico, foram selecionadas amostras para as análises geoquímicas realizadas no Laboratório Acme, no Canadá.

As análises isotópicas de Sm-Nd e de ID-TIMS U-Pb foram realizadas no laboratório de Geocronologia da Universidade de Brasília.

1.4. Localização e acesso

O Complexo de Niquelândia está localizado na porção central do estado de Goiás entre os meridianos 14° 30´S e 14° 00´S e os paralelos 48° 42´W e 48° 22´W, a cerca de 200 km ao norte de Brasília-DF. A principal via de acesso ao Complexo de Niquelândia é a GO 080, passando por Dois Irmãos e Padre Bernardo (Fig. 1.1).

O Complexo de Niquelândia, mais especificamente a série acamadada inferior, contém importantes depósitos de níquel supergênico e depósitos de EGP, cromo e cobalto atualmente explorados pela empresa CNT - Companhia Níquel Tocantins.

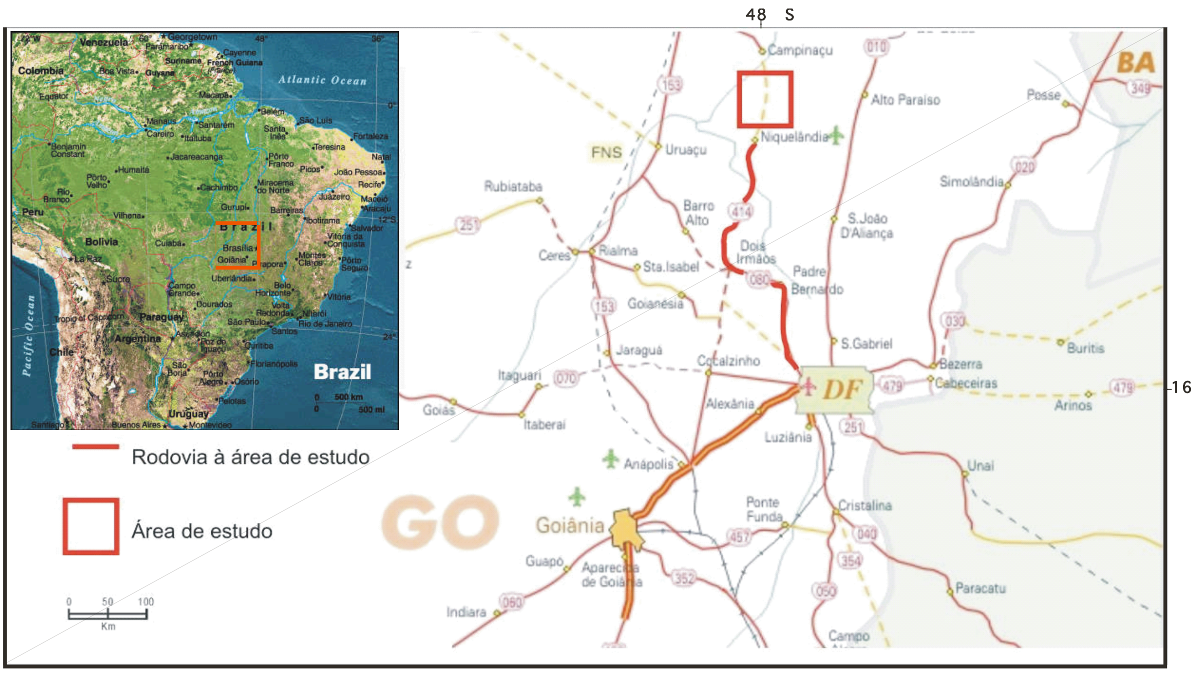

Figura 1.1 – Mapa de localização e vias de acesso ao Complexo de Niquelândia.

O Complexo Kunene é um dos maiores complexos gabro - anortosíticos do mundo e está localizado na região sudoeste de Angola e noroeste da Namíbia. Ocorre alongado na direção norte-sul, cobrindo uma área de aproximadamente 15000 km^2 (300 km x 50 km) (Fig. 1.2). A principal via de acesso parte da cidade do Lubango, capital da província da Huila e localizada a aproximadamente 70 km da Suíte Plutônica Kunene. As cidades de Oncócua, Chitado e Cahama são também pontos de apoio a esta Suíte.

Atualmente existem mais de 10 pedreiras que exploram granito e anortosito como rocha ornamental, porém, o complexo tem potencial para conter depósitos magmaticos de Ni-Cu-EGP, bem como depósitos de óxidos de Fe-Ti-V.

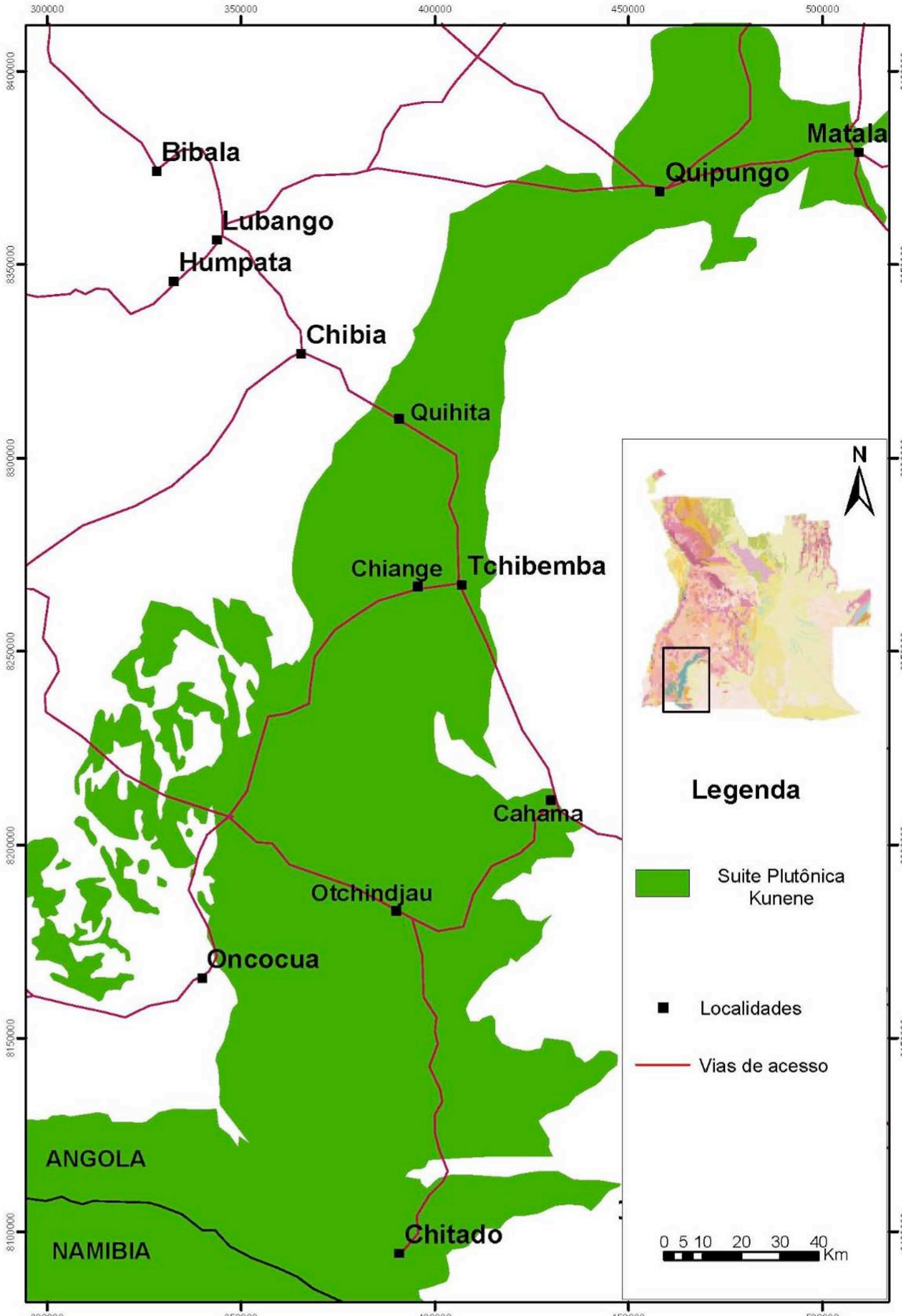

Figura 1.2. Mapa de localização e vias de acesso ao Complexo Kunene.

Capítulo 2

Este Capítulo apresenta os resultados isotópicos, geoquímicos e petrológicos referentes à Série Superior do Complexo de Niquelândia. As informações serão apresentados na forma de artigo completo, que será submetido ao periódico *Journal of South American Earth Sciences*, com o título: **Mesoproterozoic Magmatic and Neoproterozoic Metamorphic Ages of the Upper Series of the Niquelândia Complex, in central Brazil: further ID-TIMS U–Pb and Sm–Nd isotopic evidence**.

Mesoproterozoic Magmatic and Neoproterozoic Metamorphic Ages of the Upper Series of the Niquelândia Complex, in central Brazil: further ID-TIMS U–Pb and Sm–Nd isotopic evidence

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Abstract

The age and tectonic significance of the Barro Alto, Niquelândia, and Cana Brava layered mafic–ultramafic complexes in Goiás have been a matter of debate and controversy during the last two decades. In some models, they have been considered to be representative of Paleoproterozoic intrusions metamorphosed during the Neoproterozoic, at approximately 0.79–0.76 Ga. In particular, the Niquelândia Complex has been described as formed by two different intrusions known as the Lower Series (800 Ma) and the Upper Series, of disputed age. New ID-TIMS U–Pb zircon data and Sm–Nd data presented in this study indicate that the Upper Series of Niquelândia Complex crystallized at 1245 ± 4 Ma and was metamorphosed around 780 Ma. The positive value of ε_{Nd} (T) indicates that the original magma of the Upper Series derived from a strongly depleted mantle. Anorthositic rocks have positive Eu anomaly and gabbroic rocks have a REE pattern similar to MORB. These new data reinforce the concept that the Upper Series of the Niquelândia Complex is associated to an environment of oceanic crust and, therefore, considerably different from the Lower Series which presents negative ε_{Nd} (T) values and trace element characteristics indicating extensive contamination with continental crust.

Keywords: Niquelândia; Layered complex; Zircon U–Pb; Sm–Nd; Upper Series

2.1. Introduction

The three large layered mafic–ultramafic complexes of Barro Alto, Niquelândia, and Cana Brava form a 350 km long discontinuous belt, representing one of the most outstanding and controversial geologic features of the Neoproterozoic Brasília Belt, in central Brazil. To the west they are bordered by bimodal volcanosedimentary successions known as the Juscelândia, Indaianópolis, and Palmeirópolis sequences, respectively, together with their plutonic counterparts, including gabbro, leucogabbro, anorthosite, and granite intrusions. A west dipping mylonite zone marks their eastern limit. (Fig. 2.1).

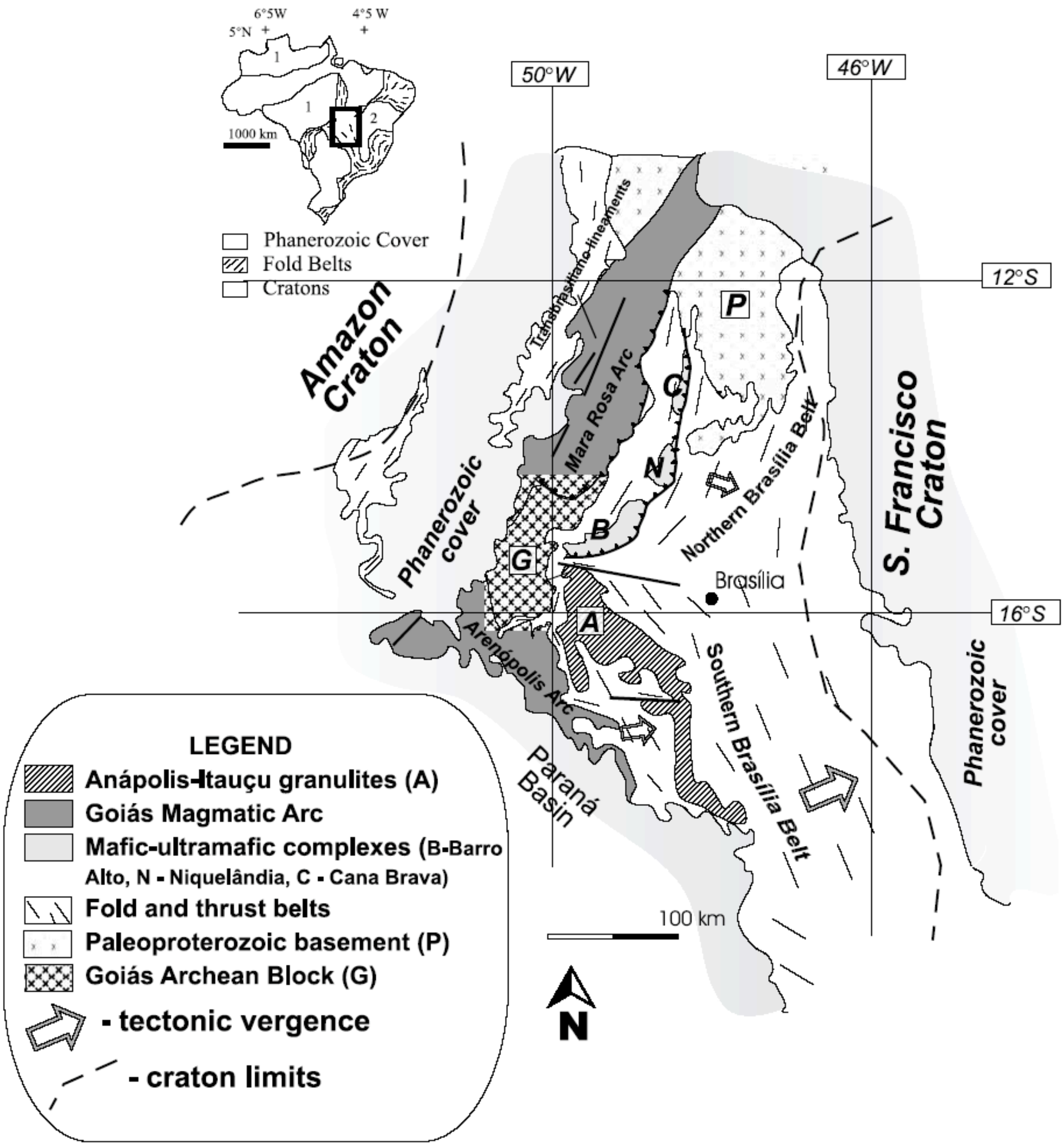


Figure 2.1. Regional sketch map of the Brasília Belt, in the eastern part of the Tocantins Province.

During the last two decades these complexes have been intensely studied due to their metallogenetic potential and tectonic significance. Distinct tectonic models have been proposed and advocate that they represent either fragments of Archean or Paleoproterozoic oceanic crust (Danni et al., 1982; Moores, 2002), or Neo- to Paleoproterozoic rift-related layered intrusions (e.g. Ferreira Filho et al., 1994; Brito Neves et al., 1995; Correia et al., 1996; Pimentel et al., 2004). Original igneous stratigraphy of the complexes has been partially disrupted by intense deformation associated with high-grade heterogeneous metamorphism that preserved some igneous textures and structures (Danni et al., 1982; Ferreira Filho et al., 1992). Several geological similarities among the three complexes have been used to suggest that they originally constituted a single continuous magmatic structure that was tectonically disrupted (Ferreira Filho, 1998). More recently, Pimentel et al. (2004) suggested that these complexes are made of two distinct layered intrusions emplaced during the Mesoproterozoic (ca. 1.25 Ga) and Neoproterozoic (ca. 0.80 Ga).

Field and petrological studies supported by conventional and SHRIMP U–Pb and Sm–Nd geochronology of the Niquelândia complex, have indicated that they have been metamorphosed at approximately 760–780 Ma (U–Pb ages of metamorphic zircon crystals) during progressive metamorphism from granulite facies in the east to amphibolite facies in the west (Ferreira Filho et al., 1994, 1998a; Pimentel et al., 2004). Garnet Sm–Nd and rutile U–Pb ages also indicate a younger metamorphic event, at approximately 610 Ma (Ferreira Filho et al., 1994; Ferreira Filho and Pimentel, 2000).

Conventional and SHRIMP U–Pb, Rb–Sr, Sm–Nd, and Re–Os ages for these intrusions have generated debate regarding the age of igneous crystallization of the complexes. Dates vary from approximately 2.0 to 0.8 Ga (Fuck et al., 1989; Fuji, 1989; Ferreira Filho et al., 1994; Suita et al., 1994; Correia et al., 1996, 1997, 1999; Ferreira Filho and Pimentel, 2000; Pimentel et al., 2004, 2006) and have been interpreted in various ways. Available geochronological data for rock units comprising the three complexes and associated volcanosedimentary sequences are summarized in Table 2.1. These issues have been recently studied by Pimentel et al. (2004, 2006). Based upon ID-TIMS and SHRIMP zircon data the authors considered that the age of high-grade metamorphism (ca 770 Ma) and the magmatic crystallization of the Lower Series (LS) (ca 797 Ma) are now properly dated. The age of magmatic crystallization of the Upper Series (US) (ca 1250 Ma) was constrained by Sm-Nd data (Ferreira Filho and Pimentel, 2000) and SHRIMP U–Pb data of Pimentel et al. (2004) for mylonitic rocks within the US. The latter are suggestive of a Mesoproterozoic (ca. 1.27 Ga) age for that series, despite the discordant nature of the analytical data.

The highly different magmatic ages of the US and LS suggested by Pimentel et al. (2004, 2006) were recently challenge by Girardi et al. (2006). These authors presented new data suggesting similar Neoproterozoic ages for both series. In this study, new ID-TIMS U–Pb geochronological data support that the US of the Niquelândia complex crystallized during the Mesoproterozoic at ca. 1.25 Ga, and was metamorphosed at ca. 780 Ma.

2.2. Geological Setting: Barro Alto, Niquelândia, and Cana Brava Complexes

The Brasília Belt, in central Brazil, is a Neoproterozoic collisional orogen formed between the Amazon and São Francisco cratons during the Brasiliano Orogeny (Fuck et al., 1994; Pimentel et al., 2000). Important constituents of the Brasília Belt (Figure 1.1) are: (i) sedimentary and metassedimentary sequences deposited and deformed along the western margins of the São Francisco Craton, (ii) a Neoproterozoic juvenile arc (the Goiás Arc) in the western portion of the belt, (iii) the Goiás Massif, exposed in the central part of the Brasília belt mainly comprising the Goiás Archean Block, made of granite-greenstone terrains, and the three layered complexes of Barro Alto, Niquelândia, and Cana Brava complexes (Fig. 2.1), and (iv) a NNW-oriented metamorphic complex of Neoproterozoic granulites and granites known as the Anápolis-Itauçu Complex (for recent data, see Piuzana et al., 2003) (Fig. 2.1). Final ocean closure and continental collision happened at approximately 630 Ma (Pimentel et al., 2000).

An important gravimetric discontinuity separating a gravimetric high in the west and a gravimetric low in the east runs parallel to the complexes (Marangoni et al., 1995; Fig. 2.1). This discontinuity has been used as evidence to suggest that all geological/geotectonic units, including the three large complexes, the Goiás Archean Block, and the Goiás Magmatic Arc to the west, are allochthonous (Pimentel et al., 2000).

To the west of the complexes is the Rio dos Bois fault, a west-dipping thrust representing another important tectonic boundary running in a NNE direction, parallel to the gravimetric anomaly (Fig. 2.2), separating rocks of the Goiás Magmatic Arc in the west from older Paleoproterozoic sialic rocks and metasedimentary in the east. The most important tectonic features across the Niquelândia Complex are high-grade N-N10E ductile shear zones with mylonitic textures and structures (Ferreira Filho et al., 1992). The deformation is heterogeneous as indicated by the highly deformed and metamorphosed zones adjacent to areas presenting poorly developed foliation or rocks completely preserved from deformation exhibiting primary texture and mineral chemistry.

On the basis of field and petrological data, the Barro Alto and Niquelândia complexes have been interpreted as composite bodies comprising two distinct intrusions separated from each other by an important shear zone (Ferreira Filho et al., 1995, 1998a). Their eastern sectors (or southeastern, in the case of the Barro Alto complex) consist of mafic–ultramafic rocks made of several cyclic units comprising dunite, harzburgite, websterite, and gabbronorite, whereas in the western portion, the rocks are mainly mafic and include interlayered leucotroctolite, anorthosite, gabbro, and minor pyroxenite (for detailed descriptions of the geology and petrology of the mafic–ultramafic sequences, see Ferreira Filho et al., 1992, 1998b) (Figures. 2.2 and 2.3).

The mafic rocks of the US of the Niquelândia and Barro Alto complexes are in tectonic contact to the west with metavolcanic and metasedimentary rocks of the Indaianópolis and Juscelândia sequences, respectively. The igneous stratigraphy and crystallization sequence within the three complexes are very similar to each other (Fig. 2.2). In the Cana Brava complex, the US seems to be missing, possibly due to tectonic obliteration, and rocks corresponding to the LS are in direct tectonic contact with the metavolcanic rocks of the Palmeirópolis sequence. The volcanosedimentary sequences are bimodal, with amphibolites and felsic metavolcanic rocks associated with fine-grained detrital metasedimentary rocks, metacherts and minor quartzite. Small, highly tectonized granitic intrusions are also exposed within the supracrustal sequence. Recent U-Pb SHRIMP zircon ages, Nd isotopic data and trace element geochemistry demonstrate that the Juscelândia sequence, associated with the Barro Alto Complex, is an approximately 1.26–1.28 Ga rift sequence, with metabasalts at the base showing evidence of contamination with Paleoproterozoic continental crust and grading upwards to tholeiitic metabasalts with strongly positive ε_{Nd} (T) +5.0 values, similar to mid-ocean ridge basalts (MORB) (Moraes et al., 2003, 2006).

