



**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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Dissertação de Mestrado

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Brasília DF

Março

2007

Aos meus pais e amigos Helena e Baxe:

“Todo ponto de vista é apenas a vista de um ponto”.

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RESUMO

Esta dissertação reúne um conjunto de dados petrográficos, geoquímicos e geocronológicos 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 Suíte Plutônica 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 $\epsilon_{Nd}(T)$ 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 $\epsilon_{Nd}(T)$ 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 suíte básica é relativamente mais antiga que a suíte ácida. Os valores negativos de $\epsilon_{Nd}(T)$ 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 contam

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 Goiás, 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 $\epsilon_{Nd}(T)$ 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 $\epsilon_{Nd}(T)$ 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 km². 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-Oncócuá 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 $\epsilon_{Nd}(T)$ 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 $\epsilon_{Nd}(T)$ 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

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 Brasileira (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 km². 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 gênese 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 geotectônica, como também pelo potencial econômico 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 síalico mais antigo ($\epsilon\text{Nd}(T)$ 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 Al_2O_3 , 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 basálticos.

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 Oncócuca 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 $14^{\circ} 30' S$ e $14^{\circ} 00' S$ e os paralelos $48^{\circ} 42' W$ e $48^{\circ} 22' W$, 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.

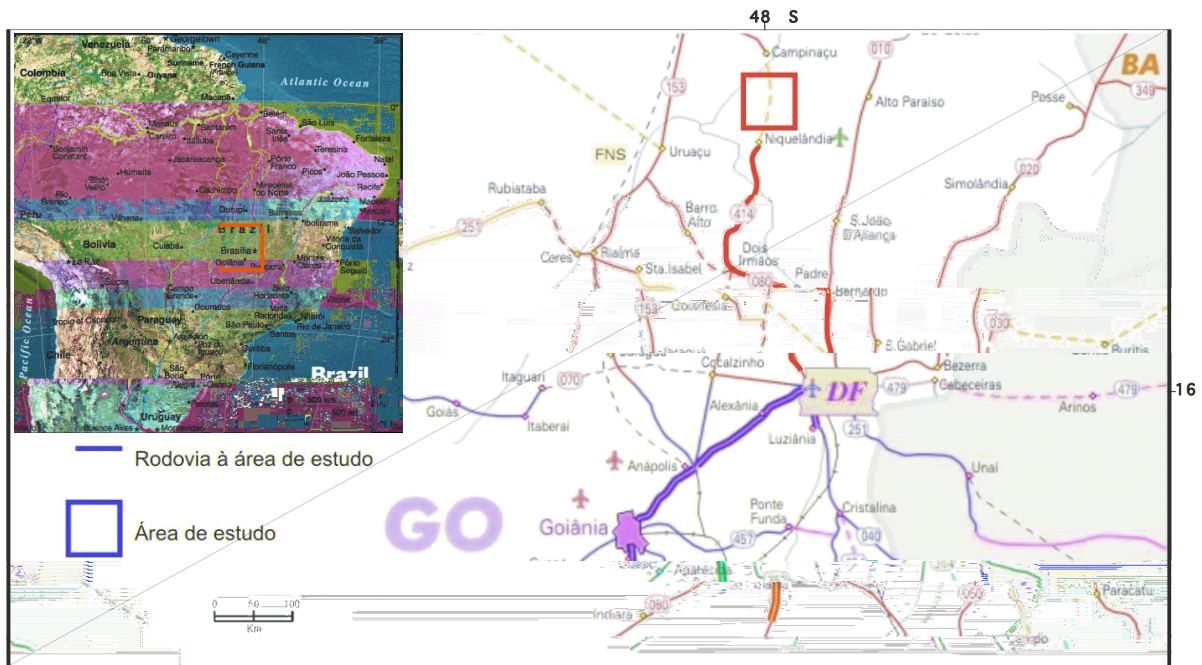


Figura 1.1 – Mapa de localização e vias de acesso ao Complexo de Niquelândia.

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 ($300 \text{ km} \times 50 \text{ km}$) (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 Oncóua, 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 magmáticos de Ni-Cu-EGP, bem como depósitos de óxidos de Fe-Ti-V.

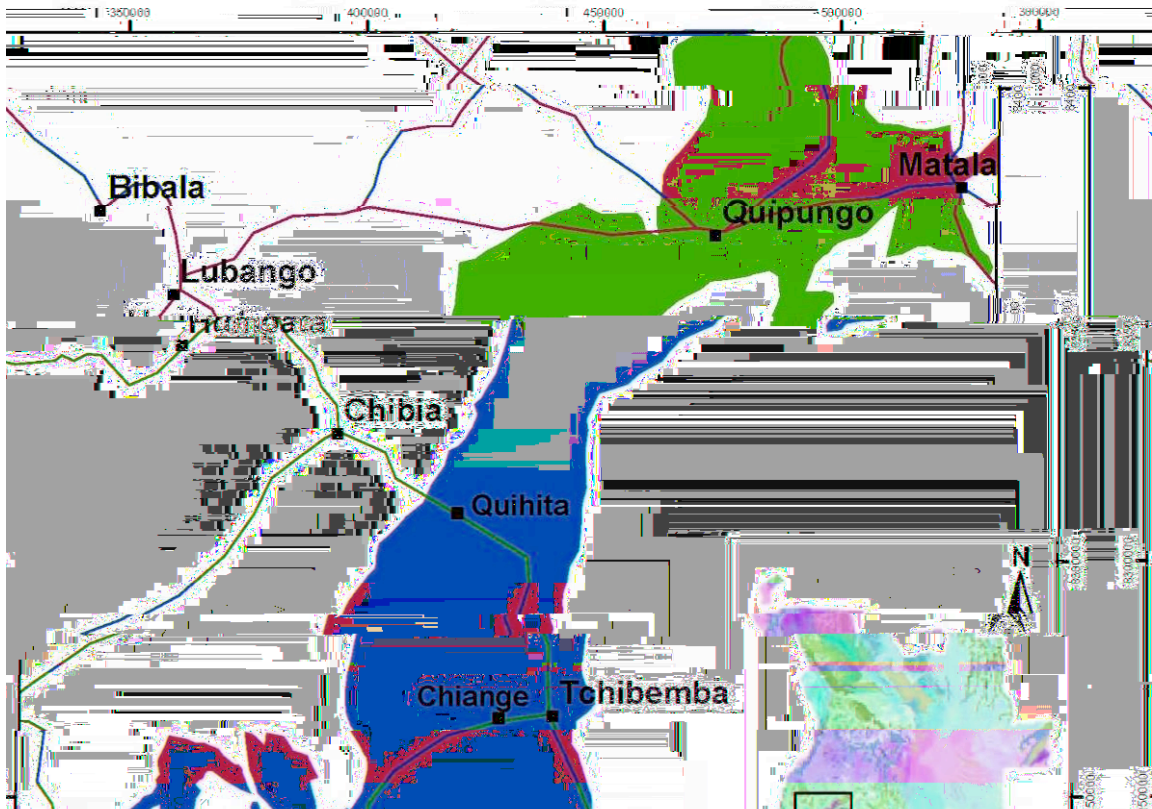


Figura 1.2. Mapa de localização e vias de acesso ao Complexo Kunene.

Capítulo 2

Este Capítulo apresenta os resultados isotópicos, geoquímicos e petrológicos referentes à Série Superior do Complexo de Niquelândia. As informações serão apresentadas 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
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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 $\epsilon_{Nd}(T)$ 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 $\epsilon_{Nd}(T)$ values and trace element characteristics indicating extensive contamination with continental crust.

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



cent r or l di r a a

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 a l ,

he he a me t a e a s nt

During the last two decades these complexes have been intensely studied due to their metallogenic 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 metasedimentary 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 gabbro, 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 $\epsilon_{Nd}(T) +5.0$ values, similar to mid-ocean ridge basalts (MORB) (Moraes et al., 2003, 2006).

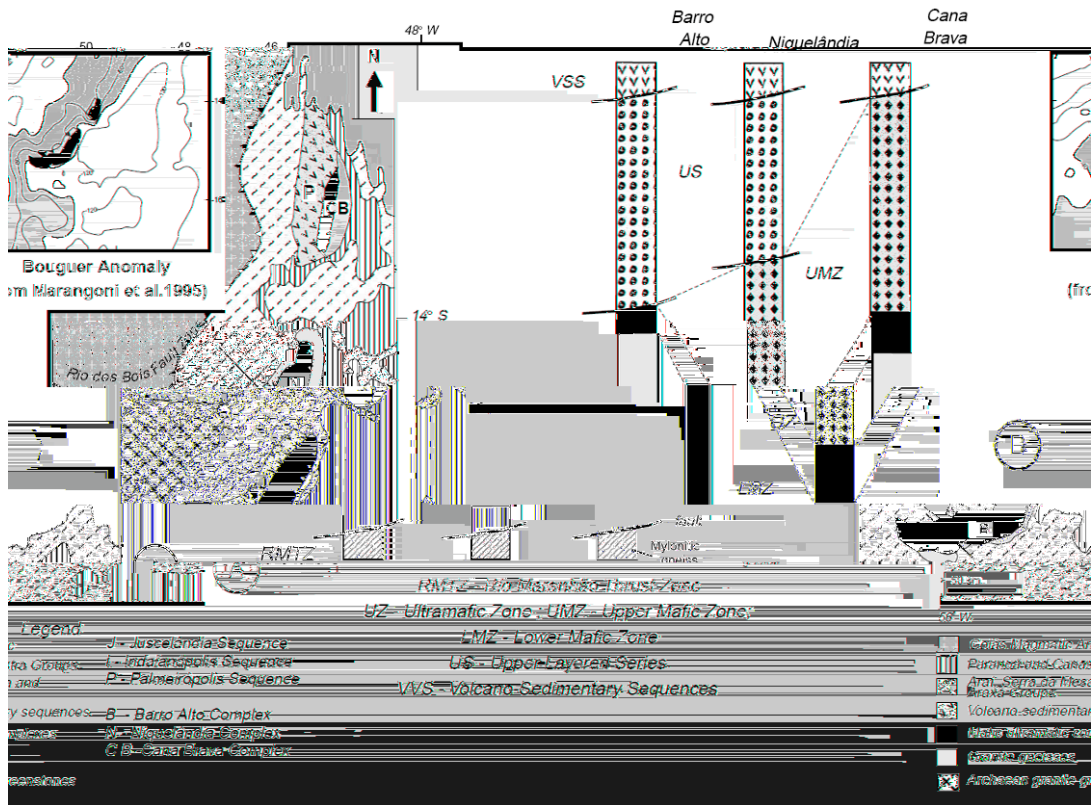


Figure 2.2. The Barro Alto, Niquelândia, and Cana Brava mafic–ultramafic complexes in central Brazil. (A) Geological sketch map, (B) comparative stratigraphic/structural columns of the three complexes. The inset map is a Bouguer anomaly map from Marangoni et al. (1995).

