UNIVERSIDADE DE SÃO PAULO
INSTITUTO DE GEOCIÊNCIAS
DEPARTAMENTO DE MINERALOGIA E GEOTECTÔNICA

LIVRE-DOCÊNCIA

**O MÉTODO Re-Os E O ESTUDO DA ORIGEM E DA EVOLUÇÃO
TECTÔNICA DOS GRANDES COMPLEXOS MÁFICOS-
ULTRAMÁFICOS, DO CENTRO-OESTE DO BRASIL.**

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Compilação das contribuições ao tema, análise crítica e estudos em andamento. Texto apresentado para o Concurso de Livre-Docente, na área de Petrologia Ígnea, junto ao Departamento de Mineralogia e Geotectônica.

São Paulo
2001

Para a amada Lucília
e aos meus queridos filhos Eduardo e Matheus

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CAPÍTULO 1

Apresentação

Essa tese de Livre-Docência corresponde a compilação dos trabalhos científicos desenvolvidos após a conclusão do doutorado em 1994 e da publicação dos resultados daquela pesquisa (Correia et al., 1997a e Correia, 1998). Porém, relaciona-se diretamente com o objeto principal de nosso interesse científico desde o mestrado, a saber, o estudo das diferentes associações de rochas máficas-ultramáficas e o contexto tectônico de sua colocação e evolução.

Ainda durante o andamento do doutoramento, tivemos nossa atenção voltada para duas técnicas cuja utilização começava a se difundir na comunidade geológica e que estavam se revelando como importantes ferramentas para o estudo da origem ígnea e dos eventos relacionados com a evolução de diferentes corpos rochosos entre eles os que se constituíam como de nosso interesse: as determinações isotópicas U-Pb pontuais em minerais como zircão, monazitas, rutilo, etc., pela sonda iônica desenvolvida pelos australianos na década de 80, denominada SHRIMP (*Sensitive High Resolution Ion Micro-Probe*) e o método isotópico Re-Os, que se difundiu a partir do início dos anos 90, em consequência da chegada ao mercado dos equipamentos para espectrometria de massa capazes de operar com campos negativos (N-TIMS: *Negative Thermal Ionization Mass Spectrometry*), com precisão suficiente para determinações reprodutíveis aos níveis de confiança necessários para medições de razões isotópicas com fins geoquímicos e geocronológicos (Correia, 1998).

Dessa forma, solicitamos e fomos contemplados pela FAPESP com uma bolsa de pós-doutorado, para desenvolver em Melbourne na Austrália, em colaboração com o Dr. David D. Lambert, do Departamento de Ciências da Terra (que se integra no âmbito do *Victorian Institute of Earth and Planetary Sciences*) da *Monash University*, o projeto de pesquisa intitulado: "Geoquímica isotópica e petrologia dos complexos máficos-ultramáficos de Barro Alto, Niquelândia e Cana Brava, Go". Nesse projeto além da previsão do aprendizado da metodologia Re-Os e da obtenção de análises por esse método, encontrava-se também contemplado o desenvolvimento de um programa analítico U-Pb, via SHRIMP, nos laboratórios da *Curtin University of Technology*, e estava ainda manifesta nossa intenção de, ao regressar ao Brasil após a estadia na Austrália (setembro/95 a julho/96), envidar esforços em conjunto com a equipe do Centro de Pesquisas Geocronológicas (CPGeo), para a implantação do método Re-Os no Instituto.

Esse objetivo foi atingido no início do ano 2000, dado apoio financeiro recebido do Ministério da Ciência e Tecnologia via o Projeto PRONEX (41.96.0899.00, coordenado pelo Dr. Umberto Cordani) e da FAPESP (Projeto Temático 97/00640-5, coordenado pelo Dr. Vicente A. V. Girardi), além da bolsa para visita de pesquisador estrangeiro, projeto nº 98/13426-4 que, sob nossa responsabilidade, possibilitou a vinda ao Brasil durante o primeiro semestre de 1999, para colaborar na implantação do laboratório Re-

Os, da Dra. Louise Frick, especialista nessa técnica e responsável na época pelo Laboratório da *Monash University*.

Assim, essa tese foi estruturada com base nos trabalhos preparados para publicação dos resultados desse esforço tanto no que concerne à implantação do método Re-Os no CPGeo, como aos resultados obtidos durante e após a realização da pesquisa de pós-doutorado na Austrália.

O capítulo 2 corresponde ao texto da publicação submetida aos Anais da Academia Brasileira de Ciências sob o título: "*Establishment of Re-Os isotope geochemistry facility at Geochronological Research Centre of the University of São Paulo (CPGeo-USP), Brazil*", de autoria de Ciro Teixeira Correia, Louise R. Frick, Liliane A. Petronilho, Colombo C.G. Tassinari e Kei Sato.