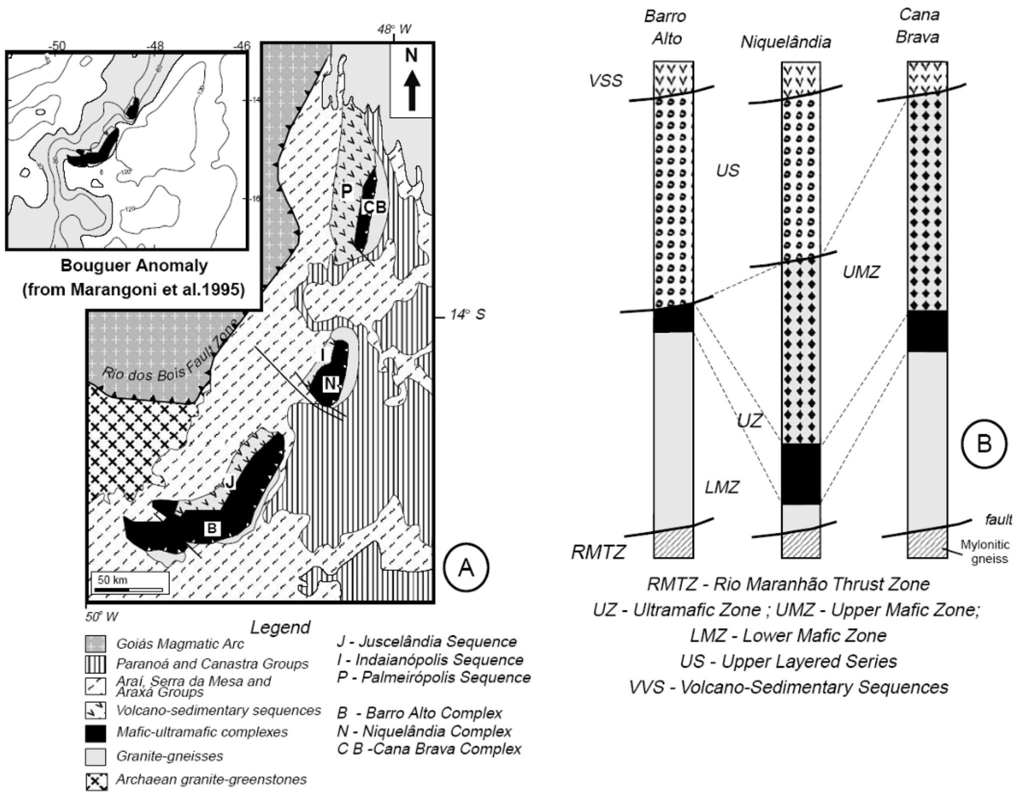


Figure 2.2. The Barro Alto, Niquelândia, and Cana Brava mafic–ultramafic complexes in central Brazil. (A) Geological sketch map, (B) comparative stratigraphic/structural columns of the three complexes. The inset map is a Bouguer anomaly map from Marangoni et al. (1995).

On the basis of mineral assemblages of the metamorphosed mafic rocks, Ferreira Filho et al. (1992, 1998a) identified three metamorphic zones from west to east: amphibolite zone (pl + hbl + cpx + grt), amphibolite–granulite transition zone (pl + hbl + opx + cpx), and granulite zone (opx + cpx + pl). U-Pb zircon ages combined with geothermobarometry and mineral stability data indicate P–T conditions of peak metamorphism at approximately 770 Ma and 6–8 kbar in the amphibolite zone and temperatures higher than 800 ºC in the granulite zone. A nearly isobaric cooling trajectory followed peak metamorphism, suggesting cooling in the absence of tectonic unroofing. The timing of these two metamorphic events is indicated by the available geochronological data. The older event, at approximately 770–780 Ma, is constrained by SHRIMP and conventional U–Pb analyses on metamorphic zircon grains (Ferreira Filho et al., 1994; Suita et al., 1994; Correia et al., 1996). This age is considerably older than the approximately 610–630 Ma event, which is recorded across the Brasília Belt (Pimentel et al., 2000). A younger metamorphic event at approximately 610 Ma is indicated by rutile U–Pb and garnet Sm–Nd isotopic data (Ferreira Filho et al., 1994; Ferreira Filho and

Pimentel, 2000) and interpreted as coeval with the eastward thrust that uplifted the complex at the end of the Neoproterozoic.

The western part of the UMZ is dominated by hornblende gabbronorite, within which several small bodies of dioritic, tonalitic and granitic rocks are found (Figs. 2.3 and 2.4). These are interpreted as late-stage crystallization products produced by intense contamination of the mafic magma with Paleo- to Mesoproterozoic country rocks.

Complex	Unit	Data interpreted as igneous crystallization ages	Data interpreted as metamorphic ages
Barro Alto	Juscelândia volcano-sedimentary sequence	1266 ± 17 Ma $_{2,6}$ (granite)	782 Ma$_{3,7}$ 740–760 Ma$_{5,10}$ 1.29–1.30 Ga$_{3,7}$
	Upper Series gabbro	1.29–1.35 Ga $_{2,6}$	-
	Lower Series mafic rocks	1.72–1.73 Ga $_{2,6}$	770–790 Ma$_{2,6}$ 796 ± 20 Ma$_{3,7}$
Niquelândia	Indaianópolis volcano-sedimentary sequence	-	1.3 Ga3,7 (metavolcanic rock)
	Upper Series gabbro	1.35 Ga (ε_{Nd}(T) = + 4.1, +4.8) $_{4,9}$	
	Lower series mafic rocks	1.60 Ga 2,11; 1.99 Ga $_{3,8}$; 2.07 Ga $_{1,8}$ 799 ± 6 Ma. (εNd(T)= -6.5) 759 ± 65 Ma and (εNd(T)= -8.8) $_{12}$	790 Ma $_{2,11;}$ 778 Ma $_{3,8;}$ 610 ± 32 Ma $_{5,9}$
Cana Brava	Lower series amphibolite	-	770 Ma $_{5,7}$

Table 2.1. Available geochronological data for the Niquelândia, Barro Alto and Cana Brava complexes, and associated volcano-sedimentary sequences *Note.* 1: Re–Os whole-rock isochron, 2: Conventional U–Pb age, 3: SHRIMP U–Pb age, 4: whole-rock Sm–Nd isochron, 5: Sm–Nd garnet age, 6: Suita et al. (1994), 7: Correia et al. (1999), 8: Correia et al. (1997), 9: Ferreira Filho and Pimentel (2000), 10: Moraes et al. (2003, 2006), 11: Ferreira Filho et al. (1994), 12: Pimentel et al., (2006).

2.3 The Niquelândia Complex

The Niquelândia Complex displays the best exposed and studied stratigraphic sequence of the three large layered intrusions in central Brazil and has been described in detail by Ferreira Filho et al. (1992). It is limited to the south and to east by an important curved shear zone dipping to the N and W (Rio Maranhão thrust zone, Fig. 2.3).

The LS is divided into a lower mafic zone (LMZ) dominated by gabbronorite with minor pyroxenite; an ultramafic zone (UZ) comprising cyclic units with dunite, harzburgite, websterite, and orthopyroxenite; and an upper mafic zone (UMZ) dominated by gabbronorite with intercalations of norite, websterite, and minor harzburgite (Fig. 2.3).

The LMZ lies on the eastern portion of the intrusion and is considered to be a border group; this interpretation is supported by the stratigraphic position of the LMZ, as well as the relatively more primitive nature of its gabbroic rocks compared with those of the UMZ. The UZ has a very characteristic stratigraphic succession, with dunite and minor harzburgite forming the base of the sequence and websterite layers becoming progressively more abundant toward the top (west). The composition of the most magnesian olivine (Fo 92–93) indicates the primitive nature of the primary magma (Rivalenti et al., 1982; Ferreira Filho et al., 1998b); and the UMZ displays a trend of progressive Fe enrichment in pyroxene, accompanied by strong enrichment in incompatible trace elements, which is compatible with an open system behaviour involving both crystal fractionation and contamination of the original magma with sialic country rocks Ferreira Filho et al., 1998b). Extreme contamination has generated facies of dioritic/gabbrodioritic compositions that underlie small areas in the westernmost part of the UMZ. This feature is similar to the small dioritic bodies also found in the upper stratigraphic portions of the LS of the Barro Alto and Cana Brava complexes.

The US is formed of leucotroctolite, anorthosite, gabbro, and minor pyroxenite. Pyroxenes lack the strong Fe enrichment that, together with the presence of Fe–Ti oxide layers, suggests crystallization of the US at higher oxygen fugacity conditions compared with the LS. Trace element data indicate a distinct parental magma for the US, with a much more primitive nature than that of the LS (Ferreira Filho et al., 1998b). Sm–Nd isotopic data (Ferreira Filho and Pimentel, 2000) of gabbros and coarse-grained amphibolites give isochron ages of approximately 1.35 Ga and ε_{Nd} (T) values between 4.8 and 4.1, which indicate the depleted nature of the mantle source, whereas the SHRIMP U–Pb method indicates a younger age of approximately 1248 Ma.

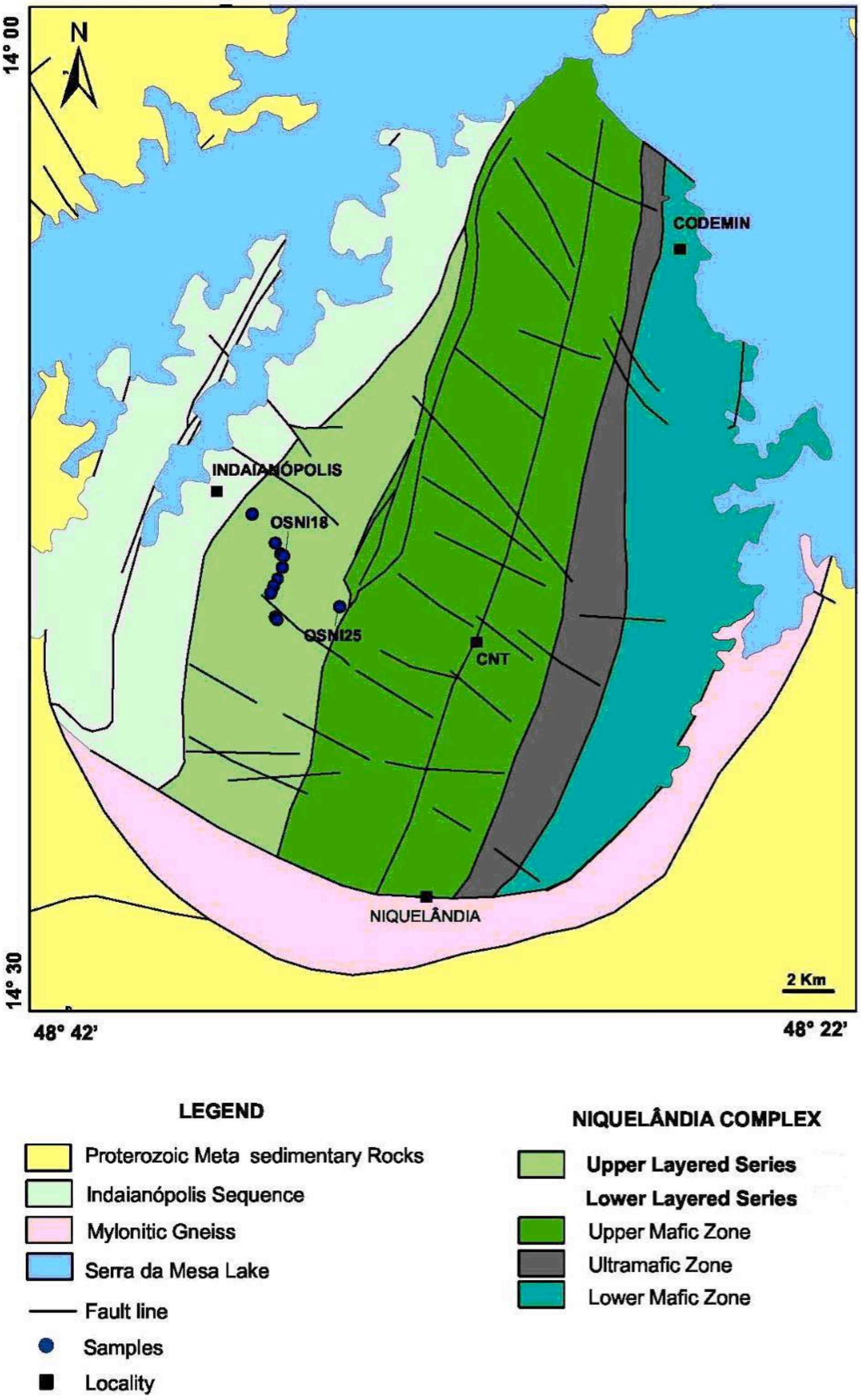


Figure 2.3. Geological sketch map of the Niquelândia Complex (from SIG de Goiás, 2000).

2.4. Analytical procedures

Zircon and titanite concentrates were extracted from samples OSNI18 and OSNI25 using conventional gravimetric (DENSITEST®) and magnetic (Frantz isodynamic separator) techniques at the Geochronology Laboratory of the University of Brasília. Final purification was achieved by hand picking using a binocular microscope. Zircon grains were selected for single-grain ID-TIMS analyses. They were dissolved in concentrate HF and HNO_3 (HF:HNO_3 = 4:1) using microcapsules in Parr-type bombs. A mixed ^{205}Pb–^{235}U spike was used. Chemical extraction followed standard anion exchange techniques, using Teflon microcolumns, after procedures modified from Krogh (1973). Pb and U were loaded together on single Re filaments with H_3PO_4 and Si gel, and isotopic analyses were carried out using a Finnigan MAT-262 multicollector mass spectrometer equipped with secondary electron multiplier-ion counting at the Geochronology Laboratory of the University of Brasília. Procedural blanks for Pb, at the time of analyses, were better than 10 pg. PBDAT (Ludwig, 1993) and ISOPLOT-Ex (Ludwig, 2001) programs were used for data reduction and age calculation. Errors for isotopic ratios shown in Table 2 are 2σ. Sm–Nd isotopic analyses followed the method described by Gioia and Pimentel (2000). Whole-rock powders (~50 mg) were mixed with ^{149}Sm–^{150}Nd spike solution and dissolved in Savillex capsules. Sm and Nd extraction of whole-rock samples followed conventional cation exchange techniques, using Teflon columns containing LN-Spec resin (HDEHP = di-ethylhexil phosphoric acid supported on PTFE powder). Sm and Nd samples were loaded on Re evaporation filaments of double filament assemblies, and the isotopic measurements were carried out on a multicollector Finnigan MAT 262 mass spectrometer in static mode. Uncertainties for Sm/Nd and $^{143}Nd/^{144}Nd$ ratios are better than ±0.2% (σ2) and ±0.005% (σ2), respectively, based on repeated analyses of international rock standards BHVO-1 and BCR-1. $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd$ of 0.7219, and the decay constant used was 6.54×10^{-12} y^{-1}. T_{DM} values were calculated using DePaolo's (1981) model.

The samples for geochemical analyses were cleaned and weathered and veined surfaces were cut off. The rocks were crushed and milled to a very fine powder. Major elements and Ni and Sc (ppm) were made by ICP-ES and trace element analyses were made by ICP-MS at ACME Laboratories in Vancouver, Canada.

2.5. Petrography and Geochemistry

The Niquelândia Upper Series consists mainly of anorthosite, olivine gabbro, leucotroctolite, and their metamorphic equivalents, meta-anorthosite and amphibolite. Igneous rocks consist of plagioclase and olivine cumulates or plagioclase, olivine and cpx cumulates, with variable amounts of intercumulus opx and amphibole. The samples selected for petrographic, geochemistry and isotopic analyses were collected southeastward of Indaianópolis in the Serra dos Borges region (Figure 2.3)

Sample OSNI17 is a dark grey coarse-grained gabbronorite. It consists of cumulus plagioclase (60-70 %) and cpx (20-30%) with large intercumulus Opx (10-20 %). Plagioclase occurs as tabular and subhedral crystals associated to anhedral Cpx. Opx occurs as large (up to 1 cm) oikocrysts enclosing plagioclase and cpx. Exsolution lamellae (unmixing) occur in cpx and opx. Magnetite and hornblende (2 %) occur as accessory phases (Fig. 2.4).

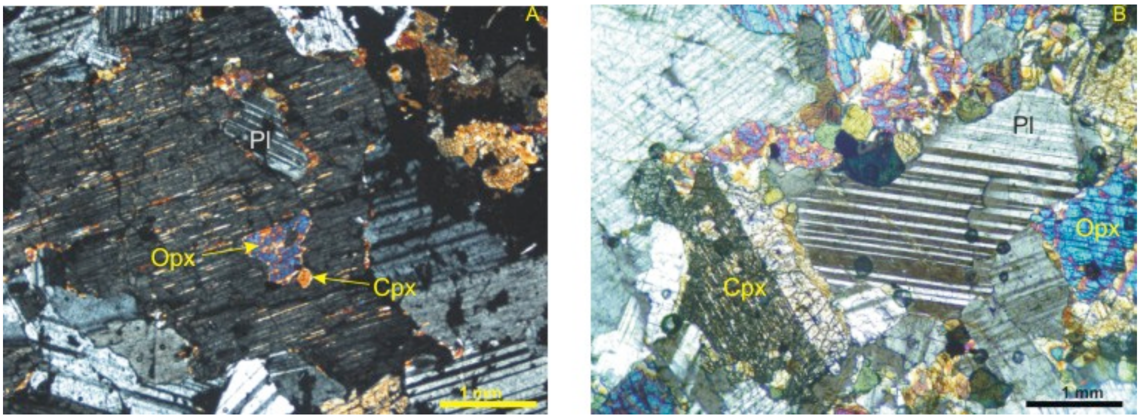
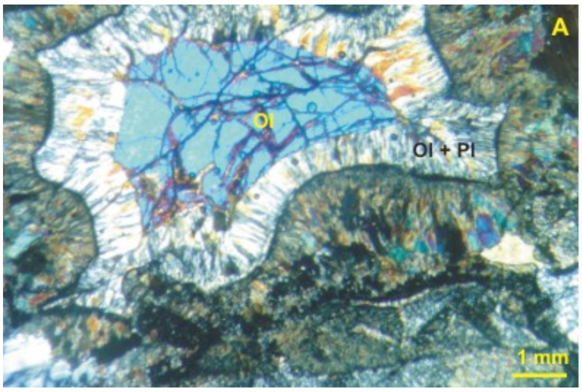


Figure 2.4. Gabbronorite A) Exsolution lamellae between Opx e Cpx, Pl. B) Coronitic texture of Opx +Pl with rims of Cpx.

Gabbronorite samples display horizontal chondrite-normallized REE patterns (Figure 2.7 a). Their overall trace element patterns show enrichment in LILE, in special Cs and Rb (multi-element diagram in Figure 2.7 b).

Samples OSNI20 and OSNI23 are coronitic olivine gabbros. They are coarse-grained dark rocks consisting of cumulus olivine and plagioclase, with intercumulus clinopyroxene. Reaction coronas between olivine and plagioclase occur in olivine gabbros. The corona consists of a layer of lamellar Opx adjacent to olivine and a second layer consisting of sympletictic intergrowth of Cpx and green spinel adjacent to plagioclase (Figure 2.5). Sample

(OSNI20) is the most primitive of the samples investigated, with 168 ppm Ni and 0.169 wt% Cr_2O_3 reflecting the presence of cumulate olivine. These samples are slightly LREE depleted with patterns similar to N-MORB (Figure 2.7). When normalized to primitive mantle olivine gabbro shows enrichment in Rb and Ba and are depleted in Zr.



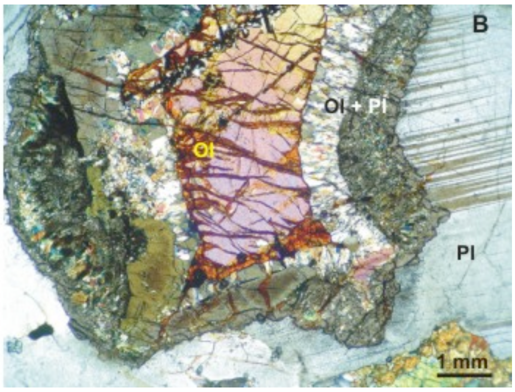


Figure 2.5. A, B) Olivine gabbro with coronitic texture formed by reaction between Ol and Pl.

Anorthositic rocks are represented by samples OSNI19, OSNI21 and OSNI24. They are grey to white and made of cumulus plagioclase (80-90 %) and olivine (20-10 %) with magnetite and epidote as accessory phases. The mottled texture is given by spots of olivine (0.5 mm). They have a REE fractionation pattern with enrichment in the LREE and a small depletion in the HREE. They have Eu positive anomaly caused by high percentage of cumulus plagioclase.

Sample OSNI25 is a banded meta-anorthosite consisting mainly of plagioclase (85%) and cpx (15%) with accessory titanite and minor zircon. This sample has medium-grained granoblastic texture originated during high-grade metamorphism (Figure 2.6). Metamorphic titanite was separated from this sample for ID-TIMS U-Pb analysis.

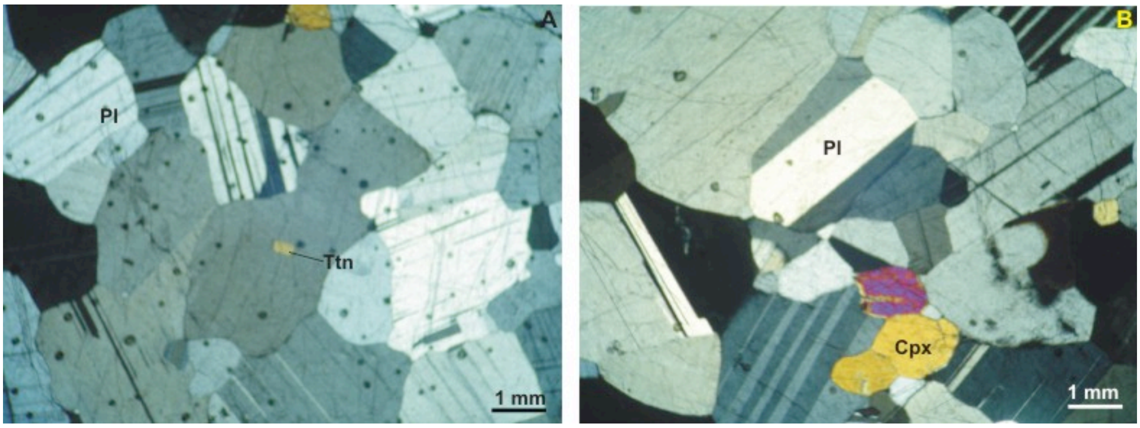


Figure 2.6. A, B) Meta-Anorthosite with granoblastic texture.

Sample OSNI16 is a dark green banded amphibolite. It consists of pleochroic hornblende (60-70%), plagioclase (30-40%) and small amounts of quartz (02-04%). Mafic bands have abundant oriented amphibole and nematoblastic texture, while felsic bands have abundant plagioclase and granoblastic texture. This is the most fractionated of the rock samples investigated in this study. Chondrite-normalized REE patterns are almost horizontal with a slight LREE enrichment (Figure 2.7).

The overall trace and major element geochemical features displayed by the rocks investigated (e.g. SiO_2 between 47.77 and 49.74%; K_2O between 0.04 and 0.36%; Sr between 136.2 and 256.9 ppm) are similar of those of N- MORB and T- MORB which is compatible with the positive ε_{Nd} (T) (see below) indicates an oceanic setting of origin for the US of the Niquelândia Complex.