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 °C 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 gabbro

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 $\epsilon_{\text{Nd}}(T)$ 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.

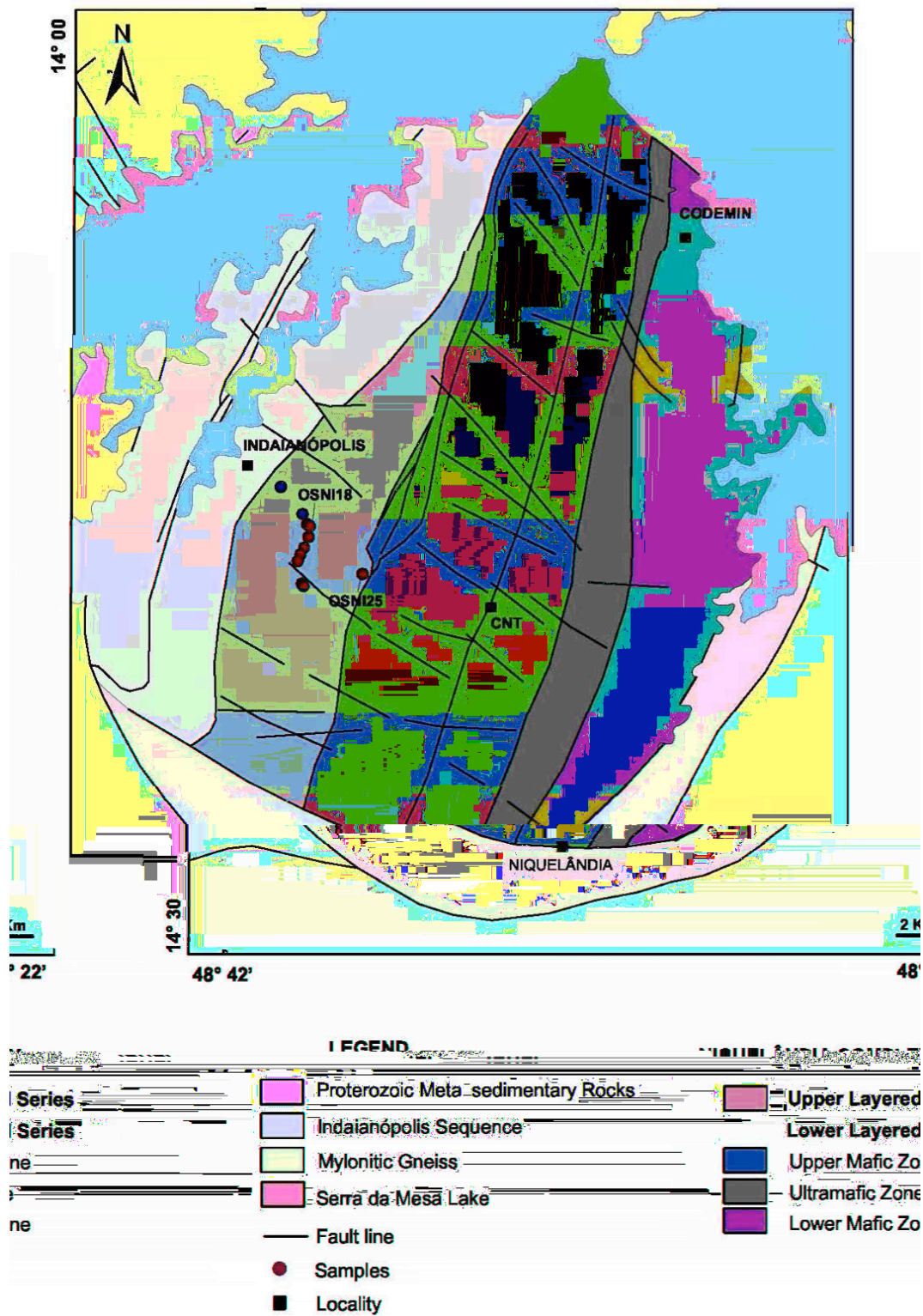


Figure 2.3. Geological sketch map of the Niquelândia Complex (from SIG de Goiás, 2000).

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 HNO₃ (HF:HNO₃ = 4:1) using microcapsules in Parr-type bombs. A mixed ²⁰⁵Pb–²³⁵U 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 H₃PO₄ 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 ¹⁴⁹Sm–¹⁵⁰Nd 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 ¹⁴³Nd/¹⁴⁴Nd 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. ¹⁴³Nd/¹⁴⁴Nd ratios were normalized to ¹⁴⁶Nd/¹⁴⁴Nd of 0.7219, and the decay constant used was 6.54x10⁻¹² 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

(OSNI20) is the most primitive of the samples investigated, with 168 ppm Ni and 0.169 wt% Cr₂O₃ 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.

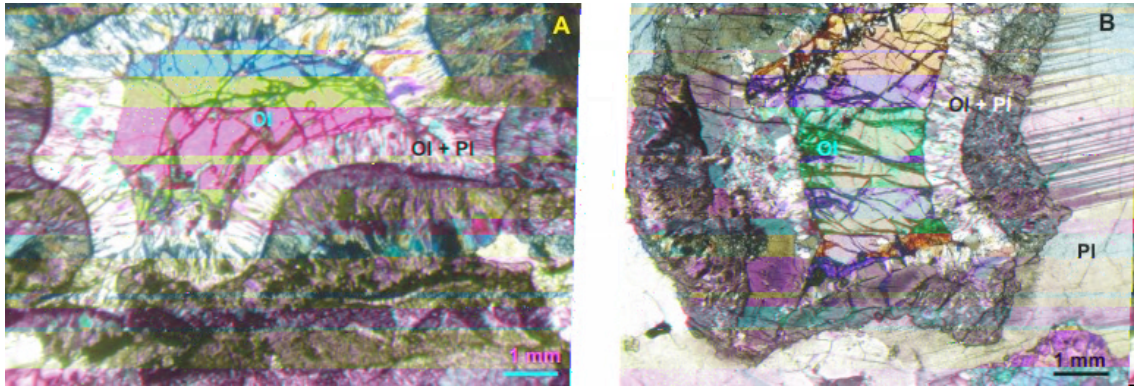


Figure 2.5. A, B) Olivine gabbro with coronitic texture formed by reaction between Ol and Pl.

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.

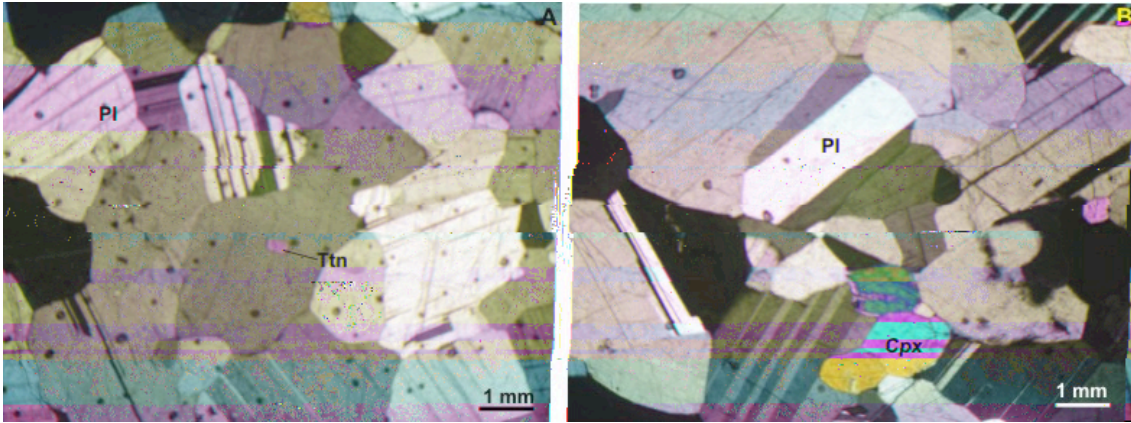


Figure 2.6. A, B) Meta-Anorthosite with granoblastic texture.

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 $\epsilon_{\text{Nd}}(\text{T})$ (see below) indicates an oceanic setting of origin for the US of the Niquelândia Complex.