No capítulo 3 encontra-se o texto da publicação preparada para a revista *Precambrian Research*, com resultados Re-Os e U-Pb relativos ao Complexo de Niquelândia: "*2.0 Ga U-Pb and Re-Os ages for the Niquelândia basic-ultrabasic layered intrusion, Central Goiás, Brazil*", de autoria de Ciro Teixeira Correia, Peter D. Kinny, David D. Lambert e Vicente A.V. Girardi.

No capítulo 4 são apresentados outros dados U-Pb na maioria ainda inéditos, que em conjunto com as demais informações isotópicas e geoquímicas disponíveis na literatura fornecem o suporte necessário para as correlações sobre a origem e evolução tectônica dos grandes complexos máficos-ultramáficos da porção Central do Brasil (Barro Alto, Niquelândia e Cana Brava), conforme proposta no capítulo 5, que nos esforçaremos para melhor organizar na forma de publicação ainda a ser preparada.

Por premências atinentes ao tempo disponível para essa empreitada e aos prazos inerentes, os capítulos 2 e 3 são apresentados conforme originalmente preparados, do título aos agradecimentos, para serem publicados em inglês. As referências bibliográficas foram integradas ao final da tese no capítulo 6.

Após esta apresentação procuraremos tratar os demais itens, em particular os capítulos 5 e 6, de forma impessoal. Foi nossa intenção escrevê-los da forma mais objetiva e breve possível tanto pelos motivos expressos no parágrafo anterior, como pelo objetivo de não tornar a leitura demasiado cansativa.

CAPÍTULO 2

Establishment of Re-Os isotope geochemistry facility at Geochronological Research Centre of the University of São Paulo (CPGeo-USP), Brazil.

Abstract

The Re-Os isotopic system is an important tool in the study of mantle processes, geochronology and ore deposit studies. This is principally due to the difference in behaviour of Re from Os during partial melting, coupled with the chalcophilic behaviour of both elements. A low-blank technique for the analysis of Re-Os isotopes in geological materials has been established at CPGeo. The technique uses isotope dilution to determine the concentration of Os and Re in the sample. Sample and isotopic spike equilibration and sample digestion are achieved in sealed glass tubes at high temperature. Osmium is separated from the resulting solution by solvent extraction using carbon tetrachloride. The Os is then extracted back into hydrobromic acid, where it is dried down and purified by microdistillation. Rhenium is separated from the aqueous residue of the solvent extraction by ion exchange chromatography. Accuracy of the concentration and isotopic determinations is monitored by the analysis of a certified reference material for which there have been Re-Os isotopic determinations published in the literature, and the use of the Department of Terrestrial Magnetism (DTM) Os isotopic standard. Data obtained for real samples compare well with previously obtained data from Monash University.

2.1 - Introduction

The Re-Os isotopic system has recently become one of the most sought after systems that is available using existing laboratory facilities and mass spectrometer instrumentation. It has been widely used within the earth and planetary sciences in the study of ore deposits (Foster et al. 1996; Lambert et al. 1998), mantle geochronology (Pearson et al. 1995a,b,c), cosmochemistry (Walker et al. 1989), and meteoritics (Smoliar et al. 1996). Laboratories fall into two categories, those who analyse rocks and meteorites and those who analyse recent sediments and seawater to understand the circulation of the oceans and establish osmium isotope records for the recent past. It is the aim of the *Centro de Pesquisas Geocronológicas (CPGeo)* to establish a world class Re-Os isotope facility for the application of Re-Os isotopes to geological problems, one of only a handful in the world, and the only such laboratory in Latin America.

The most outstanding of the characteristics of the Re-Os system that make it such a potentially powerful tool is the differing chemical behaviour of the parent and daughter elements in geological processes. Both elements are siderophile in nature and therefore most of the Re and Os in the earth are found in the core and mantle. Osmium is a compatible element, being retained in mantle residues (including sulphides and refractory alloys) during mantle melting processes, whereas Re is relatively more lithophile, and is partially removed from the source with the resulting melt.

The decay of ^{187}Re to ^{187}Os results in reservoirs (with time) which have quite different isotopic signatures (Fig. 1). No such fractionation occurs in the Sm-Nd system, where both parent and daughter elements are lithophilic and behave in a very similar fashion during initial melting, which results in very similar ratios of the parent and daughter elements in the crust and mantle.

The disparity in Os isotopic composition between the crustal, mantle and subcontinental lithospheric mantle reservoirs makes the Re-Os isotope system useful as a geodynamic tool, as well as a geochronological tool.