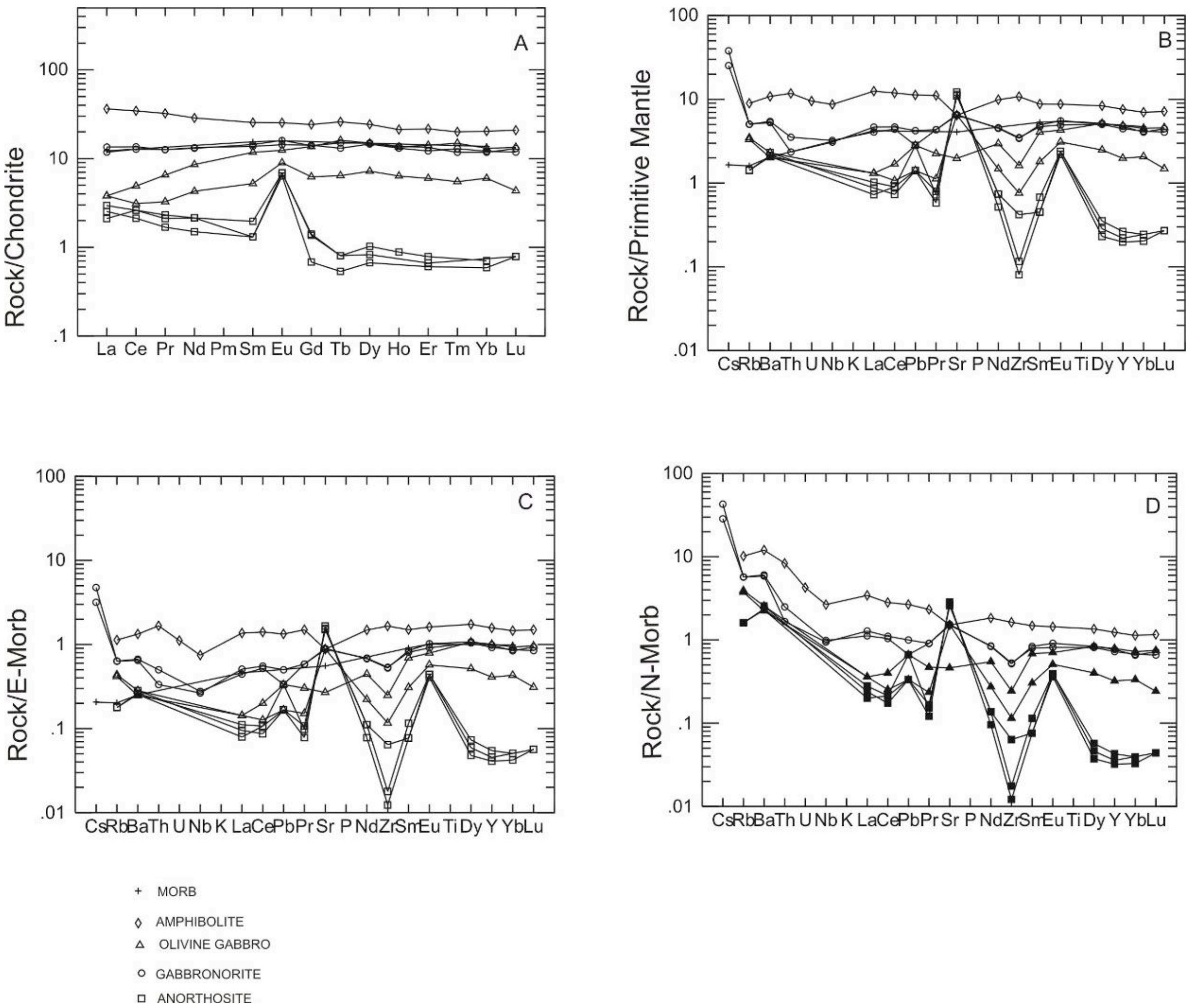


Figure 2.7. A) Samples normalized to chondrite. B) Normalized to Primitive Mantle. (Sun & Mc Donough, 1989) C,D) Rocks normalized to E-Morb and N-Morb respectively (Pearce, 1983).

Table 2.2. Geochemical data of major and trace and rare earth elements of Upper Series of Niquelandia Complex.

Rock type Sample	Gabbronorite OSNI17	***Olivine Gabbro*** ***OSNI18***	Olivine gabbro OSNI20	Olivine gabbro OSNI23	Anorthosite OSNI19	Anorthosite OSNI21	Anorthosite OSNI24	Amphibolite OSNI16
SiO_2	49.54	49.56	49.78	49.19	49.05	47.77	48.21	49
Al_2O_3	15.25	14.9	6.74	16.19	30.93	30.91	30.62	16.66
Fe_2O_3	10.89	10.8	11.92	7.92	1.01	1.81	1.75	11.99
MgO	8.32	8.19	14.28	9.84	0.61	1.34	1.34	5.68
CaO	11.86	12.42	14.62	13.57	14.55	14.87	14.75	10.78
Na_2O	2.13	2.07	0.77	1.92	2.84	2.24	2.59	2.45
K_2O	0.13	0.13	0.04	0.08	0.06	0.07	0.08	0.36
TiO_2	0.98	1.03	0.79	0.39	0.08	0.09	0.06	1.59
P_2O_5	0.07	0.07	0	0.01	0	0.01	0	0.15
MnO	0.19	0.19	0.27	0.15	0.01	0.02	0.02	0.19
Cr_2O_3	0.03	0.04	0.16	0.04	0.03	0.02	0	0.02
Ni	67	75	168	102	13	22	18	44
Sc	53	54	95	50	2	1	2	42
L0I	0.6	0.6	0.6	0.7	0.9	0.9	0.6	1.1
TOTAL	**100.01**	**100.02**	**100.02**	**100.02**	**100.05**	**100.04**	**100.03**	**99.99**
Ba	36.9	38.1	16.1	14.1	16.1	14.9	14.5	75.8
Be	0	1	0	0	1	0	0	1
Co	59.4	53.2	83.5	61.5	26.5	25.4	40.7	46.9
Cs	0.3	0.2	0	0	0	0	0	0
Ga	17.4	17.7	9.8	14.5	21.4	19.8	18	19.3
Hf	1.4	1.5	0.9	0	0	0	0	3.5
Nb	2.2	2.3	0	0	0	0	0	6.2
Rb	3.2	3.2	2.2	2.1	0	0.9	0.9	5.7
Sn	0	0	0	0	0	0	0	1
Sr	135.5	138.6	41.6	137.3	256.9	231.9	240.7	136.2
Ta	0.3	0.3	0	0.2	0.3	0	0.2	0.5
Th	0.2	0.3	0	0	0	0	0	1.7
U	0	0	0	0	0	0	0	0.4
V	305	331	414	206	11	10	13	310
W	148.2	121	79.7	148.6	214.6	185	192.4	55
Zr	39.1	38.3	18.1	8.5	0.9	1.3	4.7	120.7
Y	20.3	21.6	22.1	9	0.9	1	1.2	34.6
La	3.2	2.8	0.9	0.9	0.6	0.7	0.5	8.6
Ce	8.3	7.8	3	1.9	1.3	1.6	1.6	21.1
Pr	1.2	1.2	0.62	0.31	0.16	0.22	0.2	3.07
Nd	6.2	6.1	4	2	0.7	1	1	13.4
Sm	2.1	2.2	1.8	0.8	0.2	0.3	0.2	3.9
Eu	0.83	0.93	0.72	0.52	0.37	0.4	0.4	1.47
Gd	2.91	2.88	2.8	1.28	0.14	0.28	0.29	4.98
Tb	0.49	0.56	0.6	0.24	0.02	0.03	0.03	0.97
Dy	3.7	3.81	3.8	1.83	0.17	0.21	0.26	6.17
Ho	0.74	0.78	0.76	0.36	0	0	0.05	1.2
Er	2.02	2.21	2.34	0.99	0.1	0.11	0.13	3.58
Tm	0.33	0.3	0.38	0.14	0	0	0	0.51
Yb	2.06	2	2.22	1.02	0.1	0	0.12	3.46
Lu	0.3	0.33	0.34	0.11	0.02	0.02	0	0.53
Cu	64.6	71.2	119.4	45.9	7.4	5.3	0.6	61.4
Pb	0.3	0.2	0.2	0.1	0.1	0.1	0.2	0.8
Zn	7	6	6	4	3	2	2	18
Ni	32.8	35.5	68.6	43.9	3.2	9.4	2.7	18.1
Au	0	1.7	0	0.5	1.4	0.5	0.6	0.6
Hg	0.03	0.04	0.02	0.03	0.05	0.02	0.02	0.01
La/Sm	1.5	1.2	0.5	0.8	0.3	0.23	0.25	2.2

2.6. Age and Isotopic Results

In this study we have combined the use of U-Pb and Sm-Nd analyses in order to provide new information on the magmatic age and petrological nature of the original magma of the Niquelândia US, matter which has been much debated in the recent literature.

Samples OSNI18 and OSNI25 were selected for zircon and titanite U-Pb analyses and the analytical results are in Tables 2.3 and 2.4. Sm–Nd isotopic data are in Table 2.5.

Zircon grains from OSNI18 vary from well formed, small, equant to stubby prismatic grains, to large (200µm) prismatic and clear crystals with well defined crystal faces. Zircon yielded discordant analyses forming a discordia with the upper intercept age of 1245 ± 4 interpreted as representative of the time of crystal growth and thus the crystallization age of the original magma of the gabbronorite. This new date is identical to the zircon 1248 ± 23 Ma obtained in quartz-rich mylonitic rock (CF-04) from a shear zone within gabbros of the US (Pimentel et al., 2004) which was equally interpreted by those authors as the age of igneous crystallization of the US gabbros.

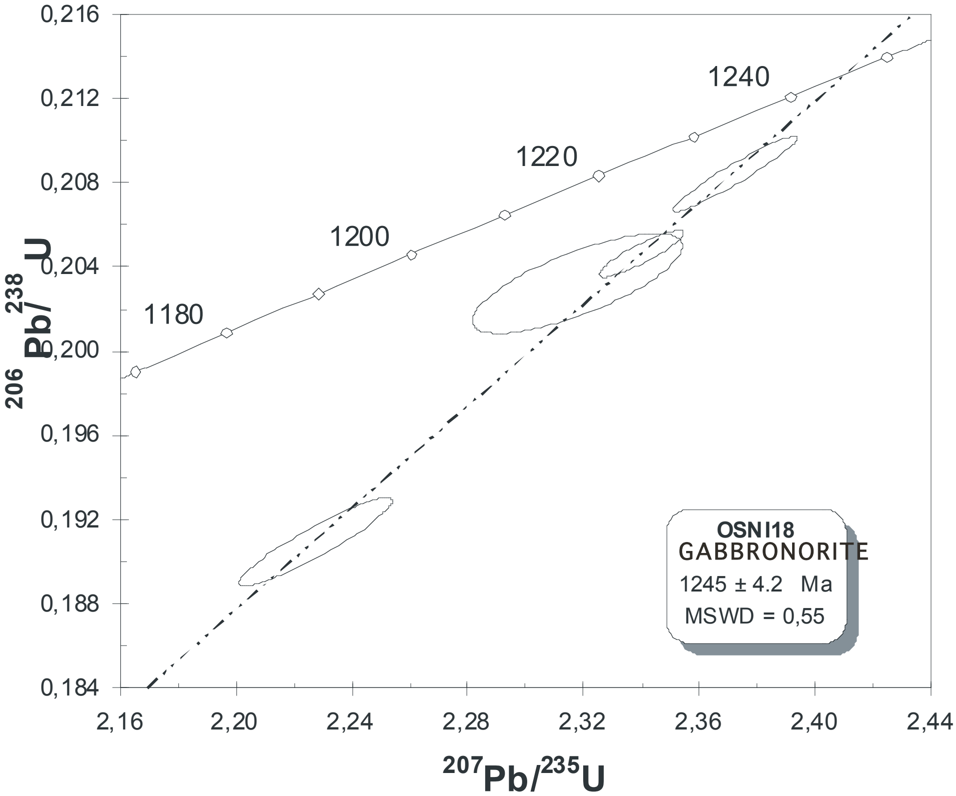


Figure 2.8. U-Pb diagram of Gabbronorite - OSNI18 from Upper Series of Niquelândia Complex.

Sample Fraction	Size (mg)	U ppm	Pb Ppm	^{206}Pb / ^{204}Pb	$^{207}Pb^*$ / ^{235}U	(pct) [a]	$^{206}Pb^*$ / ^{238}U	(pct) [b]	Correl. Coeff.	$^{207}Pb^*$ / $^{206}Pb^*$	(pct) [c]	$^{206}Pb^*$ / ^{238}U Age	$^{207}Pb^*$ / ^{235}UAge	$^{207}Pb^*$ / ^{206}PbAge	(Ma)
E11	0,047	89,93	20,12	999,69	2,35	0,922	0,205009	0,909	0,98	0,0832	0,156	1202,2	1228,9	1276,2	3
E12	0,056	66,64	15,31	5002,92	2,40	0,546	0,21107	0,538	0,98	0,0826	0,087	1234,5	1244,5	1261,9	1,7
E15	0,05	116,82	26,09	2072,42	2,34	0,511	0,204639	0,444	0,89	0,0829	0,232	1200,2	1224,5	1267,6	4,5
D15	0,032	122,53	27,89	3245,73	2,37	0,742	0,208444	0,709	0,95	0,0825	0,215	1220,5	1234,3	1258,5	4,2

Table 2.3. Summary of U–Pb data for sample OSNI18.

Titanite grains from meta-anorthosite (OSNI25) were also investigated in order to assess the age of metamorphism. Titanite crystals are yellow and transparent. The age of 780 ± 9 Ma reported in the concordia diagram of Figure 2.9 is the average $^{206}Pb/^{238}U$ ages of the two less discordant fractions analysed and is here interpreted as the best estimate for titanite growth and hence amphibolite facies metamorphism.

Sample Fraction	Size(mg)	U(ppm)	Pb(ppm)	Th(ppm)	U/Th	$^{206}Pb/^{204}Pb$	$^{207*}Pb/^{235}U$	(pct)	$^{206*}Pb/^{238}U$	(pct)	Correl. Coeff.	$^{207*}Pb/^{206*}Pb$	(pct)	$^{206*}Pb/^{238}U$ Age (Ma)	$^{207*}Pb/^{235}U$ Age (Ma)	$^{207*}Pb/Pb^{206*}$ Age (Ma)
OSNI25A	0,018	70,314	9,9642	60,45	0,8598	777,5646	1,11774	1,44	0,12881	1,42	0,9922	0,062934	0,179	781,08	761,89	706,01
OSNI25B	0,162	36,768	5,5373	6,717	0,1827	724,9963	1,29768	2,39	0,126342	2,36	0,9875	0,074494	0,371	766,96	844,7	1054,9
OSNI25C	0,121	6,1934	1,6231	8,993	1,452	276,7674	1,74813	1,97	0,132116	1,86	0,9511	0,095966	0,608	799,93	1026,5	1547,1
OSNI25D	0,15	28,241	4,4022	7,255	0,2569	768,9771	1,16957	2,24	0,128237	2,22	0,9935	0,066148	0,255	777,8	786,44	811,05

Table 2.4. Summary of U-Pb data for sample OSNI25

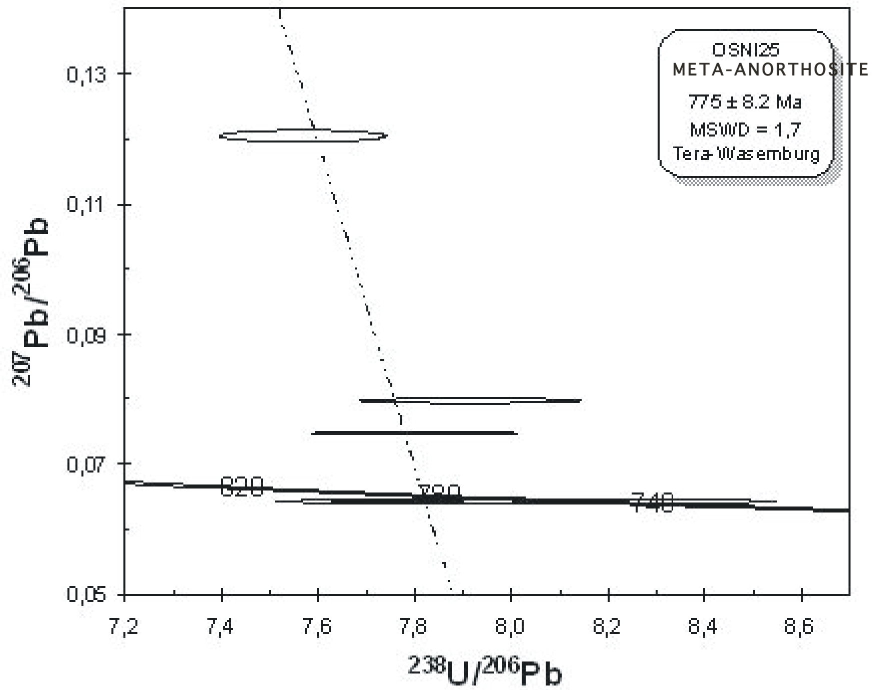


Figure 2.9. Tera–Wasserburg diagram of meta-anorthosite (OSNI25) from Upper Series of Niquelandia Complex.

The Nd isotopic data reveal positive, although rather varied, values of ε_{Nd} (*T*). The values between +1.29 and +6.63 are roughly within the same range as those observed for metabasic rocks of the Juscelândia Sequence, adjacent to the Barro Alto Complex (Moraes et al. 2003, 2006), contrasting with the negative values observed for Lower Series rocks. This supports the idea that the Upper and Lower Series of the Niquelândia Complex represent two distinct intrusions, formed by magmas derived from different sources, probably emplaced in different tectonic settings, at different epochs. The 1245 Ma gabbros of the Upper Series are, therefore, primitive and derived from a depleted mantle, possibly with some limited contamination with continental crust originating the large variation in ε_{Nd} (*T*), whereas the ca 800 Ma old Lower Series rocks are strongly contaminated with continental crust, as indicated by the inheritance pattern of the zircon analyses, as well as by the negative values of ε_{Nd} (*T*) reported by Pimentel et al. (2004, 2006)pode entrar n discussao. The sharp differences between the two magmatic systems are displayed in the Nd isotopic evolution diagram of Figure 2.10. Mafic rocks of the LS have typically lower $^{147}Sm/^{144}Nd$ ratios, indicating important LREE enrichment, and rendering mostly Paleoproterozoic T_{DM} model ages and negative ε_{Nd} (T) values. On the other hand, the basic rocks of the US have higher Sm/Nd ratios and positive ε_{Nd} (T) values.

Table 2.5. Sm–Nd isotopic data, the results of εNd (T) were calculated with age of 1.2 Ga.

Rock	**Sample**	**Sm(ppm)**	**Nd(ppm)**	**$^{147}Sm/^{144}Nd$**	**$^{143}Nd/^{144}Nd \pm$ 2SE**	**εNd (o)**	**εNd (T)**
Anorthosite	OSNI 19	0,63	1,88	0,2030	0,512875+/-20	4,61	3.67
Anorthosite	OS NI 21	0,39	1,36	0,1759	0,512628+/-15	-0,19	3.01
Gabbronorite	OSNI 17	1,88	6,27	0,1811	0,512854+/-9	4,22	6.63
Gabbronorite	OSNI 18	2,06	6,14	0,2029	0,512753+/-48	2,24	1.29
Olivine gabbro	OSNI 20	1,71	3,84	0,2694	0,513529+/-12	17,38	6.23
Meta-anorthosite	OSNI 25	0,19	0,728	0,1582	0,512697 +/-20	1,15	7,09

2.7 Discussion and Conclusions

The new ID-TIMS U-Pb zircon data presented in this study indicate that the Upper Series of the Niquelândia Complex crystallized during Mesoproterozoic at 1245 ± 4 Ma obtained ina gabbronorite. The US was metamophosed in Neoproterozoic around 780 ± 8.2 Ma constrained in titanite grains of meta-anorthosite, and not during the Neoproterozoic as suggested elsewhere (Girardi et al., 2006).

These data clearly shows that Upper Series is older than Lower Series to the east, dated at 800 Ma by Pimentel et al (2004, 2006) in contrast with previous studies that have considered it a Paleoproterozoic layered intrusion. New data also reinforce that Niquelândia Complex is composed of two distinct intrusions. The Nd isotopic data reveal positive, although rather varied, values of ε_{Nd} (T). The values between +1.29 and +6.63 are roughly within the same range as those observed for metabasic rocks of the Juscelândia Sequence, adjacent to the Barro Alto Complex (Moraes et al. 2003, 2006), contrasting with the negative values observed for Lower Series rocks. These fact is also confirmed by geochemistry signature of US that is similar to those of N-Morb and T-Morb which indicates that US was formed in an oceanic setting.

The age of 1245 ± 4 Ma of Upper Series is coeval with supracrustal rocks of the Indaianópolis volcanosedimentary sequence, dated by U-Pb SHRIMP at 1.25 Ga (Correia et al., 1997; Pimentel et al., 2004). The striking similarities between the three large layered complexes of Goiás, suggest that each one of them is made of two different complexes: an older Upper Series and/or coeval volcanosedimentary sequences and a younger Neoproterozoic Lower Series. The two different rock series were tectonically juxtaposed during the Brasiliano orogeny, towards the end of the Neoproterozoic.

Alternatively, it is possible that the mafic–ultramafic rocks and volcanosedimentary sequences represent an important preexisting crustal discontinuity used by the Mesoproterozoic magmas of the Niquelândia US to ascend and crystallize. In this case, the US and volcanosedimentary sequences represent country rocks for the LS magmas. This fact is supported by the presence of inherited 1.25–1.30 Ga zircon grains in dioritic rocks of the LS (Pimentel et al., 2004). In this case, the two magmatic systems could have been side by side originally and subsequently deformed and metamorphosed together, then preserved today as two parallel to a Meso - Neoproterozoic rifts extending in the NNE direction for more than 300 km in central Brazil (Fig. 2.1).

The emplacement of the US probably took place into a rift environment, probably recording the evolution from a continental to an oceanic rift suggested by ε_{Nd} (T) positive values and geochemistry spidergram patterns (Figures 2.7 and 2.10). In contrast, the LS that was strongly contaminated with older sialic crust, in a continental rift, as indicated by the ε_{Nd} (T) negative values and zircon inheritance pattern. Extensional events at approximately 1.25 and 0.8 Ga, although well documented in other continents (e.g. Laurentia, Baltica), are not usual in the Precambrian terrains of South America, suggesting that the continental block including these complexes and associated volcano-sedimentary sequences may be allochthonous, being accreted to the Brasília Orogen during the Neoproterozoic.

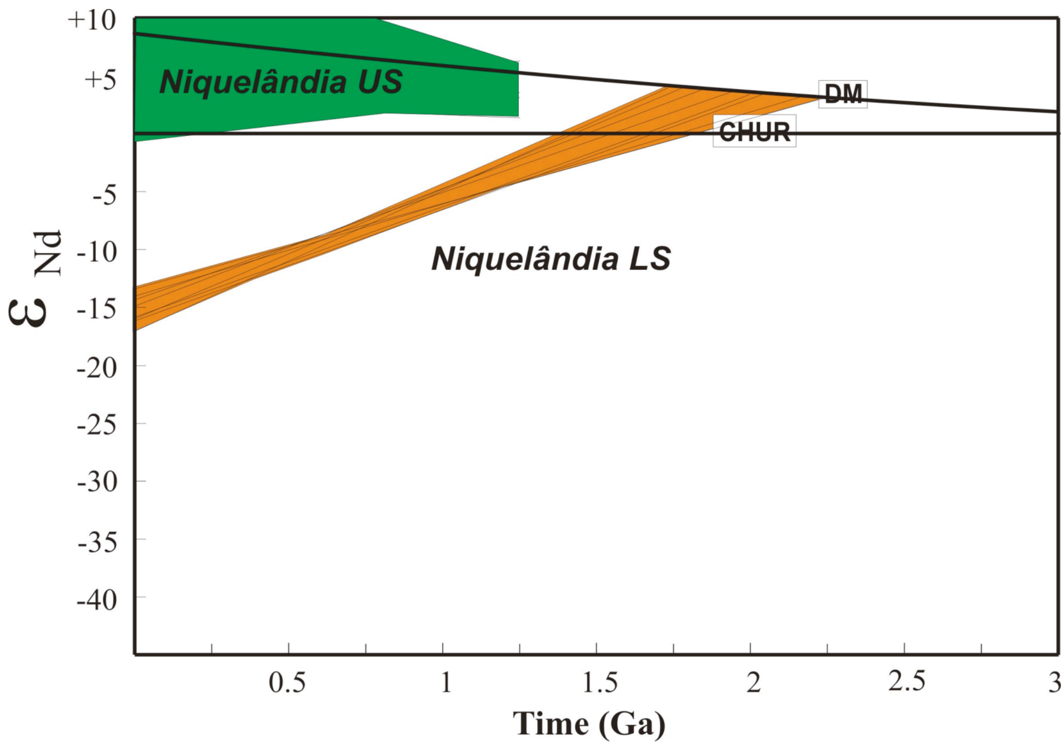


Figure 2.10. Differences between US and LS displayed in the Nd isotopic evolution diagram.