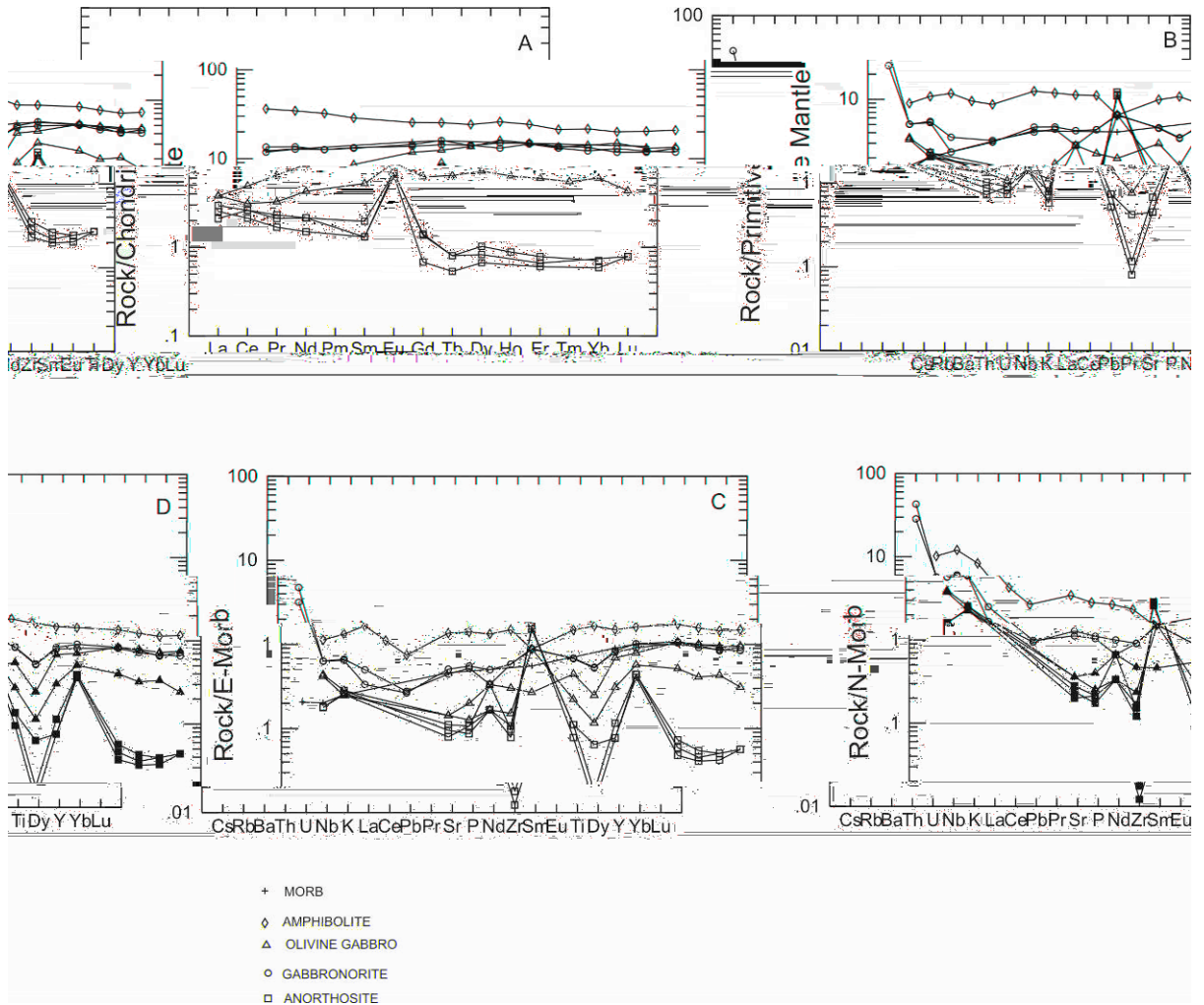


Figure 2.7. A) Samples normalized to chondrite. B) Normalized to Primitive Mantle. (Sun & Mc Donough, 1989) C,D) Rocks normalized to E-Morb and N-Morb respectively (Pearce, 1983).

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

Rock type Sample	Gabbrorite OSNI17	<i>Olivine Gabbro OSNI18</i>	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 ₂ O ₃	15.25	14.9	6.74	16.19	30.93	30.91	30.62	16.66
Fe ₂ O 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 ₂ O	2.13	2.07	0.77	1.92	2.84	2.24	2.59	2.45
K ₂ O	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 ₂ O 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 ₂ O 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
LOI	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	1.7
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

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 (200 μ m) 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.

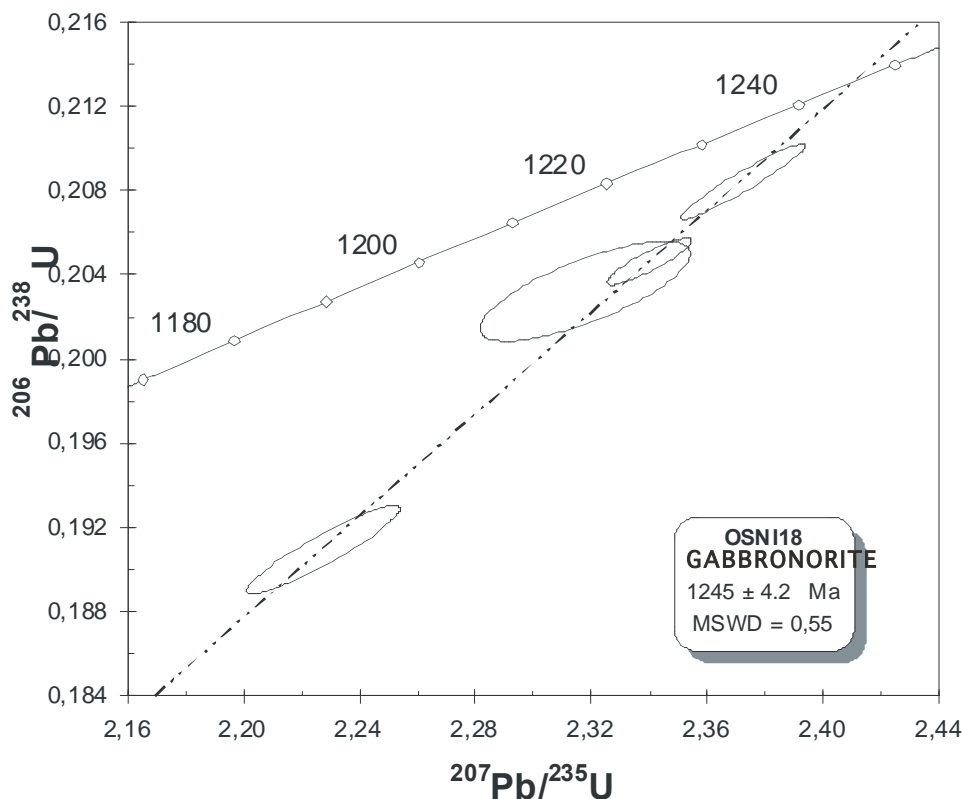


Figure 2.8. U-Pb diagram of Gabbronorite - OSNI18 from Upper Series of Niquelândia Complex.

Sample Fraction	Size (mg)	U (ppm)	Pb (Ppm)	²⁰⁶ Pb / ²⁰⁴ Pb	²⁰⁷ Pb* / ²³⁵ U (pct) ^a	(pct) ^a	²⁰⁶ Pb* / ²³⁸ U	(pct) ^b	Correl. Coeff.	²⁰⁷ Pb* / ²⁰⁶ Pb* (pct) ^c	(pct) ^c	²⁰⁶ Pb* / ²³⁸ U Age	²⁰⁷ Pb* / ²³⁵ U Age	²⁰⁷ Pb* / ²⁰⁶ Pb* Age	(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 $^{206}\text{Pb}/^{238}\text{U}$ 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/ ²⁰⁶ Pb 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

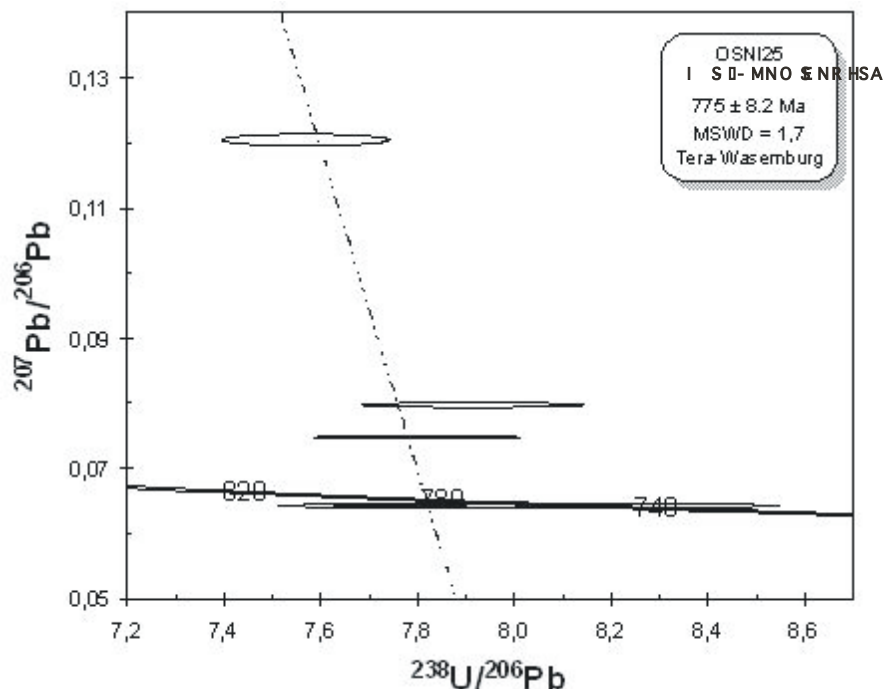


Figure 2.9. Tera–Wasserburg diagram of meta-anorthosite (OSNI25) from Upper Series of Niquelandia Complex.