2.8. Acknowledgements

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2.9. References

Brito Neves, B.B., Sa, J.M., Nilson, A.A., Botelho, N.F., 1995. A tafrogênese estateriana nos blocos paleoproterozóicos da América do Sul e processos subsequentes. Geonomos 3 (2), 1–21.

Correia, C.T., Girardi, V.A.V., Lambert, D.D., Kinny, P.D., Reeves, S.J., 1996. 2 Ga U-Pb (SHRIMP II) and Re-Os ages for the Niquelândia Basic–Ultrabasic Layered Intrusion, central Goiás, Brazil. In: Congresso Brasileiro de Geologia 39., Anais v. 6, Salvador, SBG, pp. 187–189.

Correia, C.T., Girardi, V.A.V., Tassinari, C.C.G., Jost, H., 1997. Rb–Sr and Sm–Nd geochronology of the Cana Brava layered mafic–ultramafic intrusion, Brazil, and considerations regarding its tectonic evolution. Revista Brasileira de Geociências 27 (2), 163–168.

Correia, C.T., Jost, H., Tassinari, C.C.G., Girardi, V.A.V., Kinny, P., 1999. Ectasian Mesoproterozoic U–Pb ages (SHRIMP-II) for the metavolcanosedimentary sequences of Juscelândia and Indaianópolis and for high grade metamorphosed rocks of Barro Alto stratiform igneous complex, Goiás State, central Brazil. In: South American Symposium on Isotope Geology 2., Actas. SEGEMAR, Cordoba, pp. 31–33.

Danni, J.C.M., Fuck, R.A., Leonardos Jr., O.H., 1982. Archean and Lower Proterozoic Units in Central Brazil. Geologische Rundschau 71, 291–317.

DePaolo, D.J., 1981.A neodymium and strontium isotopic study of the Mesozoic calc-alkaline granitic batholiths of the Sierra Nevada and Peninsular Ranges, California. Journal of Geophysical Research 86, 10470–10488.

Ferreira Filho, C.F., Naldrett, A.J., Gorton, M.P., 1995. Petrology of the Mesoproterozoic Niquelândia layered mafic–ultramafic complex, central Brazil: evidence for a composite intrusion in an intracontinental rift system. In: Intern. Field Conference and Symposium, Proceedings, Duluth, p. 45.

Ferreira Filho, C.F., 1994. The Niquelândia mafic-ultramafic layered intrusion, north Goiás, Brazil: petrology, age and potential for PGE ore deposits. PhD Thesis, University of Toronto, unpublished, 270 pp.

Ferreira Filho, C.F., Kamo, S., Fuck, R.A., Krogh, T.E., Naldrett, A.J., 1994. Zircon and rutile geochronology of the Niquelândia layered mafic and ultramafic intrusion, Brazil: constraints for the timing of magmatism and high grade metamorphism. Precambrian Research 68, 241–255.

Ferreira Filho, C.F, Moraes, R., Fawcett, J.J., Naldrett, A.J., 1998a. Amphibolite to granulite progressive metamorphism in the Niquelândia Complex, central Brazil: regional tectonic implications. Journal of South American Earth Sciences 11, 35–50.

Ferreira Filho, C.F., Naldrett, A.J., Gorton, M.P., 1995. Petrology of the. Mesoproterozoic Niquelândia layered mafic-ultramafic complex, central Brazil: evidence for a composite intrusion in an intracontinental rift system. In: International Field Conference and Symposium, Proceedings, Duluth, p. 45.

Ferreira Filho, C.F., Pimentel, M.M., 2000. Sm–Nd isotope systematics and REE-Hf-Ta-Th data of troctolites and their amphibolitized equivalents of the Niquelândia Complex Upper Layered Series, central Brazil: further constraints for the timing of magmatism and high-grade metamorphism. Journal of South American Earth Sciences 13 (7), 647–659.

Ferreira Filho, C.F., Naldrett, A.J., Gorton, M.P., 1998b. REE and pyroxene compositional variation across the Niquelândia layered intrusion, Brazil: petrolo gical and metallogenetic implications. Transaction of the Institute of Mining and Metallurgy 107, B1–B21.

Ferreira Filho, C.F., Naldrett, A.J., and Asif, M., 1995, Distribution of platinum Group elements in the Niquelândia layered mafic and ultramafic intrusion, Brazil: implications with regard to exploration: Can. Mineral., v. 33, p. 156-184.

Ferreira Filho, C.F., Nilson, A.A., Naldrett, A.J., 1992. The Niquelândia mafic - ultramafic complex, Goiás, Brazil: a contribution to the ophiolite vs. stratiform controversy based on new geological and structural data. Precambrian Research 59, 125–143.

Ferreira Filho, C.F., Pimentel, M.M., 2000. Sm–Nd isotope systematics and REE-Hf-Ta-Th data of troctolites and their amphibolitized equivalents of the Niquelândia Complex Upper Layered Series, central Brazil: further constraints for the timing of magmatism and high-grade metamorphism. Journal of South American Earth Sciences 13 (7), 647–659.

Fuck, R.A., Brito Neves, B.B., Cordani, U.G., Kawashita, K., 1989. Geocronologia Rb– Sr no Complexo Barro Alto, Goiás: evidência de metamorfismo de alto grau e colisão continental há 1300 Ma no Brasil Central. Geochimica Brasiliensis 3 (2), 125–140.

Fuck, R.A., Pimentel, M.M. and D'el Rey Silva, L.J.H. 1994. Compartimentação tectônica da porção oriental da Província Tocantins. Actas, 38 ° Congresso Brasileiro de Geologia, Balneário Camboriú-SC, 1, pp. 215-216

Fuji, M.Y., 1989. REE geochemistry and Sm/Nd geochronology of the Cana Brava Complex, Brazil. Unpublished. MSc Dissertation, Kobe University, Japan, 55 p.

Gioia, S.M.C., Pimentel, M.M., 2000. The Sm–Nd isotopic method in the Geochronology Laboratory of the University of Brasília. Anais da Academia Brasileira de Ciências 72, 219–245.

Girardi, V.A.V., Rivalenti, G., Correia, C.T.,Tassinari, C.C.G., Munhá, J.M. Mazzucchelli, M., Bertotto, G.W., 2006. V South American Symposium on Isotope Geology 375-377

Girardi, V.A.V., Rivalenti, G., Sinigoi, S., 1986. The petrogenesis of the Niquelândia layered basic-ultrabasic Complex, Central Goiás, Brazil. Journal of Petrology 27 (3), 715–744.

Krogh, T.E., 1973. A low-contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determination. Geochimica et Cosmochimica Acta 37, 485–494.

Ludwig, K.R., 1993. PBDAT A Computer Programa for Processing Pb–U–Th. Isotope Data. USGS, Berkeley.

Ludwig, K.R. 2001. User’s manual for Isoplot/Ex v. 2.47. A geochronological toolkit for Microsoft Excel. BGC Special Publ. 1a, Berkeley, 55p.

Marangoni, Y., Assumpção, M., Fernandes, E.P., 1995. Gravimetria em Goiás, Brasil. Revista Brasileira de Geofísica 13 (3), 205–219.

Medeiros, E.S., 2000. A mineralização de platina e paládio da zona máfica superior do Complexo de Niquelândia, Goiás. MSc Dissertation, University of Brasília, Brasília, unpublished.

Moores, E.M., 2002. Pre-1Ga (pre-Rodinian) ophiolites: their tectonic and environmental implications. Geological Society of America Bulletin 114, 80–95.

Moraes R., Fuck R. A., Pimentel M.M, Gioia S.M.C.L., Hollanda M.H.B.M., Armstrong R., 2006 The bimodal rift-related Juscelândia volcanosedimentary sequence in central Brazil: Mesoproterozoic extension and Neoproterozoic metamorphism. Journal of South American Earth Science. Journal of South American Earth Sciences 20, 287–301.

Moraes, R., Fuck, R.A., Pimentel, M.M., Gioia, S.M.C.L., Figueiredo, A.M.G., 2003. Geochemistry and Sm–Nd isotope characteristics of bimodal volcanic rocks of Juscelândia, Goiás, Brazil: Mesoproterozoic transition from continental rift to ocean basin. Precambrian Research 125, 317–336.

Moraes, R., Gioia, S.M.C.L., Fuck, R.A., Pimentel, M.M., 2000. Relationships between the Barro Alto Complex and Juscelândia Sequence magmatism and metamorphism constrained by Sm–Nd isotopic data. 31 International Geological Congress, Rio de Janeiro, CD-ROM.

Pearce, J.A., 1983. Role of sub-continental lithosphere in magma genesis at active continental margins. In: Continental basalts and xenoliths. Shiva, Nantwich. Eds: C.J. Hawkesworth and M.J. Norry, 230-249.

Pimentel, M.M., Ferreira Filho C. F., Armele A., 2006. Neoproterozoic age of the Niquelândia Complex, central Brazil: Further ID-TIMS U–Pb and Sm–Nd isotopic evidence Journal of South American Earth Science. 21, 228 – 238.

Pimentel, M.M., Ferreira Filho, C.F., Armstrong, R.A., 2004. SHRIMP U-Pb and Sm–Nd ages of the Niquelândia Layered Complex: Meso- (1.25 Ga) and Neoproterozoic (0.79 Ga) extensional events in central Brazil. Precambrian Research 132 (1), 133–153.

Pimentel, M.M., Fuck, R.A., Jost, H., Ferreira Filho, C.F., Araújo, S.M., 2000. Geology of the central part of the Tocantins Province: Implications for the geodynamic history of the Brasília belt. In: Cordani, U.G., Milani, E.J., Thomaz Filho, A., Campos, D.A. (Eds), Tectonic Evolution of South America. 31st International Geological Congress. Rio de Janeiro, pp. 195–229.

Piuzana, D., Pimentel, M.M., Fuck, R.A., Armstrong, R.A., 2003. Neoproterozoic granulite facies metamorphism and contemporaneous granite magmatism in the Brasília Belt, central Brazil: regional implications of new SHRIMP U–Pb and Sm–Nd data. Precambrian Research 125, 245–273.

Rivalenti, G., Girardi, V.A.V., Sinigoi, S., Rossi, A., Siena, F., 1982. The Niquelândia mafic–ultramafic complex of central Goiás, Brazil: petrological considerations. Revista Brasileira de Geociências 12 (1–3), 380–391.

Suita, M.T.F., Kamo, S., Kroght, T.E., Fyfe, W.S., Hartmann, L.A., 1994. U-Pb ages from the high-grade Barro Alto mafic–ultramafic complex (Goiás, central Brazil): middle Proterozoic continental mafic magmatism and upper Proterozoic continental collision. In: Intern. Confer. On Geochron. Cosmochr. and Isot. Geol. — ICOG, 8., Abstracts. Berkeley, USGS, p. 309.

Capítulo 3

Este Capítulo apresenta os resultados isotópicos, geoquímicos e petrológicos referentes ao Complexo Kunene. As informações serão apresentados na forma de artigo completo, que poderá ser submetido ao periódico *Journal of African Earth Sciences*, com o título: **Mesoproterozoic emplacement ages of the Kunene Anorthosite Complex, SW Angola: ID-TIMS U–Pb and Sm-Nd isotopic evidence.**

Mesoproterozoic emplacement ages of the Kunene Anorthosite Complex, SW Angola: ID-TIMS U–Pb and Sm-Nd isotopic evidence

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Abstract

The Kunene Complex (KC) in southwestern Angola is one of the largest anorthositic complexes in the world, underlying an area of approximately 18.000 km^2. It is part of the so-called Kunene Plutonic Suite (KPS) which comprises a basic plutonic suite and an acid plutonic suite. The basic suite is mainly formed of gabbro-anorthositic intrusions and layered mafic bodies of different sizes. The acid suite includes mainly A-type "red granites". This study presents new ID-TIMS U-Pb and Sm-Nd data, as well as geochemistry and petrologic data for gabbroic, anorthositic and granitic rocks of the KPS. One sample from a layered gabbroic intrusion (Uanguembela) of the Otchindjau - Oncócua region was dated at 1434 ± 2 Ma. A mangeritic intrusion to the east of the Otchindjau layered mafic intrusion yielded the U-Pb age of 1403 ± 7 Ma. These ages are slightly older than the age of ca. 1.37 Ga reported previously in the literature, suggesting that the Kunene Plutonic Suite is formed by several plutons with different ages, indicating the existence of distinct magmas which underwent distinct cooling histories and crustal assimilation in multi-pulse gabbroic and anorthositic intrusions.

The dominantly negative ε_{Nd} (T) values of the basic (-0.30 to -12.42) and acid rocks (-0.67 to -11.02) indicate that KPS original mafic magmas were contaminated by crustal material. However, some mafic plutons yielded positive ε_{Nd} (T) between + 0.67 to + 1.12 which indicates that the magma of some mafic intrusions within the KPS derived from depleted mantle with less important crustal contamination. The emplacement of the Kunene Complex requires an extensional setting and a significant thermal anomaly at the margin of the Congo Craton during the Mesoproterozoic. The Kunene Plutonic Suite resembles the large Proterozoic anorthosite plutonic suites such as the Nain Plutonic Suite (Labrador, Canada) and is, therefore, of great potential for Ni-Cu-PGE and Fe-Ti-V deposits.

Keywords: Kunene, U-Pb, Sm-Nd ages, Mesoproterozoic.

3.1. Introduction

The origin of massive anorthositic complexes and the reason why most were produced in a relatively short time interval, within the Mesoproterozoic, are still open questions. Petrogenesis of the anorthosite massifs is interpreted in terms of partial melting of the upper mantle, followed by plagioclase flotation in a magma chamber at the mantle-crust boundary and buoyant ascent of the plagioclase-rich crystal mushes to their final depth of emplacement (Duchesne, 1984; Emslie, 1985, Emslie et al., 1994; Longhi and Ashwal, 1985; Ashwal, 1993; Wiebe, 1994; Mitchell et al., 1995). Although, many authors favour the hypothesis of anorthosite generation by lower crustal anatexis (Duchesne et al., 1999; Longhi et al., 1999; Schiellerup et al., 2000; Selbekk et al., 2000, Wiszniewska et al., 2002), which is supported by Re-Os isotope data and experimental investigations.

The The Kunene Plutonic Suite is one of the largest in the world, possibly second in size only to the Lac-Saint-Jean Complex of Canada. This suite has been studied for almost two decades and the most controversial aspect is related to its origin: some authors have interpreted it as a massive anorthosite complex (Simpson and Otto, 1960; Ashwal and Twist, 1994; Morais et al, 1998; Mayer, 2004), whereas others put forward the idea that it represents a layered mafic intrusion (Stone and Brown, 1958; Silva, 1990).

Massive anorthosites are often associated with granitoids ranging from mangerite–charnockite to rapakivi granite, although the genetic relationship between the basic and granitoid rocks is not completely understood (Ashwal, 1993). Therefore, the genesis of Proterozoic anorthosites is still a matter of debate. The models proposed include anatexis of the deep crust or assimilation of continental crust by mantle derived melts (e.g. Michot, 1955; Philpotts, 1968; Demaiffe et al., 1979; Demaiffe and Hertogen, 1981). In the latter case, different primary magmas ranging from komatiites and picrites to olivine tholeiites have been postulated (Emslie, 1980; Morse, 1982). A possible model involves the ascent of upper-mantle magmas from depth and underplating at the crust-mantle boundary. Olivine and Al-rich ortho/clinopyroxenes would be the first phases to crystallize, resulting in both the formation of ultramafic cumulate and enrichment of the residual melt in plagioclase components. After reaching saturation, plagioclase crystals start to float in the magma chamber. This density-buoyant plagioclase mush would then migrate upwards as a diapir and intrude at relatively shallow depths. The mush may undergo varying extents of contamination while passing through or ponding at the base of the continental crust (Ashwal, 1993).

In this work we discuss new U-Pb and Sm-Nd data, as well as geochemistry and petrographic data of basic and acid rocks of the Kunene Plutonic Suite (KPS). The new data are relevant for the geology of southwestern Africa and also for correlation with other anorthosite complexes in other parts of the world, as well as for the metallogenetic potential that it represents.

3.2. Geological setting and previous age constraints of the KPS

The Kunene Plutonic Suite (KPS) is exposed at the southern margin of the Congo Craton in SW-Angola and NW-Namibia. It extends over 300 km along the N-S direction and 30-50 km wide and underlies an area of ca 15000 km^2 (Fig. 3.1) (Carvalho and Alves, 1990).

The mafic plutonic suite of KPS is composed mainly of massive anorthosite, gabbro, troctolite, leucogabbro, leucotroctolite (Carvalho and Alves, 1990; Silva, 1990; Ashwal and Twist, 1994; Morais et al., 1998; Mayer et al., 2004). Field work supported by the interpretation of landsat images allowed us to identify that, in fact, the Kunene Complex comprises numerous intrusions of different sizes and compositions. Some intrusions were informally named the Lufinda, Quihita (Mayer et al., 2004), Uanguembela, Otchindjau, Bembe (Ferreira Filho, 2004; unpublished internal report for CVRD-Vale) Chiange (this paper). The Zebra Mountains is the largest layered intrusion and is exposed across the border between NW-Namibia and SW-Angola.

Several granitoid intrusions known collectively as “Red Granites” intruded the mafic plutonic suite and comprise granites, monzonites, syenites, charnockites, mangerites and rhyolitic porphyries (Figs. 3.1 and 3.2) (Carvalho and Alves, 1990).

At least two major anorthosite units can be distinguished, separated by a NE-SW trending belt of granitoid intrusions (Morais et al., 1998; Drüppel et al., 2001; Fig. 3.1)

At least two major anorthosite units can be distinguished, separated by a NE-SW trending belt of granitoid intrusions (Morais et al., 1998; Drüppel et al., 2001; Fig. 1). The KPS is bounded to the W-NW by gneiss, migmatite, granite, amphibolite, quartzite and schist comprising the Precambrian basement (Carvalho and Alves, 1990; Silva, 1990). To the east it is mainly covered by the Kalahari sediments (Morais et al., 1998) (Fig. 3.1).

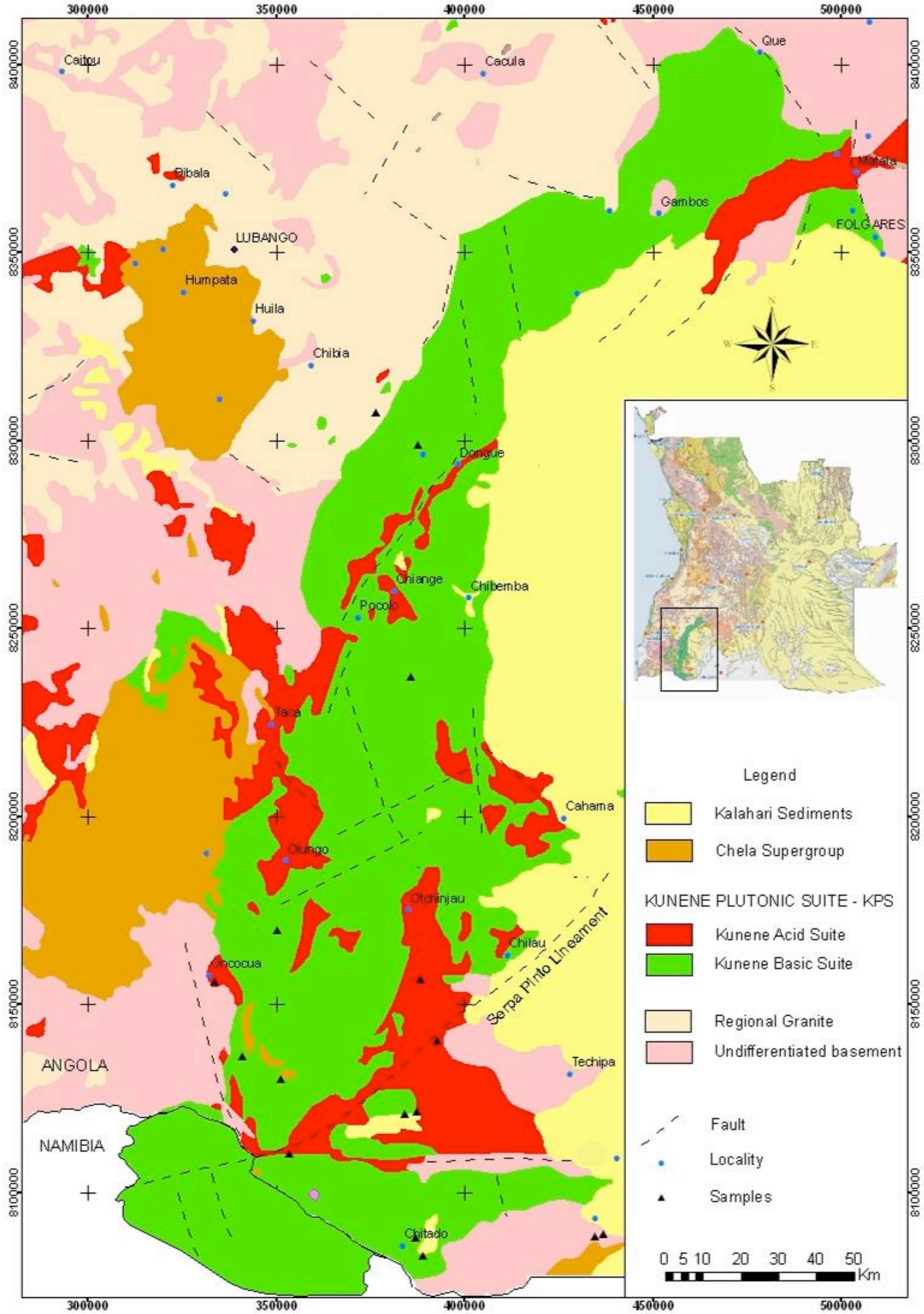

Figure 3.1. Simplified geological map of the Kunene Plutonic Suite and adjacent Precambrian rocks in SW Angola (from Instituto Geológico de Angola, 1998).

Regional anorogenic granites dated at ca. 1.6-1.7 Ga are similar the Epupa/Huab Complexes and Fransfontein Granite in northern Namibia, and probably belong to the 'Namib Event' at ca. 1.8-1.7 Ga, which constitutes an important crust - forming event in northwestern Namibia and southwestern Angola (Tegtmayer and Kroner, 1985; Carvalho et al., 2000).

The Chela Supergroup is made of sedimentary and volcano-sedimentary rocks known as the 'Kibaran Metasedimentary Rocks dated at 1.1-1.4 Ga. These ages were based on the presence of 1.4 Ga old granite clasts in detrital sediments of the Chela Supergroup. This group lies discordantly on the KPS and is intruded by mafic sills and dykes dated by Rb-Sr isochron at 1.1 Ga (Carvalho and Alves, 1990). On the other hand, Kroner and Correia (1980) and Jones et al. (1992) have suggested that the Chela Supergroup may be equivalent to the Nosib Group (<1.0 Ga) at the base of Pan-African Damara Supergroup in Namibia. The Pan-African Damara Orogen extends from northern Namibia into SW Angola and was metamorphosed during the Neoproterozoic at about 500 - 600 Ma.

Table 3.1. Available geochronological data for the crystallization age of the Kunene Complex and country rocks.

Unit / Locality	Age / Event	Method
Nosib Group and Damara Supergroup (Namibia)	1144 ± 30 Ma and < 1000 Ma [10]	Rb-Sr
Chela Supergroup – Norite and Dolerite	1100 - 1400 Ma [2]	Rb-Sr
Dolerite dykes (Changoroi and Quilengues)	1281 ± 22 Ma and 1175 ± 69 Ma [3]	K–Ar
Dolerite dykes cuts Chela SPg (Ompupa)	1197 ± 27 Ma [4]	Rb-Sr
Red Granite (Otchindjau, Chitado) - Intruded in KPS	1300 - 1400 ± 24 Ma [5]; 1302 ± 20 Ma [2]	Rb-Sr
Red Granite (Matala)	1220 ± 32 Ma [5]	
Mangerite vein (Quihita)	**1371 ± 2.5 Ga [7]**	**U-Pb**
Troctolite (Quihita)	1470 ± 25 Ma [7]	Sm-Nd
Anorthosite dyke (Quihita)	1319 ± 28 Ma [7]	Sm-Nd
Anorthosite (Quipungo)	2102 ± 43 Ma [3]	K-Ar
Anorthosite (Zebra Mountains Namibia)	1385 ± 25 Ma	U–Pb*
Olivine gabbro (Quipungo)	2157 ± 43 Ma [3;5]	K–Ar
Gneiss (southern basement of KC)	**1408 - 1470 Ma [1] - Kibaran event**	**U-Pb**
Granites	1675 ± 72 Ma [5] Namib Granitogenese event	Rb-Sr
Regional Granite – Gneiss (basement of Congo Craton)	Eburnian event:	Rb-Sr
Chicala Granite; Jamba Granite	1847 ± 62 Ma; 1853 ± 74 Ma [5; 6]	
Matala Leucograite	1761 ± 19 Ma [4]	
Quipungo, Cela-Ceriango and Serra da Ganda Granites	2191 - 2236 - 2243 ± 60 Ma [5, 6]	
Gneiss - Migmatite - Granitoids	1800 – 2800 ± 39 Ma [9]	
Schist – Quartzite - Amphibolite Complex	>2200 Ma [8, 9]	

[1]Allsopp, 1975 cited in Carvalho, 2000 et al; [2] Carvalho et al., 1987; [3] Silva et al., 1974; [4] Carvalho et al., 1987; [5] Torquato et al., 1979; [6]Carvalho, 2000; [7] Mayer et al, 2004; [8]Carvalho,1984; [9]Carvalho and Alves, 1990; [10]Carvalho et al., 1990; * Druppel et al 2007.

The Damara Supergroup is in fault contact with the older rocks to the east, in SW Angola. Neoproterozoic sedimentary rocks of the Chela Supergroup (Humpata Plateau in the north, Chela Plateau in the centre, Baynes Mountains to the south of the KPS) are intruded by dolerite sills and dykes possibly emplaced in the early Cretaceous during the opening of the South Atlantic Ocean. They are clearly identified in satellite images (Fig. 3.2 and 3.3) (Carvalho and Alves, 1990).

Quartzite-Amphibolite-Marble Complex (QAMC) of uncertain age represents another geological unit in the region. It appears to have been deformed prior to intrusion of the ca. 2.1 Ga old Eburnian granites. The Paleoproterozoic Eburnian tectonic event has resulted in the emplacement of a NNE-SSW belt of granitoid rocks close to the border between Angola and Namibia and represents the country rocks of Kunene (Carvalho et al., 1987; Carvalho and Alves, 1990).

3.3. Analytical procedures

The zircon concentrates were extracted from rock samples ONC88 and OSCK64 using conventional gravimetric (DENSITEST®) and magnetic (Frantz isodynamic separator) techniques at the Geochronology Laboratory of the University of Brasília. Final purification was achieved by hand picking using a binocular microscope. Single grains selected from the least magnetic fractions were dissolved in concentrated HF and HNO_3 (HF: HNO_3 = 4:1) using microcapsules in Parr-type bombs. A mixed ^{205}Pb–^{235}U spike was used. Chemical extraction followed standard anion exchange techniques, using Teflon microcolumns, after procedures modified from Krogh (1973). Pb and U were loaded together on single Re filaments with H_3PO_4 and Si gel, and isotopic analyses were carried out using a Finnigan MAT-262 multicollector mass spectrometer equipped with secondary electron multiplier-ion counting at the Geochronology Laboratory of the University of Brasília. Procedural blanks for Pb, at the time of analyses, were better than 10 pg. PBDAT (Ludwig, 1993) and ISOPLOT-Ex (Ludwig, 2001) programs were used for data reduction and age calculation. Errors for isotopic ratios shown in Table 2 are 2σ.

Sm–Nd isotopic analyses followed the method described by Gioia and Pimentel (2000). Whole-rock powders (~50 mg) were mixed with ^{149}Sm–^{150}Nd spike solution and dissolved in Savillex capsules. Sm and Nd extraction of whole-rock samples followed conventional cation exchange techniques, using Teflon columns packed with LN-Spec resin

(HDEHP=di-ethylhexil phosphoric acid supported on PTFE powder). Sm and Nd samples were loaded on Re evaporation filaments of double filament assemblies, and the isotopic measurements were carried out on a multicollector Finnigan MAT 262 mass spectrometer in static mode. Uncertainties for Sm/Nd and $^{143}Nd/^{144}Nd$ ratios are better than ±0.2% (σ2) and ± 0.005% (σ2), respectively, based on repeated analyses of international rock standards BHVO-1 and BCR-1. $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd$ of 0.7219, and the decay constant used was 6.54 x 10^{-12} y^{-1}. T_{DM} values were calculated using De Paolo's (1981) model.

The samples for geochemical analyses were cleaned and weathered and veined surfaces were cut off. The rocks were crushed and milled to a very fine powder. Major elements and Ni and Sc (ppm) were made by ICP-ES and trace element analyses were made by ICP-MS at ACME Laboratories in Vancouver, Canada.

3.4. Petrography and Geochemistry of Kunene Plutonic Suite

The rocks of Kunene Plutonic Suite range compositionally from basic to acid. Extensive areas of cumulatic massive anorthosite, gabbro, leucotroctolite forming different batholiths and layered intrusions were included into the basic plutonic suite. The acid plutonic suite is spatially associated with the basic suite and comprises mainly "Red Granites". The acid suite is represented by granite, syenite, monzonite, mangerite.

The gneissic rocks represent the country rocks of the southern portion of KPS.

Basic rocks are represented by several plutons of massive anorthosite and leucotroctolite. In the southern part of the KPS (Fig. 3.2) the main mafic layered intrusions are called informally Uanguembela, Otchindjau and Bembe. The Otchindjau pluton is a curved-shaped intrusion extending for ca 20 km in the N-S direction and is mainly composed of coarse-grained anorthosite interlayered with leucotroctolite. The ovoid-shaped Bembe intrusion underlying an area of ca 170 km^2 is formed of massive anorthosite, leucotroctolite and gabbro. It is partially covered by the Chela Supergroup to the north and is bordered by granitic intrusions to the south. To the east of the Bembe intrusion is located the Uanguembela mafic intrusion. It represents an ellipsoid-shaped intrusion underlying an area of ca 100 km^2 composed mainly of magnetite gabbros (Fig. 3.3) associated with red granite intrusions.

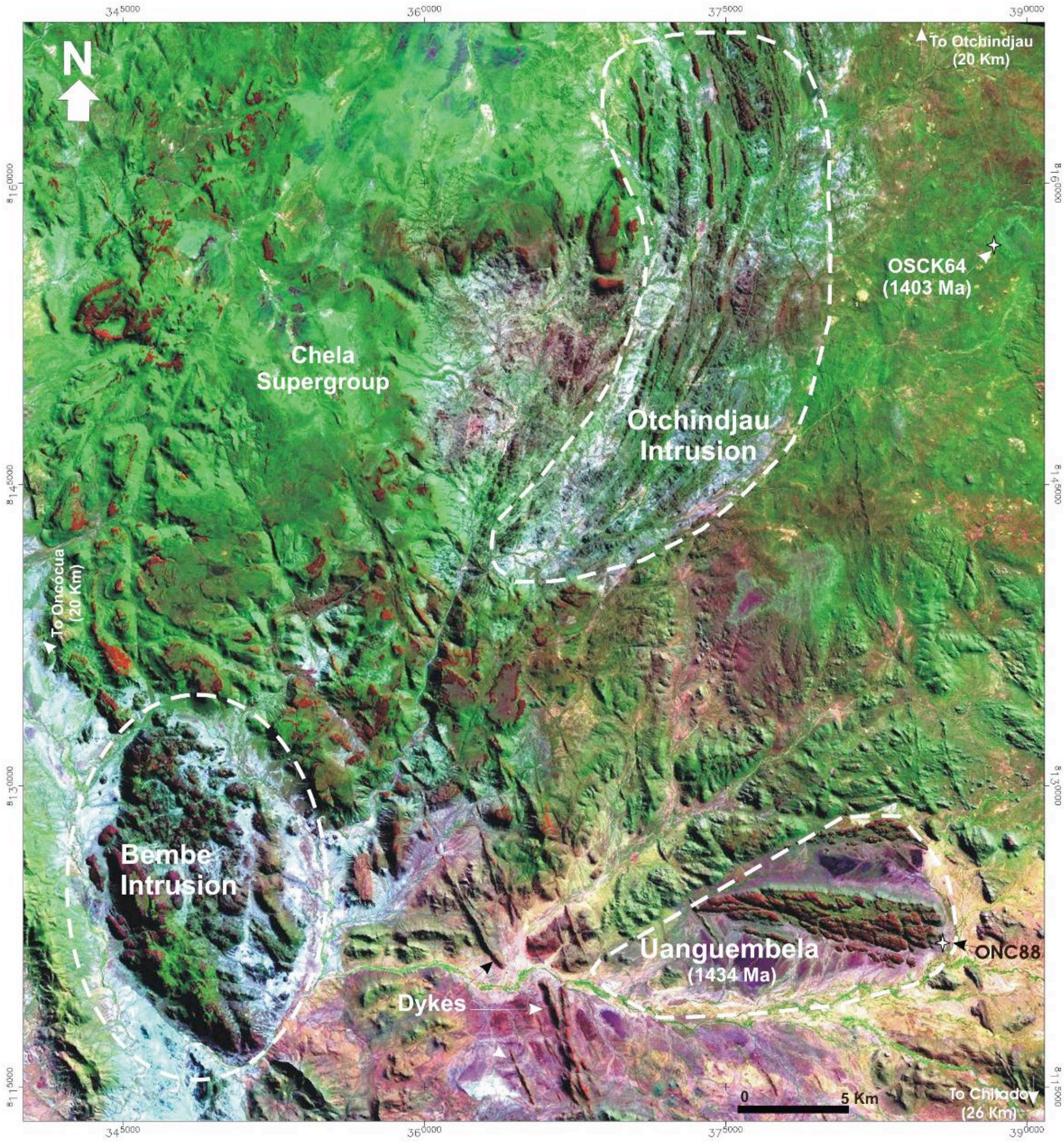

Figure 3.2. Landsat image of major mafic intrusions in the southern portion of KC at Oncócua - Otchindjau region. Gabbro ONC88 of the Uanguembela intrusion and a mangerite sample (OSCK64) were dated by ID-TIMS U-Pb.

The rocks are fresh and display well preserved igneous textures. The samples were plotted in the TAS diagram and reveal mostly sub-alkaline compositions. Two samples have higher $K_2O + Na_2O$ plotting in the monzonite field (Fig. 3.3-A).

In the AFM diagram (Fig. 3.3-B) most felsic sub-alkaline rocks form a calc-alkaline trend. On the other hand, basic rocks represented by the gabbros shows a tholeiitic signature.

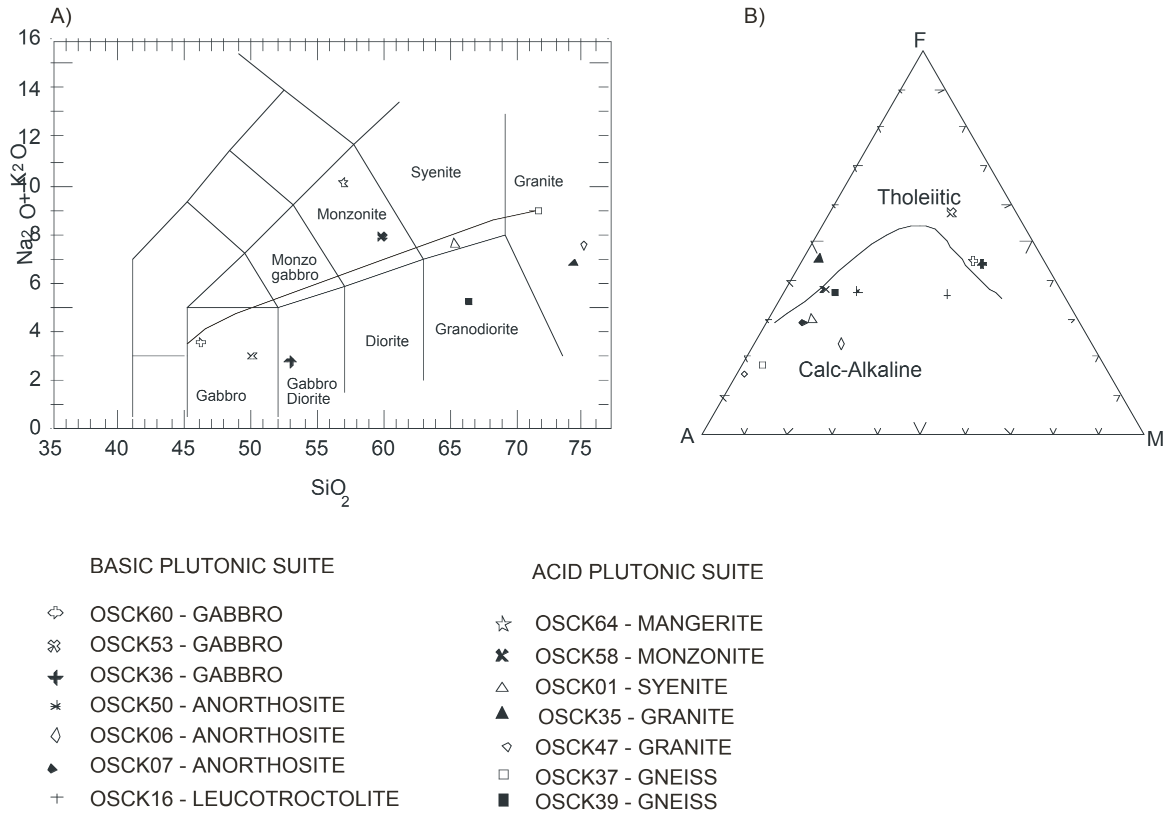

Figure 3.3. A) TAS Diagram (Le Maitre, 1989) showing the main samples of the KPS. B) Diagram A = Na_2O + K_2O; F = Fe_2O_3t; M = MgO (Irvine and Baragar, 1971).

3.4.1. Basic Plutonic Suite

3.4.1.1. Anorthositic Rocks

The anorthositic rocks of the KPS are coarse-grained cumulates of large plagioclase crystals (> 6 cm) as well as ortho- and clinopyroxene. Intercumulus minerals are olivine, ilmenite and magnetite with massive non - oriented texture. Triple junctions can be observed between subhedral plagioclase crystals. Exsolution lamellae of Fe-Ti oxides occur in a pseudo-ophitic matrix of orthopyroxene and/or olivine. Less abundant banded anorthosites are also described, and the banding is generally synmagmatic and defined by the orientation of plagioclase crystals in a matrix of non-oriented intercumulus mafic minerals. Occurrences of Fe-Ti ores are associated with the contacts between Red Granites and anorthosites that have abundant large (ca 5 cm) poikylitic crystals of ilmenite and magnetite.

Anorthositic rocks (OSCK06, OSCK07, OSCK16 and OSCK50) are mainly dark, white or grey and are composed of cumulus plagioclase (70-90 % vol and size > 2 cm) and olivine (20-10 %), clino- and orthopyroxene as well as magnetite and ilmenite (Fig. 3.4) as accessory phases. Oscillatory zoning and iridescent plagioclase are well preserved in some plutons.

Leucotroctolites are cumulatic rocks, presenting massive and equigranular medium- to coarse-grained textures. They are composed of plagioclase (± 75 % vol) and olivine (± 20 % vol), as well as magnetite (< 5 %) as the main accessory phase. Some of the leucotroctolites display a mottled texture marked by oikocrysts of olivine (Fig. 3.4). Leucotroctolites has low SiO_2 contents (47.74 to 54.33 wt %), high Al_2O_3 (between 23 to 27 wt %), moderate CaO (8.86 to 12.2 wt %) and low Na_2O (2.6 to 4.43 wt %). The anorthosites show continuously decreasing LREE values from La to Sm followed by a large positive Eu-anomaly caused by the abundance of plagioclase and a slight depletion in the HREE (Fig. 3.5-A).

Trace element concentrations normalized to primordial mantle (Sun & Mc Donough, 1989) (Fig. 3.5-B) exhibit a relatively uniform pattern characterized by positive anomalies of Ba and Sr (107-942 ppm and 439-833 ppm, respectively). Ni contents in the anorthositic rocks vary from 6 to 130 ppm reflecting the presence of olivine in leucotroctolite (Fig. 3.5 and Table 3.2).

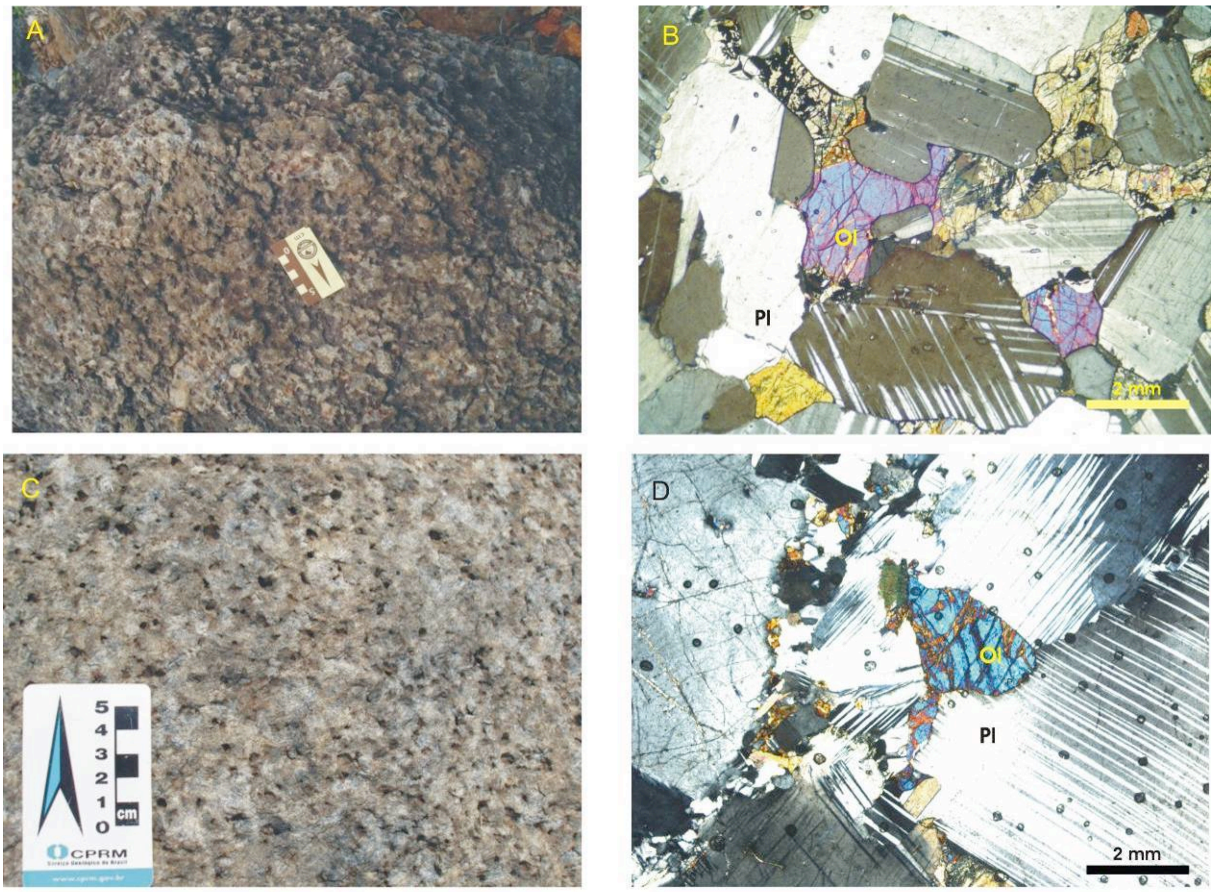

Figure 3.4. Anorthositic rocks of the KPS A-B) OSCK16-Leucotroctolite mottled with Pl cumulus and intercumulus Ol; C-D) OSCK06-medium to coarse-grained anorthosite.

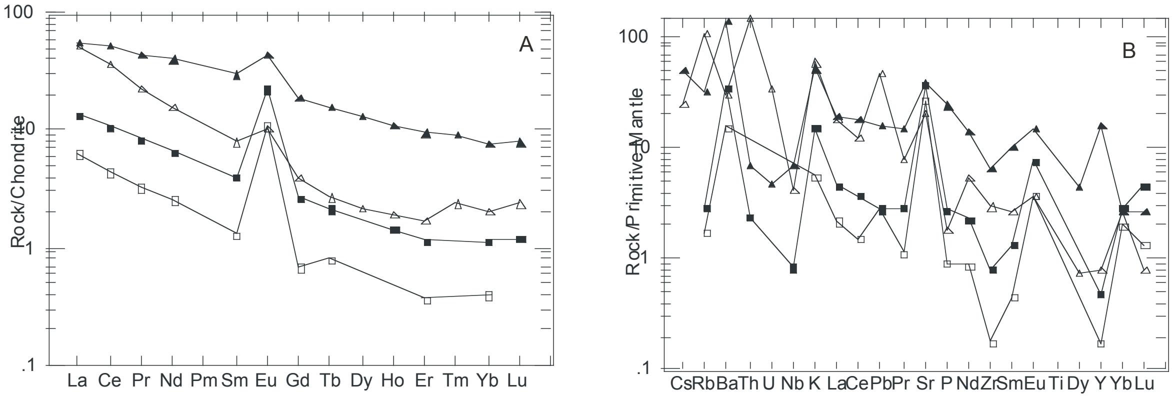

Figure 3.5. A) REE distribution pattern for anorthositic samples normalized to chondrite (Sun & Mc Donough, 1989). B) Trace elements diagram normalized to Primordial Mantle (Sun & Mc Donough, 1989).