The Nd isotopic data reveal positive, although rather varied, values of $\epsilon_{Nd}(T)$. 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 $\epsilon_{Nd}(T)$, 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 $\epsilon_{Nd}(T)$ reported by Pimentel et al. (2004, 2006). 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 $^{147}\text{Sm}/^{144}\text{Nd}$ ratios, indicating important LREE enrichment, and rendering mostly Paleoproterozoic T_{DM} model ages and negative $\epsilon_{Nd}(T)$ values. On the other hand, the basic rocks of the US have higher Sm/Nd ratios and positive $\epsilon_{Nd}(T)$ values.

Table 2.5. Sm–Nd isotopic data, the results of $\epsilon_{Nd}(T)$ were calculated with age of 1.2 Ga.

Rock	Sample	Sm(ppm)	Nd(ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd} \pm 2\text{SE}$	$\epsilon_{Nd}(o)$	$\epsilon_{Nd}(T)$
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 in a gabbro-norite. The US was metamorphosed 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 show that the Upper Series is older than the 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 the Niquelândia Complex is composed of two distinct intrusions. The Nd isotopic data reveal positive, although rather varied, values of $\varepsilon_{Nd}(T)$. 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 fact is also confirmed by the geochemistry signature of the US that is similar to those of N-MORB and T-MORB which indicates that the US was formed in an oceanic setting.

The age of 1245 ± 4 Ma of the Upper Series is coeval with supracrustal rocks of the Indaianaópolis 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 Mesoproterozoic–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 $\epsilon_{Nd}(T)$ 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 $\epsilon_{Nd}(T)$ 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.

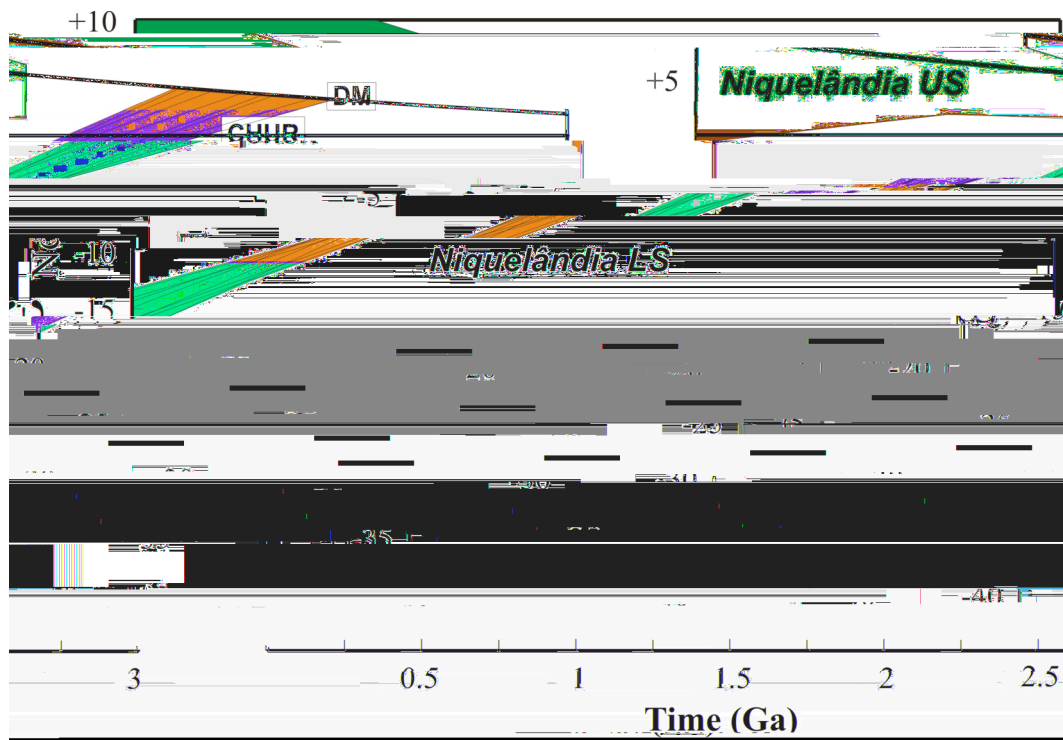


Figure 2.10. Differences between US and LS displayed in the Nd isotopic evolution diagram.

2.8. Acknowledgements

The authors are CNPq researchers and grateful for the research grant that allowed field and laboratory work. Sérgio Junges and Jorge Laux, Bárbara Lima and Sandrine Ferraz are acknowledged for technical assistance. We would like to thank also the reviewers PhD. Reinhardt A. Fuck, Bernard M. Buhn, Massimo Mateini from UnB, and an anonymous referee for their very helpful reviews of the manuscript.

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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 km². 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 - Oncócuá 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 $\epsilon_{Nd}(T)$ 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 $\epsilon_{Nd}(T)$ 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. Ge

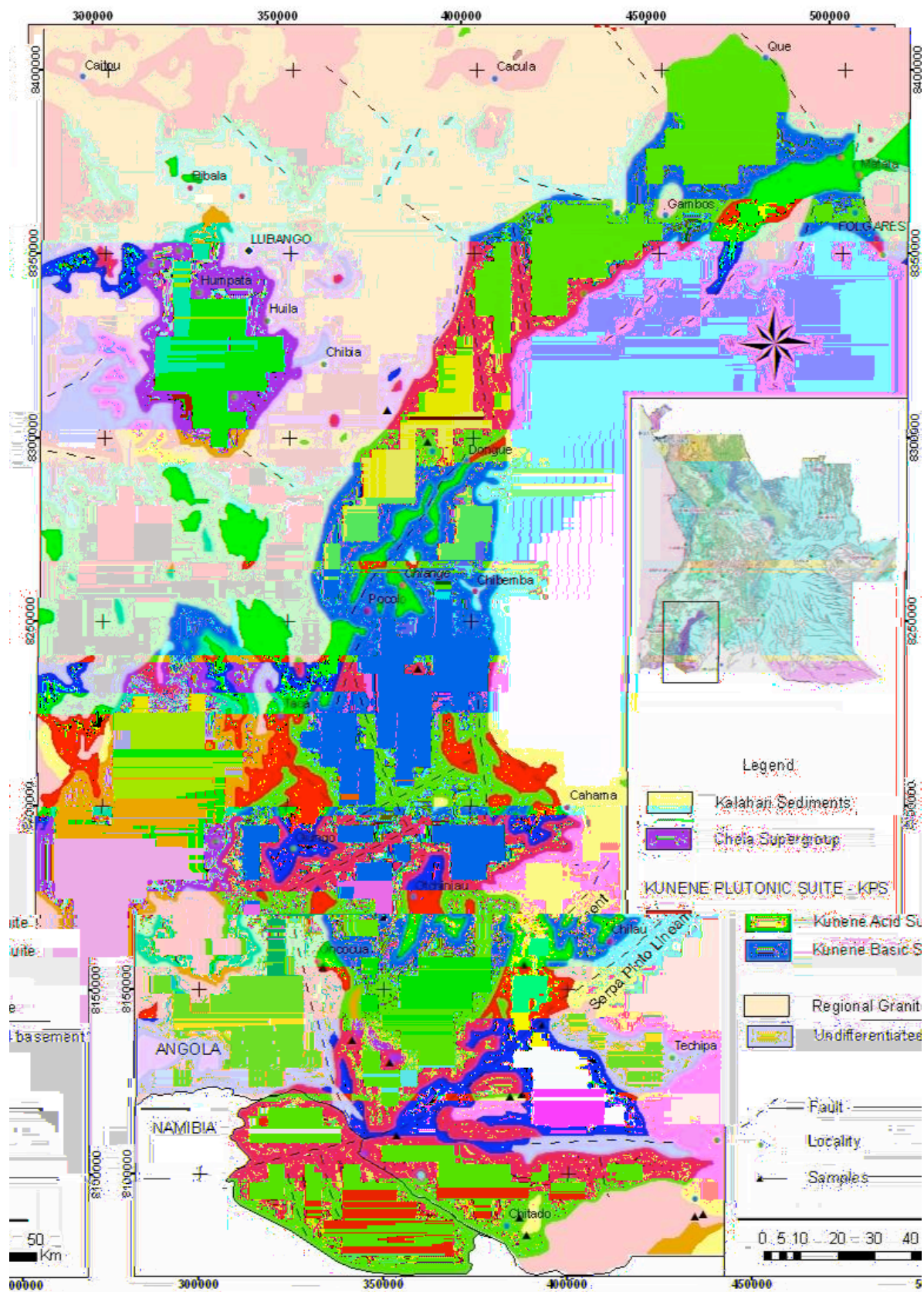


Figure 3.1. Simplified geological map of the Kunene Plutonic Suite and adjacent Precambrian rocks in SW Angola (from Instituto Geológico de Angola, 1998).

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-Cerriango 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}	

¹Allsopp, 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; ⁶Carvalho, 2000; ⁷ Mayer et al, 2004; ⁸Carvalho,1984; ⁹Carvalho and Alves, 1990; ¹⁰Carvalho 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 OSC64 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 HNO₃ (HF: HNO₃ = 4:1) using microcapsules in Parr-type bombs. A mixed ²⁰⁵Pb–²³⁵U 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 H₃PO₄ 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 ¹⁴⁹Sm–¹⁵⁰Nd 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 $^{143}\text{Nd}/^{144}\text{Nd}$ ratios are better than $\pm 0.2\%$ (σ_2) and $\pm 0.005\%$ (σ_2), respectively, based on repeated analyses of international rock standards BHVO-1 and BCR-1. $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were normalized to $^{146}\text{Nd}/^{144}\text{Nd}$ of 0.7219, and the decay constant used was $6.54 \times 10^{-12} \text{ y}^{-1}$. 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 km² 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 km² composed mainly of magnetite gabbros (Fig. 3.3) associated with red granite intrusions.