3.4.1.2. Gabbros

Gabbros of the KPS are represented by magnetite gabbro, leucogabbro and olivine gabbro. Samples ONC77 and ONC88 represent coarse-grained olivine gabbros collected in the southern part of the KPS (Fig. 3.2). They are made of 20-40 % euhedral olivine (> 01 mm), tabular plagioclase crystals (50-70 % wt), with minor clinopyroxene, magnetite and accessory zircon. The magmatic fabrics of gabbros are characterized by hypidiomorphic and subophitic textures (Fig. 3.6).

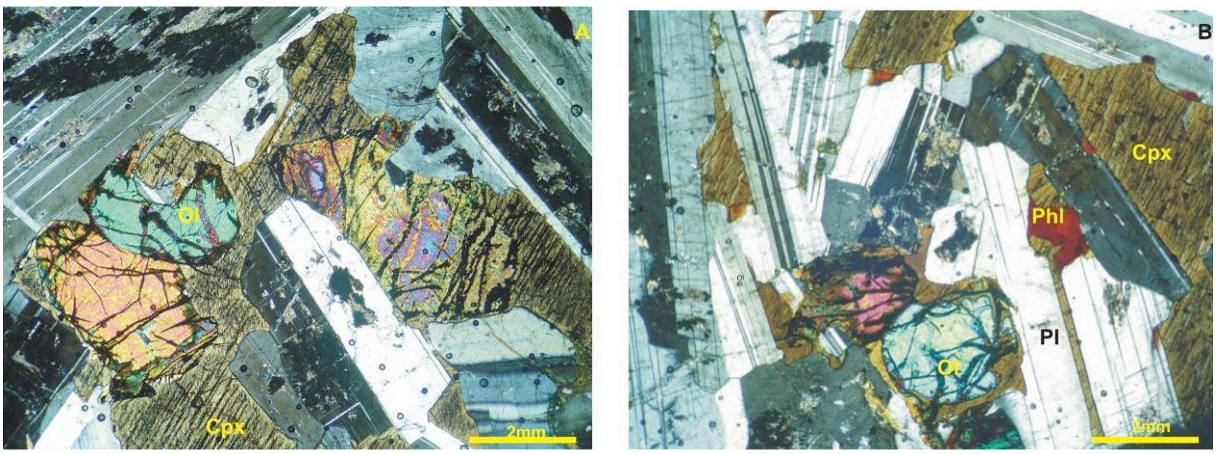

Figure 3.6. A-B) Olivine gabbro (ONC88).

The Uanguembela pluton (Fig. 3.7) is exposed ca. 50 km south of Otchindjau. It is represented mainly by magnetite leucogabbro and olivine gabbro and is surrounded by red granite. Phlogopite (02 - 05 %vol) is frequent and easily recognized in hand specimen in this particular intrusion. In some portions, igneous lamination can be observed and is marked by the orientation of plagioclase crystals. Porphyritic and equigranular textures are preserved. Plagioclase grains (> 2 mm) ranging from 65-85 %vol are subhedral and display albite and Carlsbad-albite twinning, which are deformed in places. Augite is subhedral with exsolution lamellae of orthopyroxene, ilmenite needles, with rare olivine and plagioclase inclusions.

Field observations as well in landsat image (Fig. 3.7) are possible to see presence of igneous layering in parts of the pluton (e.g. Uanguembela intrusion). It also displays moderate to well developed igneous rhythmic layering, particularly along the margin of the pluton. The layering is mainly defined by variations in the relative proportions of plagioclase and clinopyroxene.

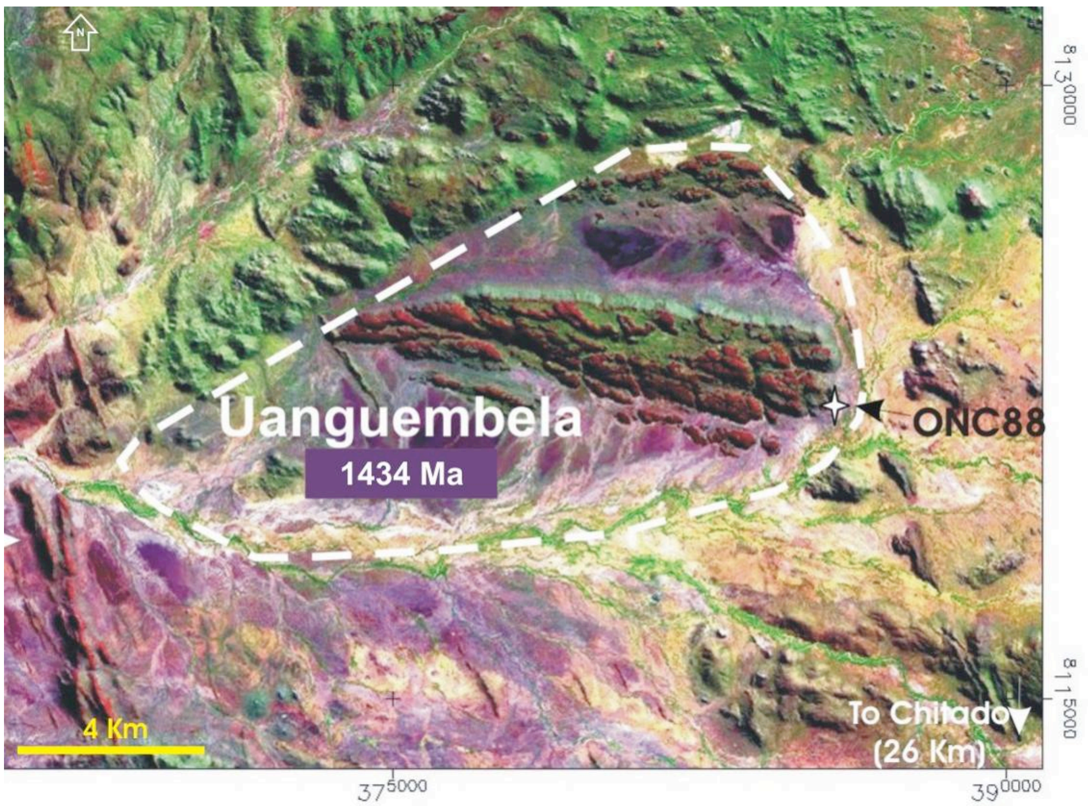

Figure 3.7. Landsat image of the Uanguembela pluton showing location of the 1434 ± 2 Ma leucogabbro – ONC88 sample.

When normalized to chondrite, gabbros are enriched in LREE and depleted in HREE. Eu-positive anomaly is considerably smaller when compared with the anorthosites. This is caused by the minor content of plagioclase and higher abundance of mafic phases as olivine and clinopyroxene. They are also characterized by higher content of Fe_2O_3 (10 to 13 wt %) and MgO (between 5.75 and 8.89 wt %).

When normalized to primitive mantle, the gabbros show enrichment in LILE. In the trace elements diagram they have Nb negative anomaly being marked by moderate contents of Ba (between 206 to 296 ppm), Sr (168.7 to 465.5 ppm) Co (60-66 ppm), Cu (70-138 ppm) and Ni (ranging from 16 to 57 ppm) (Fig. 3.8-B and Table 3.2).

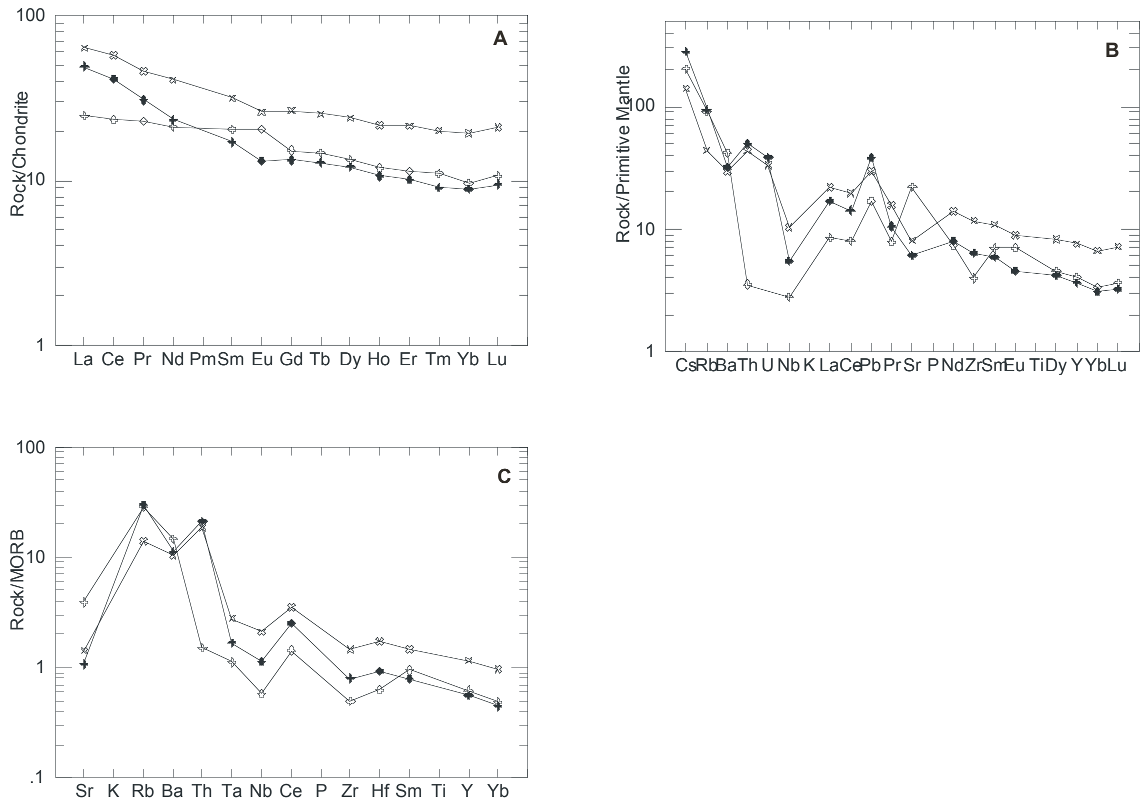

Figure 3.8. A) Gabbros compositions normalized to chondrite (A) Primordial Mantle (B) (Sun & Mc Donough, 1989) and normalized to MORB (C) (Pearce, 1983).

Table 3.2. Geochemical data of major and trace and rare earth elements of basic plutonic suite.

Sample	**OSCK 06**	**OSCK 07**	**OSCK16**	**OSCK50**	**OSCK53**	**OSCK60**	**OSCK 36**
Rock type	Anorthosite	Anorthosite	Leucotroctolite	Anorthosite	Gabbro	Gabbro	Gabbro
Utm - S	8307525	8292558	8299006	8083068	8087867	8141300	8089037
Utm - E	377679	372854	387866	389091	387013	392006	437003
Major	*elements*						
SiO_2	54.33	52.11	47.74	50.34	49.97	46.1	52.89
Al_2O_3	25.47	27.39	27.23	23.16	15.38	16.8	14.7
Fe_2O_3	2.05	2.54	4.65	5.25	13.36	11.53	9.9
MgO	1.55	0.67	4.26	2.11	5.75	8.89	8.29
CaO	10.58	11	12.2	8.86	9.6	8.85	9.69
Na_2O	2.6	4.43	2.83	4.25	2.28	2.56	1.68
K_2O	1.77	0.45	0.17	1.55	0.75	1.02	1.12
TiO_2	0.15	0.54	0.1	1.05	1.65	1.01	0.6
P_2O_5	0.04	0.06	0.02	0.52	0.16	0.13	0.08
MnO	0.04	0.03	0.06	0.11	0.19	0.18	0.17
Cr_2O_3	0.002	0	0.003	0.005	0.016	0.022	0.054
L0I	1.4	0.7	0.7	2.6	0.7	2.8	0.8
SUM	99.99	99.93	99.98	99.81	99.83	99.92	99.99
Trace	*Elements*						
Ba	206.7	249.1	107	942	206.5	293.3	222
Be	1	1	0	1	1	1	1
Co	34.7	33.3	32.6	22.1	62.7	66	59.9
Cs	0.2	0	0	0.4	1.1	1.6	2.2
Ga	17.9	25	17.6	19.9	19.6	18.8	15.3
Hf	1.1	0	0	1.8	4.1	1.5	2.2
Nb	2.9	0.6	0	4.9	7.3	2	3.9
Rb	68.8	1.8	1.1	20.4	27.8	57.4	59.3
Sn	0	0	0	0	1	0	0
Sr	439	785	566	833	168	465	128
Ta	0.3	0	0	0.4	0.5	0.2	0.3
Th	12.6	0.2	0	0.6	3.7	0.3	4.2
U	0.7	0	0	0.1	0.7	0	0.8
V	12	72	10	68	336	256	205
W	182.5	229.4	0.3	66.7	166.6	108	138.1
Zr	33	9.1	2	74	130.3	44.5	71.4
Y	3.6	2.2	0.8	71.5	34.4	18.5	16.6
La	12.2	3.2	1.5	13.1	15	5.8	11.6
Ce	22.1	6.6	2.7	31.7	34.9	14.2	25.1
Pr	2.12	0.79	0.31	4.15	4.33	2.16	2.9
Nd	7.4	3.1	1.2	18.6	18.9	9.9	10.8
Sm	1.2	0.6	0.2	4.5	4.8	3.1	2.6
Eu	0.61	1.29	0.63	2.49	1.5	1.18	0.76
Gd	0.8	0.55	0.14	3.9	5.43	3.12	2.72
Tb	0.1	0.08	0.03	0.6	0.94	0.55	0.48
Dy	0.56	0.08	0.11	3.26	6.06	3.37	3.07
Ho	0.11	0.08	0	0.61	1.22	0.67	0.6
Er	0.28	0.19	0.06	1.56	3.54	1.88	1.67
Tm	0.06	0	0	0.23	0.51	0.28	0.23
Yb	0.34	0.13	0	1.32	3.27	1.64	1.51
Lu	0.06	0.04	0	0.2	0.53	0.27	0.24
Mo	0.3	0.2	0.1	0.4	0.5	0.4	0.7
Cu	2.6	13.6	4.8	12.9	122.4	138.1	69.3
Pb	3.4	0.2	0.2	1.1	2.1	1.2	2.7
Zn	14	9	21	48	19	29	15
As	0	0	0	0	0	1.3	0.5
Cd	0	0	0	0	0.1	0.1	0
Sb	0	0	0	0	0	0.2	0
Bi	0	0	0	0	0	0	0
Ag	0	0	0	0	0	0	0
Au	0	0	0	0	0	0	2.7
Hg	0.04	0.06	0	0.03	0.03	0.03	0.03
Tl	0	0	0	0	0.1	0.1	0.1
Se	0	0	0	0	0	0	0
Ni	44	6	130	36	74	174	133
Sc	3	5	1	15	41	35	34
La/Sm	10.16	5.33	7.5	2.72	3.12	1.87	4.46
Zr/Nb	11.37	15.16	-	15.10	17.84	22.25	18.30

Table 3.2. (Continuation). Geochemical data of major and trace and rare earth elements of acid plutonic suite.

Sample	OSCK 01	OSCK 37	OSCK 39	OSCK 47	OSCK 35	OSCK58	OSCK 64
Rock type	Granite	Gnaisse	Gnaisse	Granite	Granite	Monzonite	Mangerite
Utm - S	8307523	8089045	8088170	8079213	8090078	8140386	8156623
Utm - E	376563	436672	434676	400200	451074	392845	388272
Major	*Elements*						
SiO_2	65.3	71.54	66.33	75.03	74.31	59.8	56.89
Al_2O_3	15.95	14.29	16.5	13.16	9.37	19.85	14.78
Fe_2O_3	4.23	2.34	4.23	1.64	6.93	6.31	11.64
MgO	1.28	0.58	1.2	0.16	0.51	1.38	0.15
CaO	3.48	1.05	4.3	1.02	0.16	1.57	2.17
Na_2O	3.81	2.86	4.04	4.46	1.2	2.96	4.46
K_2O	3.84	6.18	1.23	3.13	5.62	4.98	5.68
TiO_2	0.6	0.36	0.59	0.18	0.69	0.85	1.5
P_2O_5	0.22	0.1	0.22	0.09	0.06	0.22	0.17
MnO	0.09	0.03	0.04	0.03	0.03	0.14	0.27
Cr_2O_3	0.00	0	0	0	0.00	0.00	0
L0I	0.9	0.6	1.1	1	0.9	1.7	1.6
SUM	99.71	99.93	99.79	99.91	99.78	99.78	99.32
Trace	*Elements*						
Ba	1899	688.2	926.1	840.2	1413.1	1444.1	517
Be	1	1	2	2	1	2	1
Co	9.2	28.8	31.5	35.7	33.3	26	7.7
Cs	0.2	3.1	3.3	0.3	1.9	6.1	0.4
Ga	19.2	13	22.1	15.4	11.7	26.3	32.2
Hf	9.1	3.4	12.5	4.7	8.8	7.3	74.8
Nb	8.4	9.7	17.2	7.4	10.7	14.6	118.3
Rb	65.6	263.5	90.8	64	149.1	175.5	72.4
Sn	1	2	2	0	1	2	0
Sr	530.6	194.5	394.2	177.8	129.6	350.5	68.8
Ta	0.4	0.9	1.5	0.6	1.1	1.2	5.7
Th	9.3	13.1	50.8	17.3	16.8	13.8	4.1
U	0.9	1.8	4	1.8	2.7	3	1.5
V	68	25	50	12	74	82	0
W	0.2	288.2	267.9	354.5	288.2	107	58.1
Zr	346.3	113.3	487.2	151.3	304.3	242.2	4129.2
Y	22.3	28.4	41.2	29.6	27.3	49	124.3
La	63.8	26.3	37.4	31.6	31.7	59.6	216.5
Ce	126.1	59.9	289.4	71.5	74	127.7	303.7
Pr	13.55	6.68	29.8	7.17	8.41	15.11	58.26
Nd	47.9	24.3	100.5	26	32.5	56.6	232.8
Sm	7.5	5.2	15.6	4.9	6.1	11.4	38.1
Eu	2.15	1.07	1.93	1.12	1.37	2.45	5.92
Gd	5.29	4.27	10.2	4.18	4.57	9.02	30.39
Tb	0.82	0.83	1.61	0.82	0.79	1.65	4.34
Dy	4.3	4.74	8.51	4.61	4.86	8.81	23.4
Ho	0.74	0.96	1.44	0.99	0.83	1.69	4.46
Er	2.07	2.89	3.74	3	2.52	4.85	12.67
Tm	0.27	0.4	0.48	0.54	0.39	0.71	2.06
Yb	2.05	2.36	2.93	3.39	2.6	4.75	15.39
Lu	0.28	0.32	0.43	0.53	0.38	0.7	2.95
Mo	0.2	0.1	0.2	0.1	0.5	0.5	1.3
Cu	14	0.9	6.1	0.6	1.6	29.1	12.8
Pb	1.7	4.3	7.5	1.6	4.4	4	2.8
Zn	41	28	40	7	27	162	84
As	0.5	0	0.6	0	0	0	1.4
Cd	0	0	0	0	0	0	0.1
Sb	0	0	0	0	0	0.1	0
Bi	0	0	0	0	0	0.2	0
Ag	0	0	0	0	0	0.1	0
Au	1.8	0	0	0	0	0	0
Hg	0	0.1	0.08	0.05	0.1	0.04	0.02
Tl	0	0.2	0.2	0	0	0.3	0
Se	0	0	0	0	0	0	0
Ni	9	0	15	0	13	18	0
Sc	10	8	9	5	6	21	11
La/Sm	8.50	5.05	2.39	6.44	5.19	5.22	5.68
Zr/Nb	43.36	11.68	28.32	20.44	28.43	16.58	34.90

3.4.2. Acid Plutonic Suite

The acid plutonic suite is composed of various granitoids including granite, syenite, monzonite, mangerite, and are called informally as “Red Granites”. Traditionally the regional gneissic rocks have been described as part of the acid suite; however field relationships show that they represent the country-rocks to the KPS.

3.4.2.1. Granitic and Gneissic rocks

The acid plutonic rocks comprise coarse-grained porphyritic red granites. These rocks are spatially associated with and intruded into the basic plutonic suite of the KPS in several areas. They form plutons of different sizes and shapes and are mainly of red to reddish-brown color and granular to porphyritic texture.

Granites are composed of quartz (40-65 % wt), K-feldspar (30–40% wt), biotite (15-20% wt), plagioclase, muscovite, ilmenite, magnetite, zircon in a coarse-grained, phaneritic to porphyritic texture.

SiO_2 contents are between 75% and 74%, Al_2O_3 between 9.37% and 15.95%, CaO in the range between 0.16% and 3.48%, Na_2O from 1.2% to 4.46 %, and K_2O between 3.13% and 5.62 % (Table 02). They have high Ba values between 1899 and 840 ppm, and show negative Sr, P, and Ti anomalies.

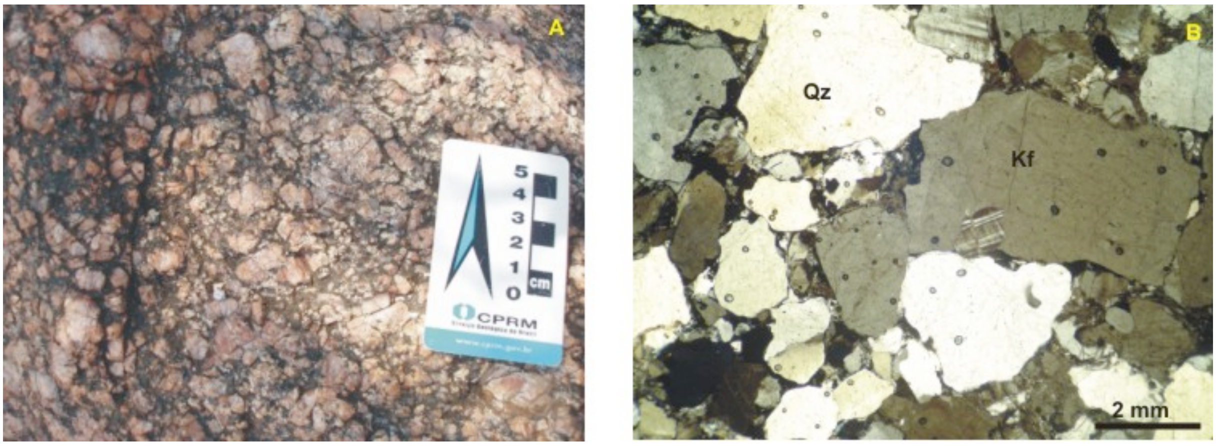

Figure 3.9. Granite of the acid plutonic suite with porphyritic texture.

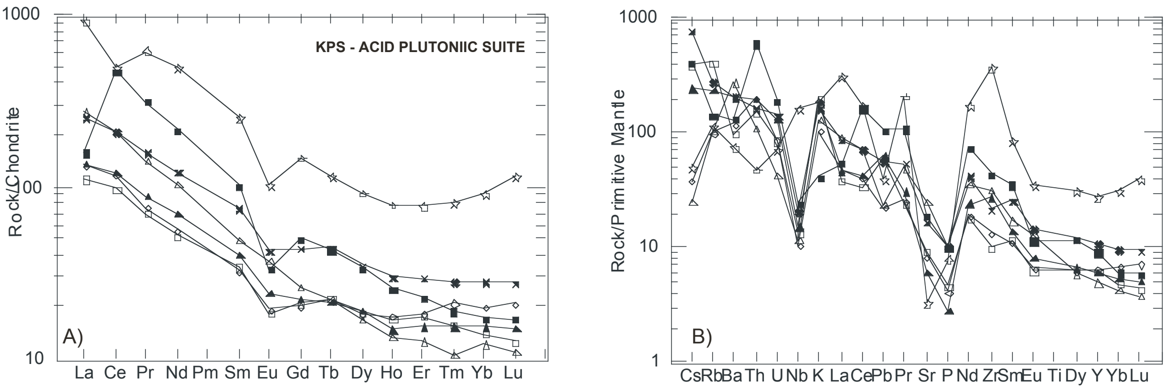

Figure 3.10. REE for anorthositic samples normalized to chondrite (Sun & Mc Donough, 1989). B) Trace elements spiderdiagram normalized to Primordial Mantle (Sun & Mc Donough, 1989).

The gneissic rocks (OSCK37 and OSCK39) from the Ruacana region in the southern border of the KPS represent the basement and occur in the southern part of KPS close to the border between Angola and Namibia. Several varieties of fine- to medium-grained banded gneisses are recognized. They are essentially composed of quartz, microcline – microperthite, plagioclase and biotite ± muscovite. The accessory phases include zircon, titanite and magnetite. Antiperthite, chess-board albite and albite rims around plagioclase at the contact with K-feldspar are observed. Textures observed in thin sections as well as in the field suggest that these are derived from granitic protoliths.

Major element compositions of the gneisses are characterized by SiO_2 ranging from 66.33% to 71.54 wt%; with moderate to high Al_2O_3 (13.16 to 16.5%); TiO_2 (0.36 to 0.59%); low CaO (1.05 to 4.3%); low MgO (0.58% to 1.2 %), variable but moderate to high contents of alkalies (Na_2O ranges from 2.86 to 4.04%, and K_2O varies from 2.34 to 6.18%) with low to moderate contents of Fe_2O_3 (2.34 to 4.23%). These gneisses are characterized by relatively enriched large ion lithophile elements (LILE) such as K, Rb, Ba with distinctive Eu negative anomalies.

The Na_2O–K_2O relationship for gneiss granite- to monzonite compositions for the protoliths. In the AFM plot the gneiss reveal a calc-alkaline character (Fig. 3.3-A).

3.4.2.2 Monzonitic rocks

Monzonite and mangerite are represented by samples OSCK58 and OSCK64 and are mainly composed of K-feldspar, hornblende and orthopyroxene. These rocks are enriched in LREE and slightly depleted in HREE (Fig. 10). Their major element compositions are variable (e.g. SiO_2 between 57 and 60 %, Al_2O_3 ca. 15 to 20%, Fe_2O_3 6,31 and 11,64%; MgO between 1,38 and 0,15%, CaO 1,57 to 2,17%, Na_2O 2,96 to 4,46% and K_2O 5 to 5,68%). Ba contents vary from 517 to 1444 ppm. An important characteristic of the mangerite sample OSCK64 is the high content of LREE, expressed by Sm (38 ppm) and Nd (233 ppm). Zr content is also very high (4129 ppm), which is compatible with the abundance of zircon in the mangeritic sample (OSCK64).

Chemical compositions of granitoid rocks are used to provide information about tectonic settings and source rock characteristics (Pearce et al., 1984; Harris et al., 1986; Whalen et al., 1987; Eby, 1990, 1992). Geological interpretations have been used in evaluating the tectonic setting of the granitoid rocks of the KPS. Here, we employ tectonic discrimination diagrams to evaluate the tectonic settings or source rocks of the acid plutonic suite (Fig. 3.10).

Based on the 10000*Ga/Al vs. Zr + Nb + Ce + Y ratio, most of the samples fall in the A-type granite field, with only two samples tending to be I- or S-type granites. On the tectonic discrimination plots, these rocks fall within the plate granite (WPG) and post-collisional granite fields (Fig. 3.13-C, D).

The acid plutonic suite is mainly peraluminous with Alumina Saturation Index (ASI) values higher than 1.1 (Fig. 3.10). Two samples are metaluminous and are represented by the syenogranite (OSCK01) and by the mangerite (OSCK64).

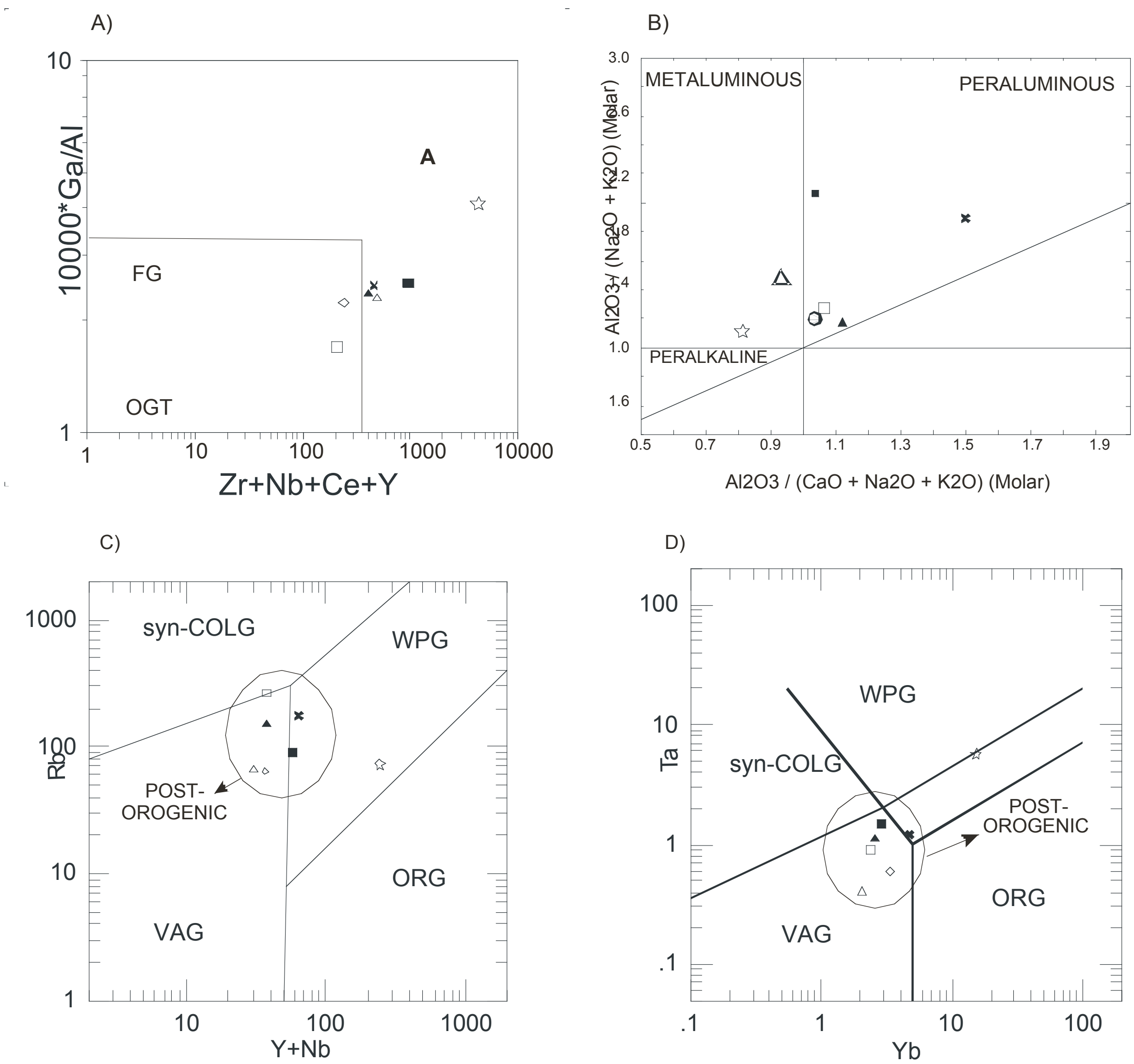

Figure 3.11. A) Zr + Nb + Ce + Y vs. 10000*Ga/Al for acid plutonic suite of the KPS indicating the predominantly A-type character. FG, Fractionated Granites; OGT, Other granite types. B) Diagram $Al_2O_3/(CaO+Na_2O+K_2O)$ vs. $Al_2O_3/(Na_2O+K_2O)$, (Shand, 1929). C) Tectonic discrimination diagrams Rb-(Y + Nb) and D) Ta vs. Yb (ppm) (Pearce et al., 1984).

3.5. Age and Isotopic Results

In this study we have combined the use of zircon U–Pb age determinations conducted by thermal ionisation mass spectrometry (TIMS) and Sm-Nd data obtained at the geochronology laboratory of the University of Brasilia. The data provide new information on magmatic ages and the petrological nature of the original magmas of the Kunene Complex. U–Pb results for samples OSCK64 and ONC 88 are in Tables 3.3 and 3.4, and Sm–Nd data are in Table 3.5.

Zircon grains from sample OSCK64 vary from well formed, small, equant to stubby prismatic grains, to large (200μm) prismatic crystals with well defined crystal faces. Analytical points shows the upper intercept age of 1403 ± 7 Ma representing time of crystal growth and, therefore, the crystallization age of the mangerite intrusion.

Sample Fraction	Size (mg)	U (Ppm)	Pb (Ppm)	Th (Ppm)	U/Th	$^{206}Pb/^{204}Pb$	$^{207*}Pb/^{235}U$	(pct)	$^{206*}Pb/^{238}U$	(pct)	Correl. Coeff.	$^{207*}Pb/^{206*}Pb$	(pct)	$^{206*}Pb/^{238}U$ Age (Ma)	$^{207*}Pb/^{235}U$ Age (Ma)	$^{207*}Pb/^{206*}Pb$ Age (Ma)
OSCK64A	0,043	117,91	32,361	25,31	0,2146	3122,906	2,98618	0,542	0,242917	0,537	0,9899	0,089157	0,077	1401,8	1404,1	1407,5
OSCK64B	0,045	167,79	51,466	24,18	0,1441	4176,135	3,0799	0,582	0,251885	0,557	0,9585	0,088681	0,166	1448,2	1427,7	1397,3
OSCK64C	0,067	81,753	20,229	16,24	0,1987	2510,032	2,89357	0,712	0,235239	0,687	0,9653	0,089212	0,186	1361,9	1380,2	1408,7
OSCK64D	0,041	86,789	26,561	26,54	0,3058	1926,833	3,06711	0,547	0,251271	0,546	0,9955	0,088529	0,052	1445	1424,5	1394

Table 3.3. U-Pb isotopic data for sample OSCK64.

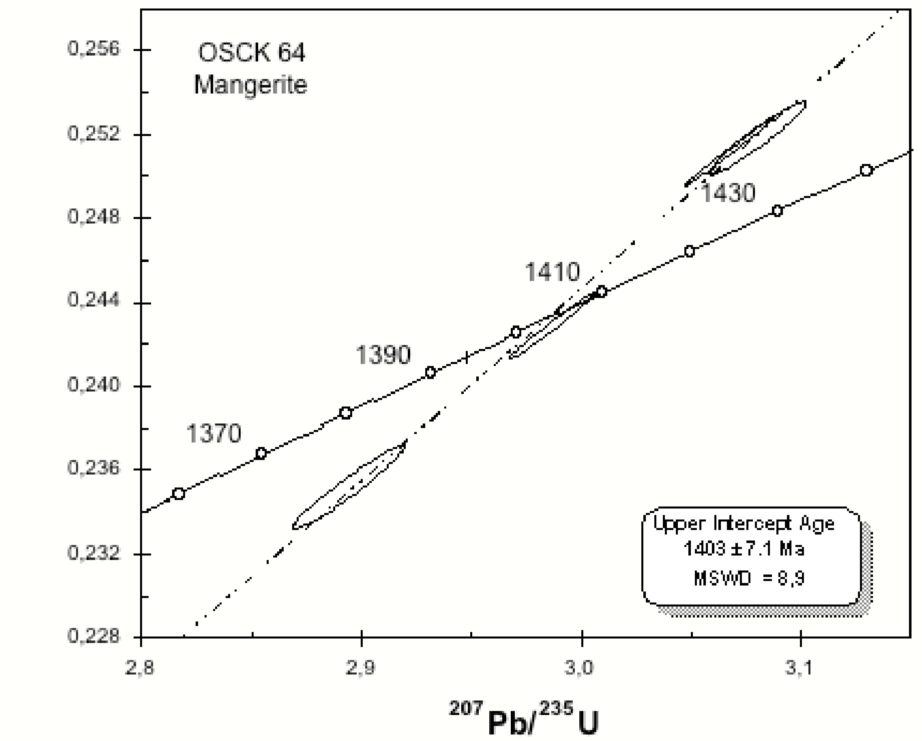

Figure 3.12. ID-TIMS U-Pb Upper intercept age of mangerite OSCK64.

Zircon grains from sample ONC 88 are also well formed, equant to stubby prismatic grains, varying from small to large (200μm) prismatic crystals with well defined crystal faces. U-Pb data for sample ONC 88 from Uanguembela pluton indicate the crystallization age of 1434 ± 2 Ma (Fig. 3.3).

These new ages of 1434 and 1403 are ca 65-30 Ma older than 1371 Ma obtained in mangerite vein in anorthosite of Quihita region (Mayer et al, 2004). These data demonstrate that the KPC probably represents a multi-pulse intrusion implying in the existence of several magmatic chambers operating at different times.

Sample Fraction	Size (mg)	U (Ppm)	Pb (Ppm)	Th (Ppm)	U/Th	$^{206}Pb/^{204}Pb$	$^{207*}Pb/^{235}U$	(pct)	$^{206*}Pb/^{238}U$	(pct)	Correl. Coeff.	$^{207*}Pb/^{206*}Pb$	(pct)	$^{206*}Pb/^{238}U$ Age (Ma)	$^{207*}Pb/^{235}U$ Age (Ma)	$^{207*}Pb/^{206*}Pb$ Age (Ma)
ONC88A	0,01	214,37	98,787	108,8	0,5076	98,0921	3,0874	0,66	0,247444	0,7	0,894	0,09054	0,443	1425,3	1430	1434
ONC88B	0,008	499,99	245,24	136	0,272	970,747	3,08532	0,55	0,24692	0,54	0,8786	0,0908	0,232	1442	1429	1442
ONC88C	0,079	395,07	93,209	13,77	0,03487	4506,56	3,10701	0,44	0,248193	0,44	0,991	0,09079	0,059	1429,1	1434	1442

Table 3.4. U-Pb data for sample ONC 88.

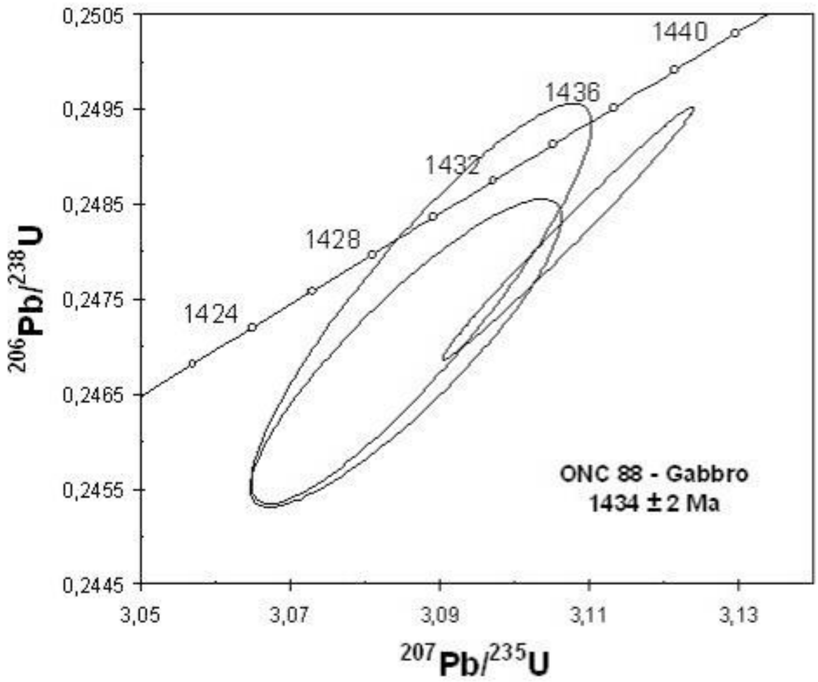

Figure 3.13. U-Pb Age of olivine-gabbro from Uanguembela Pluton in Southern of KPS.

Samples of both basic and acid suites of the KPS were analyzed for their Sm-Nd isotopic composition. The data are shown in table 3.5. The $\varepsilon_{Nd}(T)$ values were calculated with reference to the U-Pb age of 1.4 Ga. The $\varepsilon_{Nd}(T)$ of mafic rocks range from -0.67 to -12.4. Acid Plutonic Suite has $\varepsilon_{Nd}(T)$ between -11.02 and -0.67 reflecting crustal contamination. The negative values of $\varepsilon_{Nd}(T)$ indicate that crustal contamination has played an important role in the evolution of basic magmas and suggest that the granites are most likely derived from remelting of Paleoproterozoic continental crust as indicated by the model ages (Fig. 3.14).

Sample	Rock	Utm - S	Utm – E	Locality	Sm(ppm)	Nd(ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	ε (0)	ε (T)	T_{DM} (Ma)
OSCK06	Anorthosite	8307525	377679	Chibemba	1,756	13,071	0,0812	0,510941	-33,10	-12,42	2409
OSCK16	Leucotroctolite	8299006	387866	Chibemba	0,217	1,252	0,1046	0,511729	-17,73	-1,21	1822
OSCK50	Anorthosite	8083068	389091	Chitado	4,13	18,8	0,1328	0,512035	-11,76	-0,30	1883
ONC 74	Anorthosite	8169849	350280	Oncócua	0,2	1,3	0,095	0,511674	-18,80	-0,56	1745
ONC 79	Leucotroctolite	8130207	351234	Bembe	0,9998	4,33	0,1395	0,511822	-15,92	-5,67	2504
ONC 83	Anorthosite	8110356	353586	Otchindjau	5,57	25,79	0,1306	0,512064	-11,20	+0,67	1780
ONC 94	Anorthosite	8237283	385873	Chibemba	0,34	2,47	0,0844	0,511500	-22,19	+1,81	1810
OSCK36	Dolerite	8089037	437003	Chitado	2,65	11,759	0,1362	0,511893	-14,53	-3,69	2250
OSCK53	Mt Gabbro	8087867	387013	Chitado	4,99	20,01	0,1509	0,512274	-7,10	+1,12	1847
ONC 77	Ol Gabbro	8136140	341001	Bembe	0,465	1,964	0,1432	0,512181	-8,91	+0,69	1846
ONC 88	Ol Gabro	8120966	384187	Oncócua	1,96	8,99	0,1319	0,512004	-12,37	-0,74	1920
OSCK01	Granite	8307523	376563	Chibemba	7,865	50,796	0,0936	0,511127	-29,47	-11,02	2423
OSCK35	Granite	8090078	451074	Chitado	5,55	28,45	0,1178	0,511518	-21,85	-7,72	2415
OSCK39	Gneiss	8088170	434676	Chitado	15,288	100,785	0,0917	0,511638	-19,51	-0,67	1743
OSCK58	Monzonite	8140386	392845	Oncócua	11,38	60,15	0,1143	0,511612	-20,01	-5,25	2182
OSCK64	Mangerite	8156623	388272	Oncócua	40,237	237,1	0,1026	0,51169	-18,49	-1,61	1843
ONC 76	Granite	8156004	333653	Oncócua	25,86	141,441	0,1105	0,511639	-19,49	-4,04	2060
ONC 89	Granite	8121397	387398	Oncócua	11,75	62,26	0,1141	0,511722	-17,87	-3,06	2010

Table 3.5. Sm-Nd isotopic data and $\varepsilon_{Nd}(T)$ calculated with new age of 1.4 Ga for KC rocks.

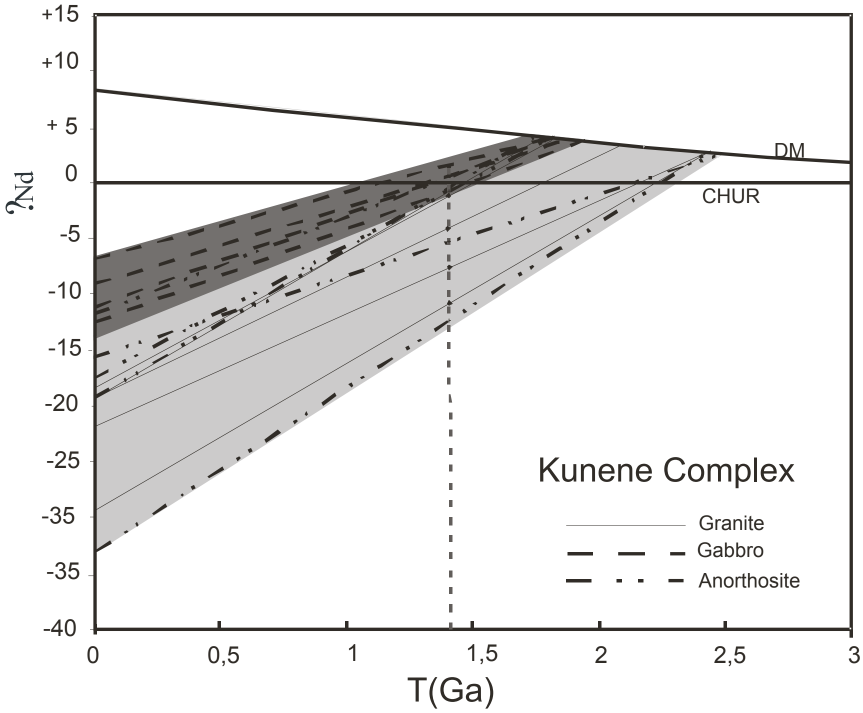

Figure 3.14. Evolution ε_{Nd} x Time diagram of KPS rocks with 1.42 Ga reference.

Four samples display positive values of $\varepsilon_{Nd}(T)$ and are represented by two anorthosites of Oncócua and Chiange regions ONC83 and ONC94 with +0,67 and +1,81, respectively, an olivine gabbro (ONC77) from Bembe intrusion with +0,69 and a magnetite gabbro (OSCK53) from Chitado in the southern border of KPS with +1,12. These samples are, therefore, the most primitive of this suite of samples and indicate the depleted nature of the mantle source.