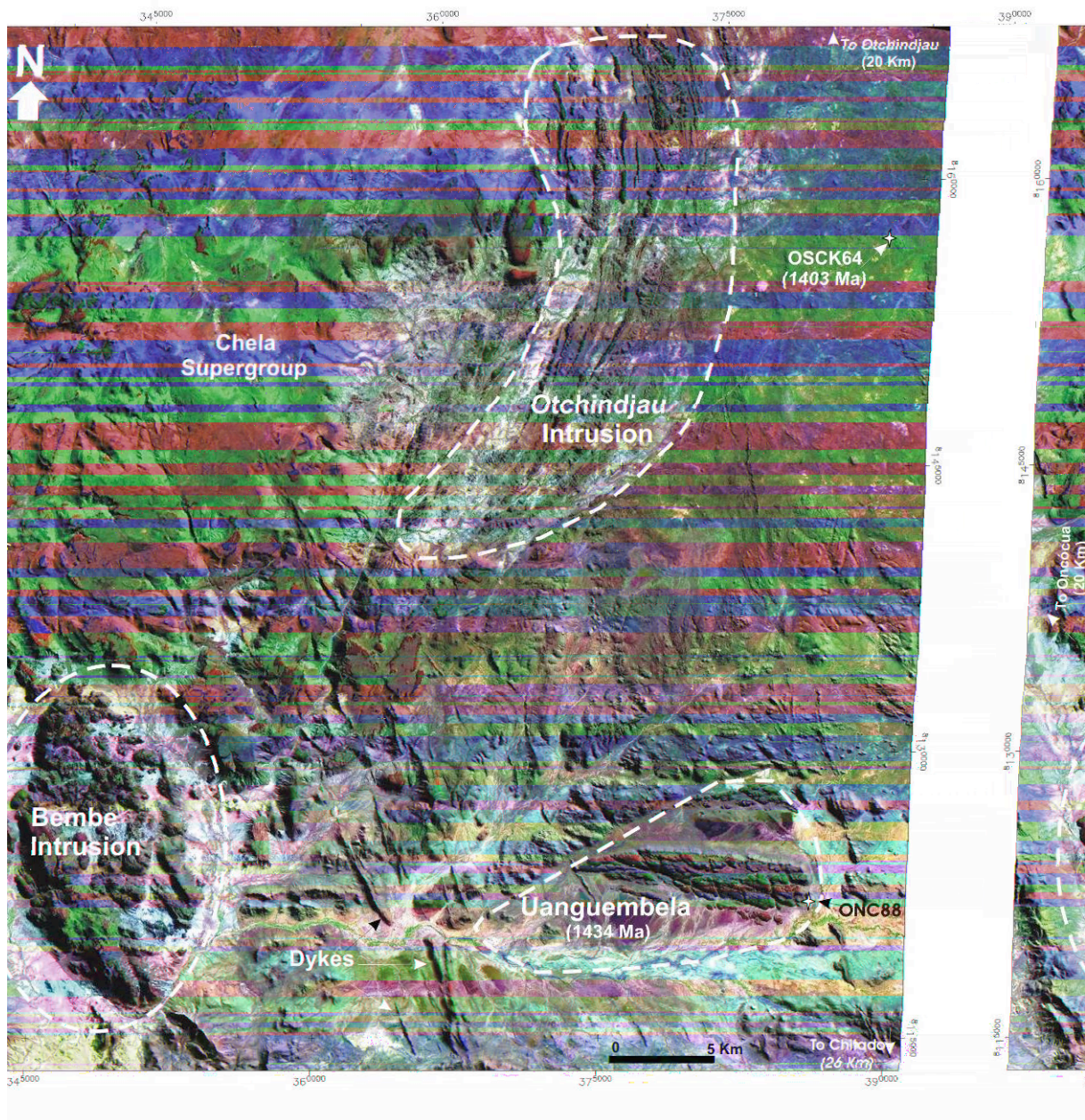
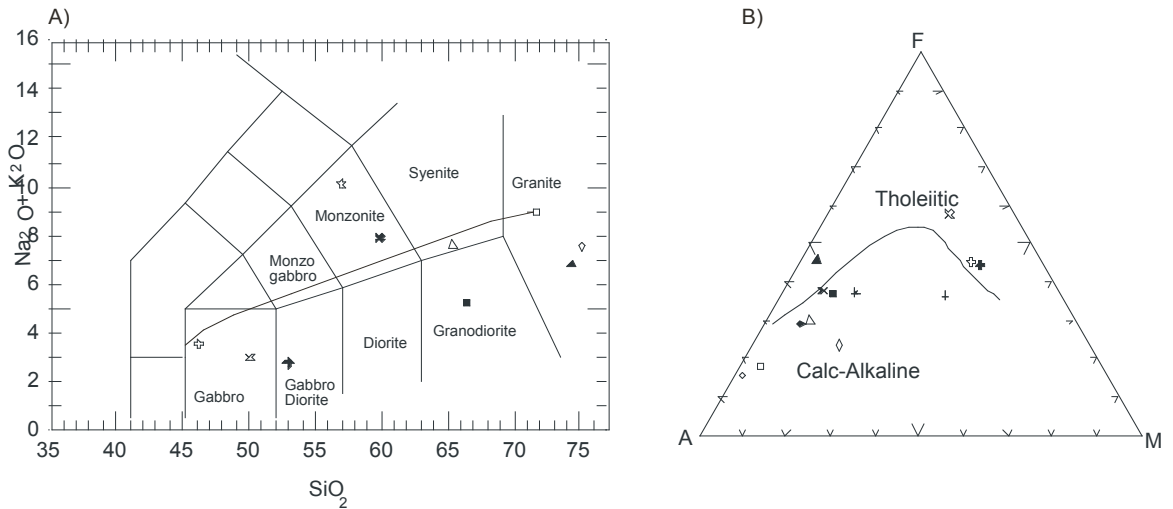


Figure 3.2. Landsat image of major mafic intrusions in the southern portion of KC at Oncócuca - Otchindjau region. Gabbro ONC88 of the Uanguembela intrusion and a mangerite sample (OSCK64) were dated by ID-TIMS U-Pb.

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.



BASIC PLUTONIC SUITE		ACID PLUTONIC SUITE	
⊕	OSCK60 - GABBRO	☆	OSCK64 - MANGERITE
⊗	OSCK53 - GABBRO	✱	OSCK58 - MONZONITE
✦	OSCK36 - GABBRO	△	OSCK01 - SYENITE
*	OSCK50 - ANORTHOSITE	▲	OSCK35 - GRANITE
◇	OSCK06 - ANORTHOSITE	◇	OSCK47 - GRANITE
◆	OSCK07 - ANORTHOSITE	□	OSCK37 - GNEISS
+	OSCK16 - LEUCOTROCTOLITE	■	OSCK39 - GNEISS

Figure 3.3. A) TAS Diagram (Le Maitre, 1989) showing the main samples of the KPS. B) Diagram A = $\text{Na}_2\text{O} + \text{K}_2\text{O}$; F = Fe_2O_3 ; 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 SiO₂ contents (47.74 to 54.33 wt %), high Al₂O₃ (between 23 to 27 wt %), moderate CaO (8.86 to 12.2 wt %) and low Na₂O (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).

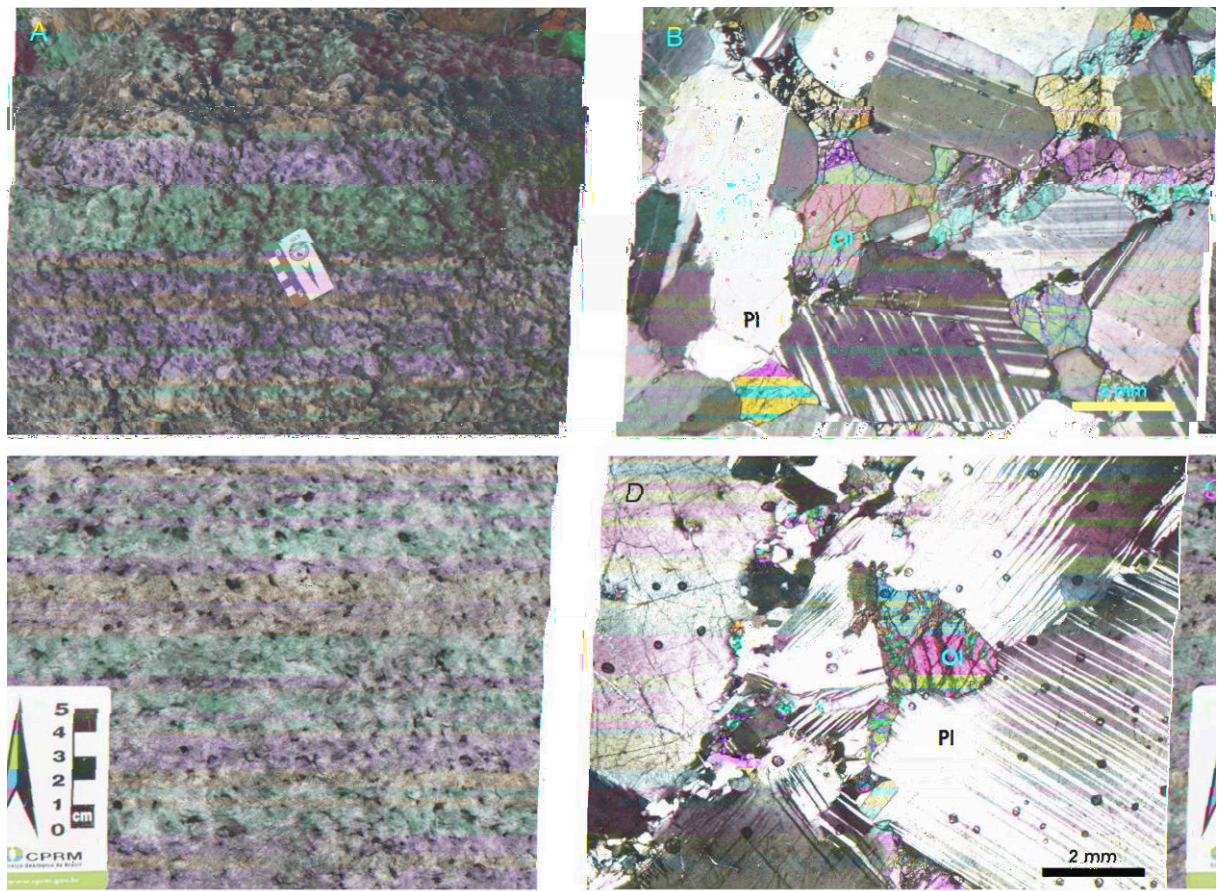


Figure 3.4. Anorthositic rocks of the KPS A-B) OSCK16-Leucotroctolite mottled with Pl cumulus and intercumulus Ol; C-D) OSCK06-medium to coarse-grained anorthosite.