The variation of negative $\varepsilon_{Nd}(T)$ values between -0,30 to -12,42 reflects different degrees of crustal contamination of the basic rocks of the KPS rocks (Fig. 3.14).

3.6. Discussion and Conclusion

The Kunene Plutonic Suite (KPS) which comprises a basic plutonic suite and an acid plutonic suite. The basic suite is mainly formed by gabbro-anorthositic intrusions and layered mafic bodies of different sizes.

The basic plutonic suite presents negative Nb anomalies, high LILE and REE contents which are general characteristics of arc tholeiitic magmas. The important variation of ε_{Nd} (T) (-12,42 to +1,81) shown by mafic rocks suggests that the basic magmas derived from a depleted mantle source and were modified by different degrees of crustal assimilation.

The acid plutonic suite is composed of two granitoid groups presenting distinct geochemistry signature (Fig.3.9? and 3.10). The first group shows sub-alkaline, peraluminous to metaluminous character (I- or S-type), Nb negative anomaly and negative ε_{Nd} (T) (-11,02 to -0,67) (Fig. 3.14), suggesting that they were probably generated by remelting processes of an heterogeneous continental upper crust. The second group is represented by mangeritic intrusions have Nb positive anomalies (Fig. 3.9?). The mangeritic intrusions post-date the gabbro–anorthositic intrusions of the KPS. They are richer in the alkalies and plot close to the peralkaline field on the ASI diagram and may be interpreted as formed in anorogenic extensional setting (Fig. 3.11 and 3.15).

The part of the KPS exposed in NW Namibia mainly comprises white anorthosites and leuconorites that are characterised by a strong sericitisation, saussuritisation, and albitisation of plagioclase and chloritization of Fe-Mg silicates. Geochemical characteristics as well as O, Sr, and Nd isotope data that indicate a mantle origin of the anorthosites and hence suggest that the magma parental to the anorthosites formed by partial melting of the upper mantle (Druppel et al., 2007).

The production of such large volumes of anorthositic magma by partial melting would presumably lead to a gravitational collapse of the lower crustal source regions. Therefore, we interpret the parental magma of the anorthosites of the KPS to be derived from partia1 melting of the upper mantle with anatexis of crustal material leading to the formation of the associated felsic rocks.

New crystallization ages of 1434 ± 2 Ma of the Uanguembela intrusion and 1403 ± 7 Ma for a mangeritic intrusion are here interpreted as the crystallization ages of the original magmas. These ages are approximately 60 to 40 Ma older than the age of 1371 ± 2 Ma for a mangeritic vein in the central portion of the KPS (Quihita region) (Mayer et al 2004), suggesting that the acid plutonic suite post-dates the basic plutonic suite represented by gabbroic and anorthositic intrusions. These new data give a new insight on the chronology of magmatic events suggesting that KPS was formed by multi–pulse magmatism in an extensional setting at the southern border of the Congo Craton.

The age of the KPS and the respective compositions of the anorthositic and the felsic rock suites resemble that of other large Proterozoic anorthosite massifs worldwide like, for example, Harp Lake, Marcy, and Nain (Ashwal, 1993).

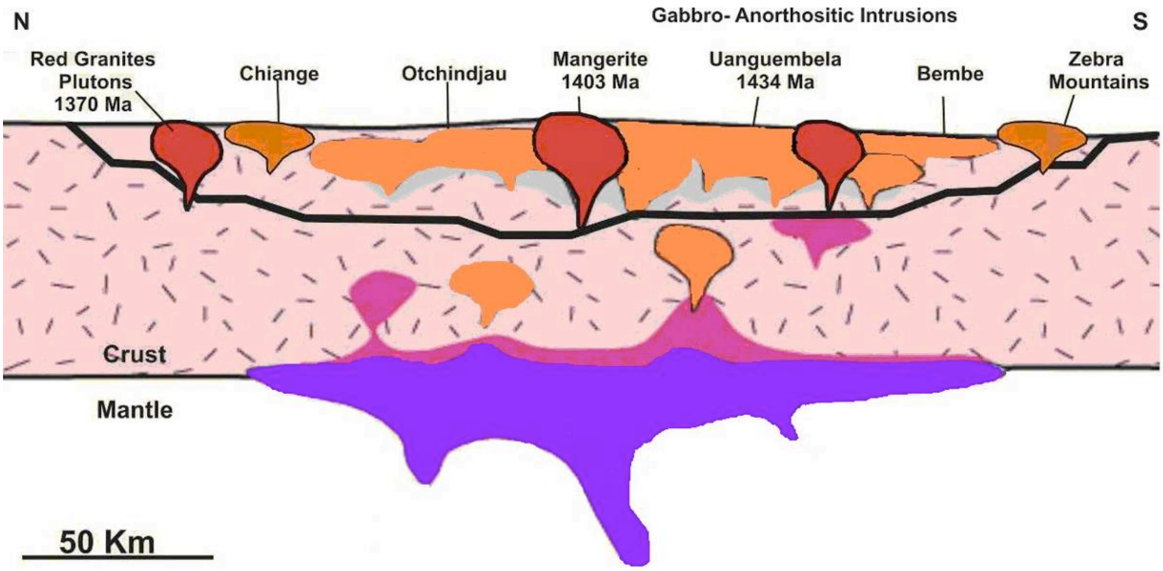

Figure 3.15. Hypothetic Tectonic Model of Kunene Plutonic Suite in an anarogenic intracratonic and extensional setting.

3.7 Acknowledgements

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3.8. References

Ashwal, L.D., 1978. Petrogenesis of massif-type anorthosites: crystallization history and liquid line of descent of the Adirondack and Morin Complexes, Ph.D. thesis, Princeton University, p. 136.

Ashwal, L.D., 1993. Anorthosites. In: Minerals and Rocks, vol. 21. Springer-Verlag, New York, p. 422.

Ashwal, L.D., Hamilton, M.A., Morel, V.P.I., Rambeloson, R.A., 1998. Geology, petrology and isotope geochemistry of massif-type anorthosites from southwest Madagascar.Contributions Mineralogy Petrology 133, 389–401.

Ashwal, L.D., Twist, D., 1994. The Kunene complex, Angola/Namibia: a composite massif-type anorthosite complex. Geological Magazine 131, 579–591.

Carvalho H. de. (1984) Estratigrafia do Precambriano de Angola., Sep Garcia da Orta, Serviço Geológico de Lisboa, (1-2), p 1-66.

Carvalho, H., Alves, P., 1990. Gabbro-anorthosite complex of SW Angola/NW Namibia. Instituto de Investigação Cienifica Tropical. Serie de Ciências da Terra, Com. No. 2, Dept. Ciências da Terra, Lisboa, p. 66.

Carvalho, H. & Alves, P., 1993. The Precambrian of SW Angola and NW Namíbia. Comunicações IICT, Série de Ciências da Terra, n° 4, 38 pp.

Carvalho, H.de, Castro, J.P., Silva Z.C.G., Viallete, Y. The Kibarian cycle in Angola - a discussion Geological Journal. Vol 22, Thematic Issue, 1987, pp. 85-102.

Carvalho, H., Tassinari, C.C., Alves, P.H., Guimarães, F. & Simões, M.C., 2000. Geochronological review of the Precambrian in western Angola: links with Brazil. Journal of African Earth Sciences, 31: 383-402.

Demaiffe, D., Duchesne, J.C., Hertogen, J., 1979. Trace element variations and isotopic compositions of charnockitic rocks related to anorthosites (Rogaland, S.W. Norway): Ahrens, L.H. (Ed.), Origin and Distribution of the Elements. Physics and Chemistry of the Earth, vol. 11, pp. 417–429.

Demaiffe, D., Hertogen, J., 1981. Rare earth element geochemistry and strontium isotopic evolution of a massif-type anorthositic charnockitic body: the Hidra Massif (Rogaland, S.W. Norway). Geochimica Cosmochimica Acta 45, 1545–1561.

DePaolo, D.J., 1981.A neodymium and strontium isotopic study of the Mesozoic calc-alkaline granitic batholiths of the Sierra Nevada and Peninsular Ranges, California. Journal of Geophysical Research 86, 10470–10488.

Druppel, K., von Seckendorff, V., Okrusch, M., 2001. Subsolidus reaction textures in the anorthositic rocks of the southern part of the Kunene Intrusive Complex, NW Namibia. European Journal Mineralogy 13, 289–309.

Druppel, K., von Seckendorff, V., Okrusch, M., 2007. Petrology and isotope geochemistry of the Mesoproterozoic anorthosite and related rocks of the Mesoproterozoic Kunene Intrusive Complex, NW Namibia.

Duchesne, J.C., Liégeois, J.P., Vender Auwera, J., Longhi, J., 1999. The crustal tongue melting model and the origin of massive anorthosites. Terra Nova 11, 100–105.

Eby, G. N. 1990. The A-type granitoids; a review of their occurrence and chemical characteristics and speculations on their petrogenesis. Lithos 26, 115-134.

Eby, G.N., 1992. Chemical subdivision of the A-type granitoids: petrogenetic and tectonic implications. Geology 20, 641–644.

Emslie, R.F., 1975. Pyroxene megacrysts from anorthositc rocks: new clues to the source and evolution of the parent magmas.Canadian Mineralogist 13, 138–145.

Emslie, R.F., 1980. Geology and petrology of the Harp Lake Complex, Central Labrador: an example of Elsonian magmatism. Geological Survey Canada Bulletin 293, 136.

Farmer, G.L., Boettcher, A.L., 1981. Petrologic and crystal-chemical significance of some deep seated phlogopites. American Mineralogist 66, 1154–1163.

Fram, M.S., Longhi, J., 1992. Phase equilibra of dikes associated with Proterozoic anorthosite complexes. American Mineralogist 77, 605–616.

Gioia, S.M.C., Pimentel, M.M., 2000. The Sm–Nd isotopic method in the Geochronology Laboratory of the University of Brasília. Anais da Academia Brasileira de Ciências 72, 219–245.

Greenwood, J.C., 1998. Barian-titanian micas from Ilha da Trinidade, South Atlantic. Mineralogical Magazine 62, 687– 695.

Harris, N.B.W., Marzouki, F.M.H., Ali, S., 1986. The Jabel Sayid complex, Arabian shield: geochemical constraints on the origin of peralkaline and related granites. Journal of Geological Society, London 143, 287–295.

Herz, N., 1969. Anorthosite belts, continental drift, and the anorthosite event. Science 164, 944–947.

I.G.A., 1998. Mineral Resources Map of Angola, scale 1:1,000,000. Luanda, Instituto Geológico de Angola.

Irvine, T.N., and Baragar, W.R.A. 1971. A guide to the chemical classification of the common volcanic rocks. *Canadian Journal of Earth Sciences,* 8:523-548.

Jones, D.L., McFadden, P.L., Kroner, A. and McWilliams, M.O., 1992. Paleomagnetic results from the late Precambrian Chela Group of southwest Angola. *Precambrian Res., 59, 1-13.*

Krogh, T.E., 1973. A low-contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determination. Geochimica et Cosmochimica Acta 37, 485–494.

Kroner. A. and Correia, H., 1980. Continuation of the Pan African Damara belt into Angola: a proposed correlation of the Chela Group in southern Angola with the Nosib Group in northern Namibia/SWA. Trans Geol. Soc. S. Afr., 83, 5-16.

Le Maitre,R.W. (ed.). 1989. A classification of igneous rocks and glossary of terms: Recommendations of the International Union of Geological Sciences-Subcommission on the Systematics of Igneous Rocks. Oxford. Blackwell Scientific Publications. 193p.

Longhi, J., Auwera, J., Fram, M.S., Duchesne, J.-C., 1999. Some phase equilibrium constraints on the origin of Proterozoic (massif) anorthosites and related rocks. Journal Petrology 40, 339–362.

Ludwig, K.R., 1993. PBDAT A Computer Programa for Processing Pb–U–Th. Isotope Data. USGS, Berkeley.

Ludwig, K.R. 2001. User’s manual for Isoplot/Ex v. 2.47. A geochronological toolkit for Microsoft Excel. BGC Special Publ. 1a, Berkeley, 55p.

Mayer, A., Hofman, A.W., Sinigoi, S., and Morais, E., 2004. Mesoproterozoic Sm-Nd and U-Pb ages for the Kunene Anorthosite Complex of SW Angola. Precambrian Res., 133, 187-206.

Markl, G., Frost, B.R., 1999. The origin of anorthosites and related rocks from the Lofoten Islands, Northern Norway. II. Calculation of parental liquid composition for anorthosites. Journal Petrology 40, 61–77.

Michot, P., 1955. Anorthosites et anorthosites. Bulletin de l'Acad_emie Royale de Belgique 41, 275–294.

Morais, E., Sinigoi, S., Mayer, A., Mucana, A., Miguel, L.G., Neto, J., 1998. The Kunene Gabbro-anorthosite Complex: preliminary results based on new field and chemical data. Africa Geoscience Review 5, 14.

Morais, E., Sinigoi, S., Mayer, A., Miguel L.G., 2000. Emplacement of a composite, massive anorthosite body within a Kibaran extensional context. Post-congress field excursion in the Kunene Complex. Geoluanda.

Morse, S.A., 1982. Layered intrusions and anorthosite genesis. In: Isachsen, Y.W. (Ed.), Origin of Anorthosite and Related Rocks, vol. 18. New York State Museum and Science Service Memoir, pp. 175–187.

Morse, S.A., 1982. A partisan review of Proterozoic anorthosites. American Mineralogist 67, 1087–1100.

Philpotts, A.R., 1968. Parental magma of the anorthosite - mangerite suite. In: Isachsen, Y.W. (Ed.), Origin of Anorthosite and Related Rocks, vol. 18. New York State Museum and Science Service Memoir, pp. 207–212.

Pearce, J. A., Harris, N. B. W. & Tindle, A. G. (1984). Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. Journal of Petrology 25, 956-983.

Shand, S. J., 1929. Eruptive rocks, D. Von Nostrand, Company. New York. 360 pp.

Silva, Z.C.G., 1990. Geochemistry of the Gabbro-Anorthosite Complex of Southwest Angola. Journal African Earth Sciences 10, 683–692.

Silva, Z.C.G., 1992. Mineralogy and cryptic layering of the Kunene anorthosite complex of SW Angola and Namibia. Mineralogical Magazine 56, 319–327.

Silva, A.T.S.F., Macedo, C.A.R., Ferreira, J.T., 1974. Interpretação das determinações de Idades Radiometricas K–Ar de algumas Rochas da Vila Paiva Coucerio, Quilenges, Chicomba e Caluquembe (Angola). Luanda, Serv. Geol. Minas. Mem. 15, 15.

Silva, A.T.S.F., Torquato, J.R., Kawashita, K., 1973. Alguns dados geocronológicos pelo método de K/Ar da região de Vila Paiva Couceiro, Quilenges e Chicomba (Angola). Boletim Geologia Minas Angola 24, 29–46.

Simpson, E.S.W., Otto, J.D.T., 1960. On the Precambrian anorthosite mass of southern Angola. 21st Int. Geol. Cong. Copenhagen 13, 216–227.

Stone, P., Brown, G.M., 1958. The Quihita-Kunene layered gabbroic intrusion of south- west Angola. Geol. Mag. 95, 195.

Sun, S.S., Mc Donough, W.F., 1989. Chemical and isotopic systematic of oceanic basalts: implication for mantle composition and processes. In: Saunders, A.D., Norry, M.J. (Eds.), Magmatism in the Ocean Basins. Geological Society of London Special Publications, Leicester, pp. 313– 345.

Tegtmayer, A. and Kroner, A., 1985. U-Pb zircon ages for granitoid gneisses in northern Namibia and their significance for Proterozoic crustal evolution of southwestern Africa. *Precambrian Res., 28, 311-326.*

Torquato, J.R., Ferreira da Silva, A.T., Cordani, U.G., Kawashita, K., 1979. Evolução Geológica do Cinturão Móvel do Quipungo no Ocidente de Angola. An. Acad. Brasil. Cienc. 51, 133–143.

Waard, D., 1967. On the origin of anorthosite by anatexis. Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen 70, 415–419.

Whalen J.B., Currie, K. L. & Chappell, B.W. 1987. A-type granites: geochemical characteristics, discrimination and petrogenesis. Contributions to Mineralogy and Petrology 95, 407-419.

Capítulo 4

Conclusões

A similaridade entre as idades de cristalização dos magmas da Série Acamadada Superior do Complexo de Niquelândia com 1248 ± 23 Ma (Pimentel et al. 2004) e da Suíte Plutônica Kunene com 1371 ± 2.5 Ma (Mayer et al. 2004), bem como a similaridade litológica, ambas constituídas por gabro, leucotroctolito e anortosito foram factores críticos que motivaram esta pesquisa, a fim de constatar alguma relação entre as mesmas. A pesquisa permitiu que estes complexos sao de natureza distinta e foram formados em ambientes. A Série Acamadada Superior foi formada em um ambiente de crosta oceânica, similar ao N e T-MORB, enquanto que a Suite Plutonica Kunene foi formada a partir da coalêscencia de diversos pulsos magmáticos em ambiente extensional, anarogênico e intracontinental.

Os novos dados isotópicos obtidos para a Série Superior do Complexo de Niquelândia indicam que a mesma cristalizou a 1245 ± 4 Ma e não durante o Neoproterozóico como havia sido sugerido por Girardi et al. (2006). Estes dados demonstram que a Série Superior (à oeste) é mais antiga que a Série Acamadada Inferior. Esta última foi datada em 800 Ma pelo método ID-TIMS, enquanto dados Sm–Nd sugerem forte contaminação com crosta continental mais antiga (ε_{Nd} (T) de -6.5 and Tdm de 1.88 Ga). Dados Sm–Nd adicionais em rochas dioríticas e graníticas tardias do complexo de Niquelândia produziram isócrona indicando a idade de 759 ± 65 Ma e ε_{Nd} (T) de -8,8, confirmando que a série acamadada inferior cristalizou no Neoproterozóico e foi fortemente contaminada pelas rochas encaixantes meso- ou paleoproterozóicas. Assim, a Série Acamadada Inferior pode ser interpretada como integrante de um rift continental desenvolvido no borda ocidental do cráton São Francisco-Congo, contemporâneo, com o desenvolvimento do Arco Magmático de Goiás a oeste. (Pimentel et al. 2006).

A Série Acamadada Superior apresenta uma assinatura geoquímica similar ao N-MORB e T-MORB, a mesma é compatível com os valores positivos de ε_{Nd} (T), indicando que a mesma foi formada em um ambiente de crosta oceânica. Por outro lado, a Série Acamadada Inferior apresenta valores negativos de ε_{Nd} (T) e o padrão de herança dos grãos de zircão indica que a mesma intrudiu na crosta siálica mais antiga.

As similaridades entre os três grandes complexos máfica-ultramáficas acamadados de Barro Alto, Niquelândia e Canabrava sugerem que cada um deles é constituído por duas intrusões distintas, com excepção de Canabrava. Uma idade Mesoproterozóica, à oeste, constituida essencialmente por gabro e anortosito, coeva com as sequências vulcano-sedimentares à oeste, e a Série Acamadada Inferior de idade Neoproterozóica à leste constituída por unidades cíclicas de rochas máfica-ultramáficas cumuláticas. As duas intrusões teriam sido tectonicamente justapostas durante a orogênese Brasiliana, no final do Neoproterozóico.

As rochas máfica–ultramáficas da Série Inferior e as sequências vulcano-sedimentares (à oeste), representam uma importante discontinuidade crustal pré-existente através da qual o magma da Série Superior intrudiu durante o Mesoproterozóico. Assim, a Série Superior e as sequências vulcano-sedimentares representam o embasamento da Série Acamadada Inferior.

Em continentes como Laurentia, Báltica são comuns eventos extensionais entre 1.25 Ga e 800 Ma, contudo, não são comuns em terrenos pré-cambrianos da América do Sul, sugerindo a presenca de um bloco continental incluindo estes três complexos e as sequências vulcano-sedimentares associadas podem ser alóctones, tendo sido acrescionados a Faixa Brasília durante o Neoproterózoico.

A Suíte Plutônica Kunene (SPK) localizada no SW de Angola é constituída por intrusões gabro-anortosíticas as além de corpos básicos acamadados que representam a suíte básica. Esta foi posteriormente intrudida por uma suíte ácida caracterizada por granitóides do tipo A, denominados genericamente de “granitos vermelhos”. Por esta razão foi designado neste trabalho de Suíte Plutônica Kunene (SPK). A SPK à exemplo da Suíte Plutônica Nain (Labrador, Canadá) aprepresenta um contexto geológico favorável para mineralizações de sulfetos maciços de Ni-Cu-PGE (tipo Voisey's Bay) bem como para depósitos de Fe-Ti-V. As intrusões básicas de Uanguembela, Otchindjau e Chiange são as maiores encontradas na SPK que apresentam acamadamento ígneo em escala regional, facilmente identificados em imagens satélite Aster e/ou Landsat. Contudo, vários outros plutons de composição básica e escala batolítica ocorrem na SPK.

A suíte básica apresenta anomalia negativa de Nb, enriquecimento em LILE e REE que são geralmente características de magmas toleíticos de arco. A importante variação de ε_{Nd} (T) (-12,42 to +1,81) mostrada pelas rochas máficas sugere que os magmas básicos derivam de fonte mantélica depletada e foram modificados por diferentes graus de assimilação e contaminação crustal. Por outro lado, a suíte plutônica ácida é constituída por dois tipos de granitóides com características geoquímicas distintas. Um grupo tem natureza sub-alcalina, peraluminosa a metaluminosa (tipo I ou S), com anomalia negativa de Nb e valores negativos de ε_{Nd} (T) (-11,02 a -0,67), sugerindo que os mesmos foram gerados a partir da re-fusão de uma crosta superior heterogênea. O segundo grupo é representado pelas intrusões mangeríticas que apresentam anomalia positiva de Nb. Estes são mais ricos em álcalis e no diagrama ISA plotam próximo ao campo peralcalino e provavelmente foram gerados em um ambiente extensional anorogênico.

As novas idades de U-Pb em zircão obtidas para a suíte básica representada pela intrusão Uanguembela foi de 1434 ± 2 Ma e para a suíte ácida representada pela intrusão de mangerito ao sul de Otchindjau foi de 1403 ± 7 Ma. Estas indicam que os magmas originais tanto da suíte básica como da ácida cristalizaram durante o Mesoproterozóico. As mesmas são relativamente mais antigas que as idades U-Pb de 1371 ± 2 Ma em veio mangerítico na região de Quihita, porção central da SPK (Mayer et al. 2004) e que as idades U-Pb de 1385 ± 25 Ma em anortosito e de 1376 ± 2 Ma em rochas félsicas nas Zebra Mountains, NW da Namíbia, obtidas por Druppel et al (2007).

Este conjunto de idades sugere que a Suite Plutónica Kunene foi formada a partir da de múltiplos pulsos magmáticos em ambiente extensional, anarogênico e intracontinental. Os dados demonstram que a suite básica é mais antiga e foi posteriormente intrudida por corpos graníticos do tipo - A incluindo mangerito, charnoquito, monzonito, sienogranito e granito rapakiwi que caracterizam a suite ácida.