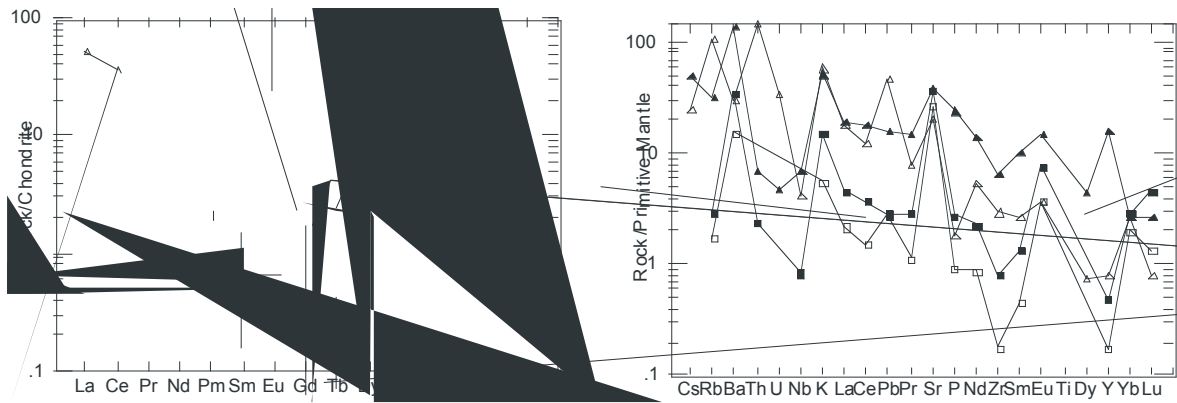


Figure 3.5. A) REE distribution pattern for anorthositic samples normalized to chondrite (Sun & Mc Donough, 1989). B) Trace elements diagram normalized to Primordial Mantle (Sun & Mc Donough, 1989).

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.

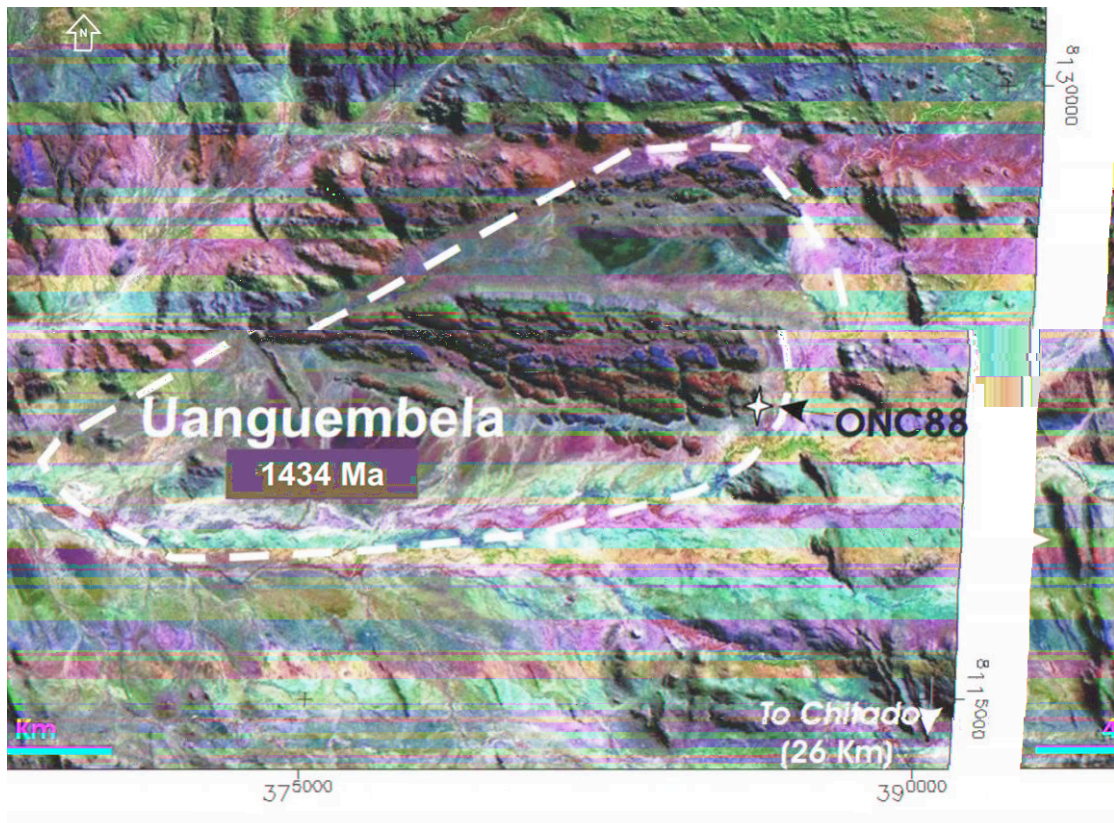


Figure 3.7. Landsat image of the Uanguembela pluton showing location of the 1434 ± 2 Ma leucogabbro – ONC88 sample.

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).

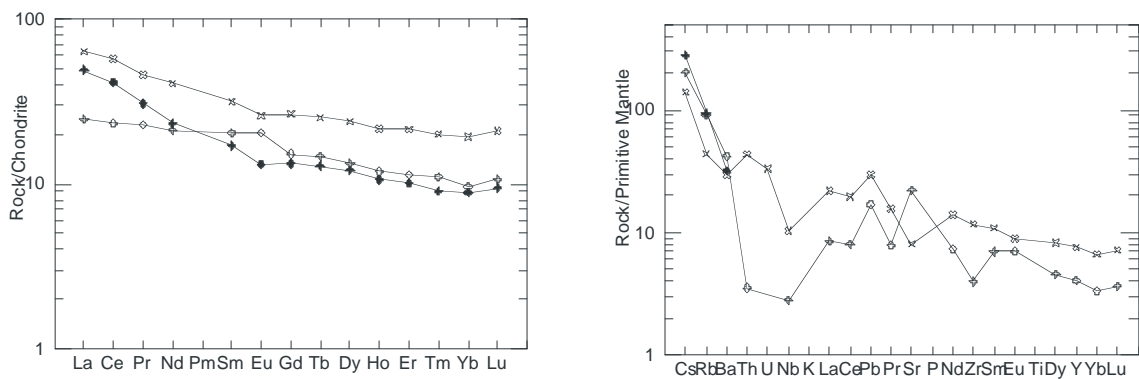


Figure 3.8. A) Gabbros compositions normalized to chondrite (A) Primordial Mantle (B) (Sun & Mc Donough, 1989) and normalized to MORB (C) (Pearce, 1983).

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
<i>Major elements</i>							
SiO ₂	54.33	52.11	47.74	50.34	49.97	46.1	52.89
Al ₂ O ₃	25.47	27.39	27.23	23.16	15.38	16.8	14.7
Fe ₂ O 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 ₂ O	2.6	4.43	2.83	4.25	2.28	2.56	1.68
K ₂ O	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 ₂ O 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 ₂ O 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
<i>Trace Elements</i>							
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
<i>Major Elements</i>							
SiO ₂	65.3	71.54	66.33	75.03	74.31	59.8	56.89
Al ₂ O ₃	15.95	14.29	16.5	13.16	9.37	19.85	14.78
Fe ₂ O 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 ₂ O	3.81	2.86	4.04	4.46	1.2	2.96	4.46
K ₂ O	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 ₂ O 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 ₂ O ₃	0.00	0	0	0	0.00	0.00	0
LOI	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
<i>Trace Elements</i>							
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	

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.

SiO₂ contents are between 75% and 74%, Al₂O₃ between 9.37% and 15.95%, CaO in the range between 0.16% and 3.48%, Na₂O from 1.2% to 4.46 %, and K₂O 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.

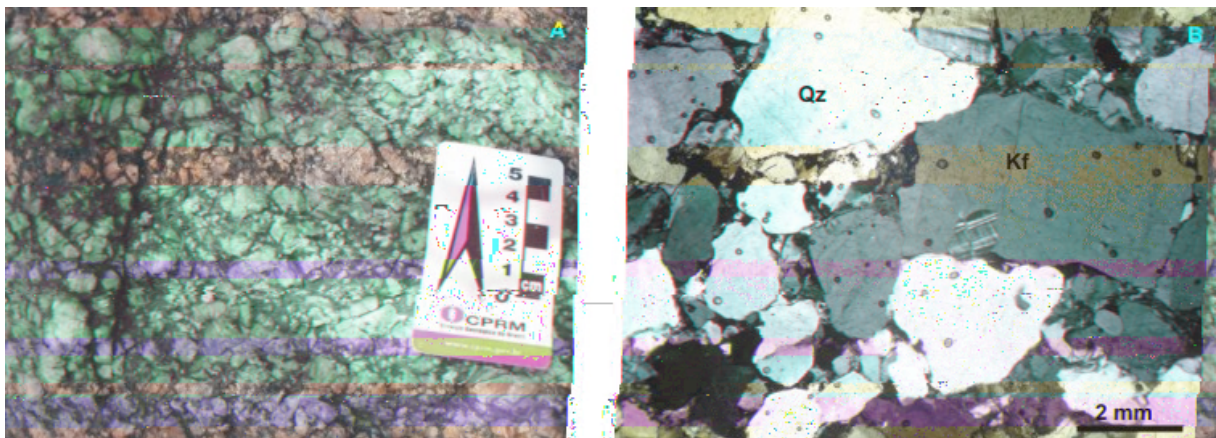


Figure 3

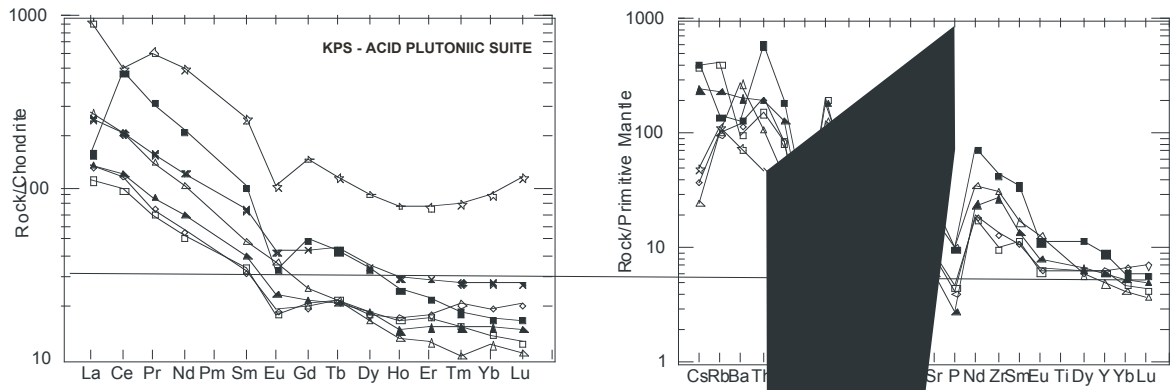


Figure 3.10. REE for anorthositic samples normalized to chondrite (Sun & Mc Donough, 1989). B) Trace elements spiderdiagram normalized to Primordial Mantle (Sun & Mc Donough, 1989).

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 \pm 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 alkalis (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. SiO₂ between 57 and 60 %, Al₂O₃ ca. 15 to 20%, Fe₂O₃ 6,31 and 11,64%; MgO between 1,38 and 0,15%, CaO 1,57 to 2,17%, Na₂O 2,96 to 4,46% and K₂O 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 $10000 \cdot \text{Ga}/\text{Al}$ vs. $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}$ 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).

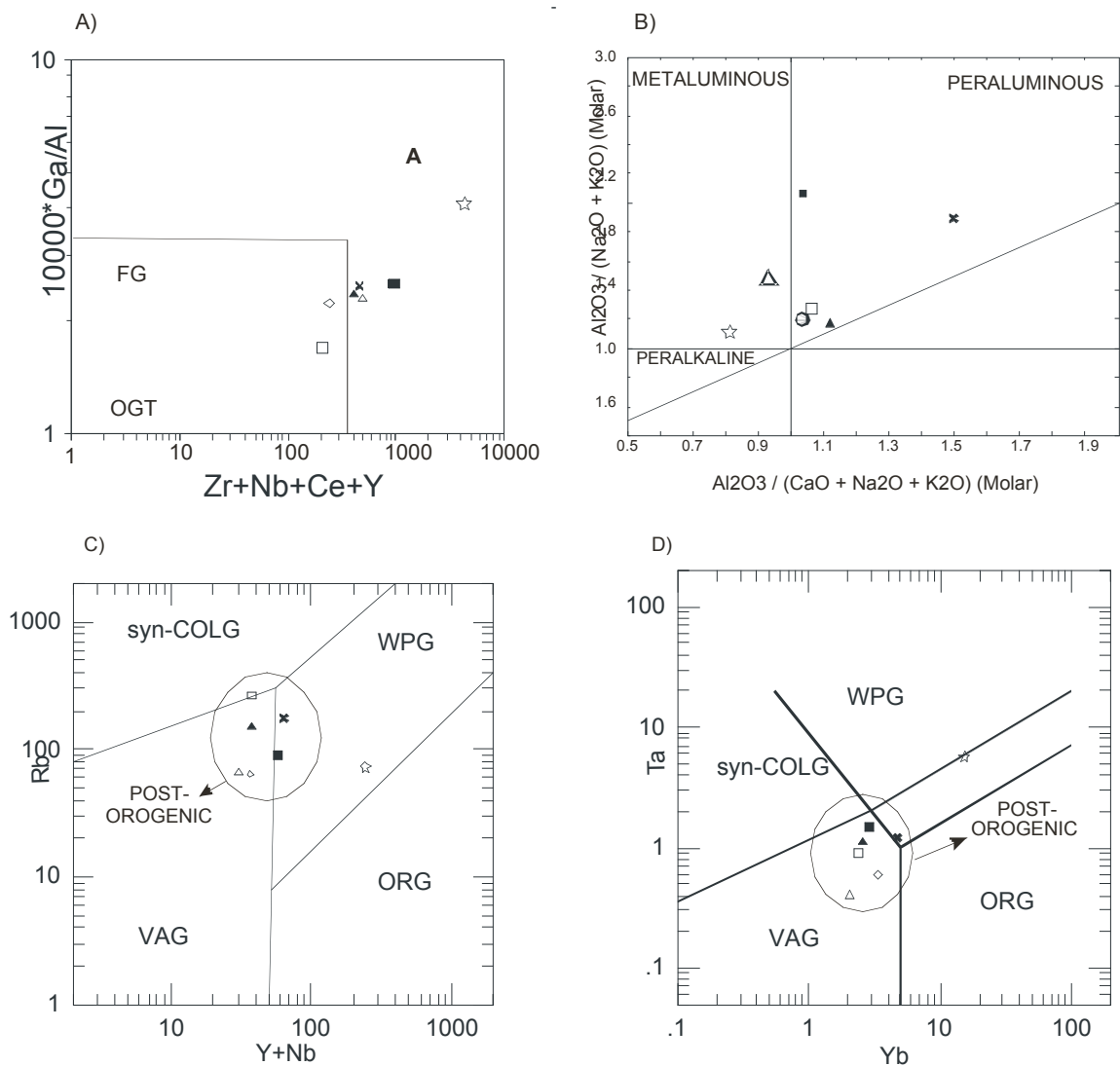


Figure 3.11. A) $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}$ vs. $10000 \cdot \text{Ga}/\text{Al}$ for acid plutonic suite of the KPS indicating the predominantly A-type character. FG, Fractionated Granites; OGT, Other granite types. B) Diagram $\text{Al}_2\text{O}_3 / (\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$ vs. $\text{Al}_2\text{O}_3 / (\text{Na}_2\text{O} + \text{K}_2\text{O})$, (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 (200 μ m) 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	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{235}\text{U}$ (pct)	$^{206}\text{Pb}/^{238}\text{U}$ (pct)	Correl. Coeff.	$^{207}\text{Pb}/^{206}\text{Pb}$ (pct)	$^{206}\text{Pb}/^{238}\text{U}$ Age (Ma)	$^{207}\text{Pb}/^{235}\text{U}$ Age (Ma)	$^{207}\text{Pb}/^{206}\text{Pb}$ 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.

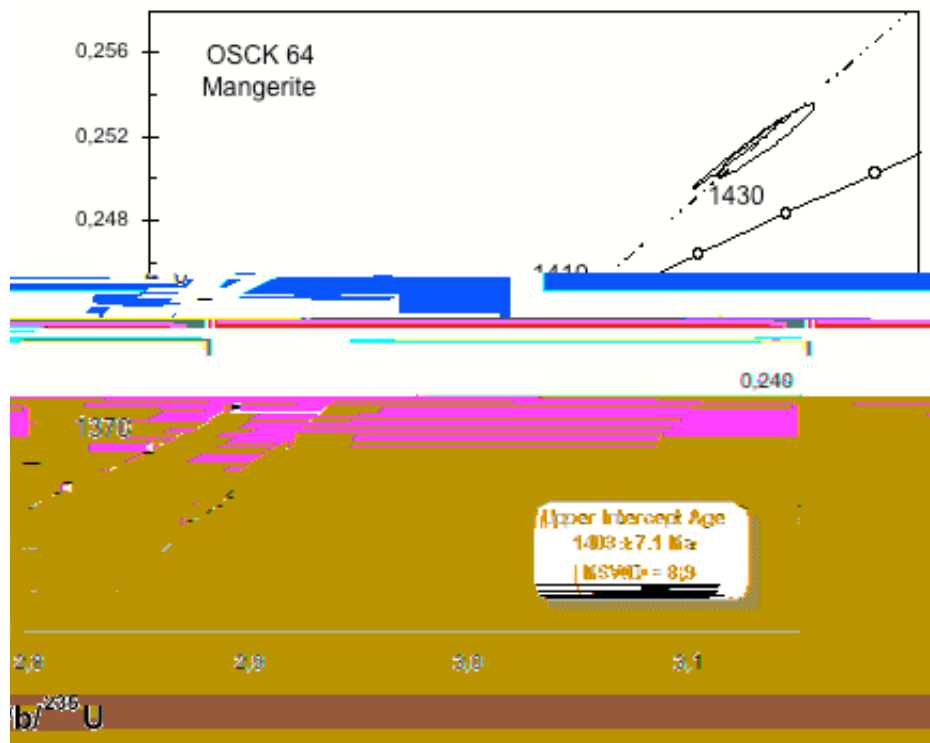


Figure 3.12. ID-TIMS U-Pb Upper intercept age of mangerite OSCK64.

Zircon grains from sample ONC 88 are also well formed, equant to stubby prismatic grains, varying from small to large (200 μ m) 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	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{235}\text{U}$ (pct)	$^{206}\text{Pb}/^{238}\text{U}$ (pct)	Correl. Coeff.	$^{207}\text{Pb}/^{206}\text{Pb}$ (pct)	$^{206}\text{Pb}/^{238}\text{U}$ Age (Ma)	$^{207}\text{Pb}/^{235}\text{U}$ Age (Ma)	$^{207}\text{Pb}/^{206}\text{Pb}$ 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.

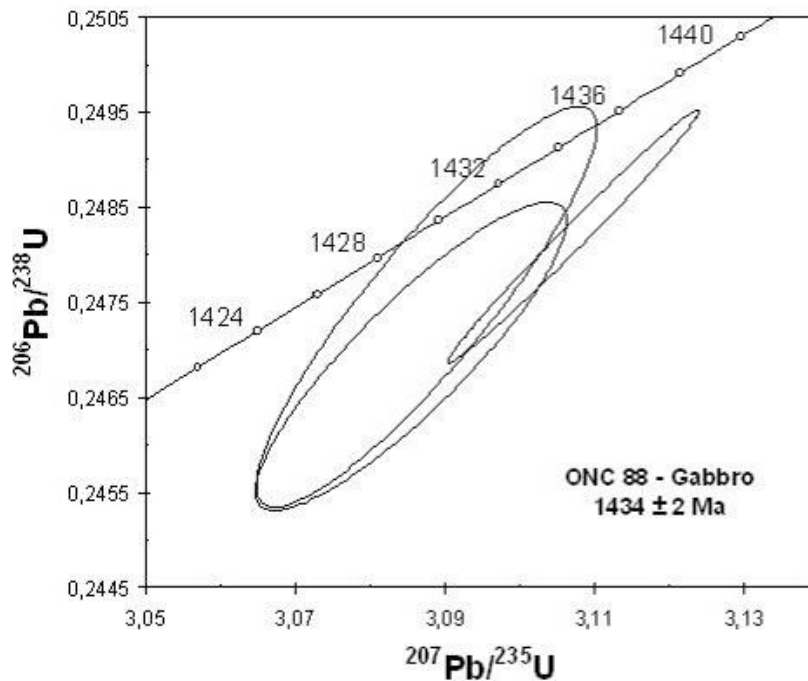


Figure 3.13. U-Pb Age of olivine-gabbro from Uanguembela Pluton in Southern of KPS.

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 $\epsilon_{\text{Nd}}(\text{T})$ values were calculated with reference to the U-Pb age of 1.4 Ga. The $\epsilon_{\text{Nd}}(\text{T})$ of mafic rocks range from -0.67 to -12.4. Acid Plutonic Suite has $\epsilon_{\text{Nd}}(\text{T})$ between -11.02 and -0.67 reflecting crustal contamination. The negative values of $\epsilon_{\text{Nd}}(\text{T})$ 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	Oncócuá	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	Oi Gabbro	8136140	341001	Bembe	0,465	1,964	0,1432	0,512181	-8,91	+0,69	1846
ONC 88	Oi Gabro	8120966	384187	Oncócuá	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	Oncócuá	11,38	60,15	0,1143	0,511612	-20,01	-5,25	2182
OSCK64	Mangerite	8156623	388272	Oncócuá	40,237	237,1	0,1026	0,51169	-18,49	-1,61	1843
ONC 76	Granite	8156004	333653	Oncócuá	25,86	141,441	0,1105	0,511639	-19,49	-4,04	2060
ONC 89	Granite	8121397	387398	Oncócuá	11,75	62,26	0,1141	0,511722	-17,87	-3,06	2010

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

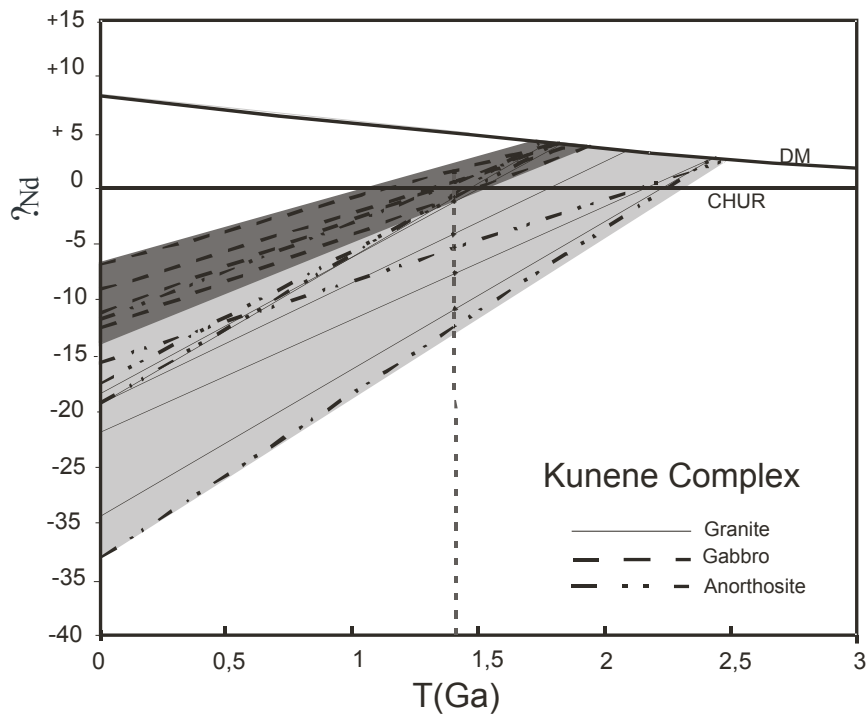


Figure 3.14. Evolution ϵ_{Nd} x Time diagram of KPS rocks with 1.42 Ga reference.

Four samples display positive values of $\epsilon_{Nd}(T)$ and are represented by two anorthosites of Oncócuá 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 +

The variation of negative $\epsilon_{Nd}(T)$ 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 $\epsilon_{Nd}(T)$ (-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 $\epsilon_{Nd}(T)$ (-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 alkalis 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 partial 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).

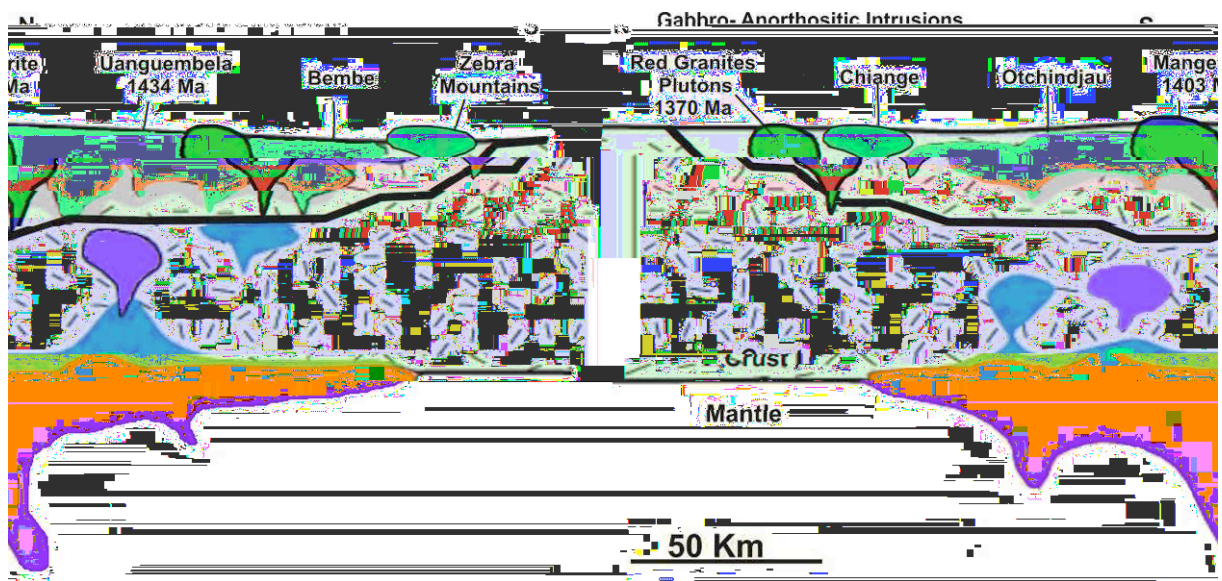


Figure 3.15. Hypothetic Tectonic Model of Kunene Plutonic Suite in an anarogenic intracratonic and extensional setting.

3.7 Acknowledgements

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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 são 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 Suíte Plutônica 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 ($\epsilon_{Nd}(T)$ 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 $\epsilon_{Nd}(T)$ 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 $\epsilon_{Nd}(T)$, indicando que a mesma foi formada em um ambiente de crosta oceânica. Por outro lado, a Série Acamadada Inferior

apresenta valores negativos de $\epsilon_{Nd}(T)$ e o padrão de herança dos grãos de zircão indica que a mesma intruiu na crosta sílica 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 exceção de Canabrava. Uma idade Mesoproterozóica, à oeste, constituída 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 Brasileira, 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 intruiu 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 presença de um bloco continental incluindo estes três complexos e as sequências vulcano-sedimentares associadas podem ser alóctones, tendo sido acrescidos a Faixa Brasília durante o Neoproterozóico.

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 intruída 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) apresenta 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~~ amadamento ígneo em o

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 $\epsilon_{Nd}(T)$ (-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 Plutônica Kunene foi formada a partir da de múltiplos pulsos magmáticos em ambiente extensional, anorogênico 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.

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