Figure 1. Schematic diagram of the evolution of crust and mantle components for a melting event at time T. $^{187}\text{Os}/^{188}\text{Os} = 0.1271$ is the present day isotopic composition of the chondrite class of meteorites.

2.1.1 - Geochronological dating of terrestrial rocks

There are three methods whereby an age estimate of a terrestrial igneous rock may be obtained using the Re-Os isotope system. The first and most precise method is the classical isochron technique. Either whole rock or mineral isochrons may be obtained.

There are two types of minerals in respect to Os: those that contain inclusions of Os-rich material (eg olivine, chromite), which may yield information as to the initial isotopic composition of a magma, and those that contain very little or no Os at all (eg. plagioclase), where virtually all of the Os is derived by radiogenic decay of ^{187}Re . On a parent-daughter isochron diagram it is these high (or even extreme) $^{187}\text{Re}/^{188}\text{Os}$ ratio rocks and minerals that define the age, and for such tiny samples the analytical error is likely to be significant. The ideal situation in order to obtain a Re-Os isochron is in a closed fractionating magma chamber, where whole rock samples may be collected that reflect different stages of the fractionating magmatic system. The whole rock samples may then provide a spread in Re/Os ratios. The spread in Re/Os ratios will be controlled jointly by sulphide processes and the partitioning of Re into phases such as magnetite

(Richter et al. 1998), and may yield a statistically significant isochron. Relatively few isochrons have been published for terrestrial rocks, probably due in the main to the difficulty in analysis of fractionated rocks due to the low abundance of Os in basaltic melts. Komatiites and picrites are an exception due to their elevated PGE contents.

For magmatic rocks that have been derived directly from the mantle such as basalts, picrites and komatiites, it may be possible to obtain an estimate of the time of extraction from the mantle. This is a familiar concept from the Rb-Sr and, in particular, the Sm-Nd systems where it is largely analogous to the T_{DM} , or depleted mantle model age, also known as the crustal residence age. The Sm-Nd system is able to yield reliable crustal residence ages in that the most significant fractionation of parent from daughter occurs during the formation of the crust. Processes of metamorphism and chemical weathering do not significantly fractionate parent from daughter due to the geochemical similarities of the rare earth elements.

For the Re-Os system, the parent-daughter fractionation that occurs on separation of a magma from its source mantle is the most significant change that is likely to occur. For this reason the model age can usually be considered to yield a reasonable estimate of the mantle extraction age. This of course relies on the assumption that there has been no disturbance of the Re/Os ratio which may not be entirely realistic. Furthermore, sulphide and oxide phases that may crystallise from picritic and komatiite melts, for instance, do contain significant amounts of Os as inclusions and may fractionate the Re/Os ratio. The formula for the calculation of the Os CHUR (chondritic uniform reservoir) mantle model age for measurements at $t = 0$ (present day) is given below:

$$T_{CHUR} = \frac{1}{\lambda} \ln \left[\frac{\left(\frac{{}^{187}\text{Os}}{{}^{188}\text{Os}}_{\text{measured}} - \frac{{}^{187}\text{Os}}{{}^{188}\text{Os}}_{CHUR}^{t=0} \right)}{\left(\frac{{}^{187}\text{Re}}{{}^{188}\text{Os}}_{\text{measured}} - \frac{{}^{187}\text{Re}}{{}^{188}\text{Os}}_{CHUR}^{t=0} \right)} + 1 \right] \quad (1)$$

where $\lambda = 1.666 \times 10^{-11} \text{ y}^{-1}$ (Smoliar et al, 1996), and $\frac{{}^{187}\text{Os}}{{}^{188}\text{Os}}_{CHUR}^{t=0}$ is the $\frac{{}^{187}\text{Os}}{{}^{188}\text{Os}}$ ratio of the chondritic mantle reservoir at the present day. The value of this model age is, strongly model dependant.

It was observed by Walker et al. (1989) that lithospheric mantle peridotites have unradiogenic isotopic compositions compared with their chondritic mantle sources, reflecting the compatible behaviour of Os relative to Re during melt generation. This observation has led to the concept of a Re-depletion model age. This model assumes that the sample was derived as a residue of the melting and that no Re was retained in the source. As such is represents a minimum age as the isotopic composition will have evolved to a slightly more radiogenic value due to in-growth of the ${}^{187}\text{Os}$ from what Re did remain in the residue. The equation for the calculation of the Re-depletion age of a rock present day (at $t = 0$) is given below:

$$T_{RD} = \frac{1}{\lambda} \ln \left[\frac{\left(\frac{{}^{187}\text{Os}}{{}^{188}\text{Os}}_{CHUR}^{t=0} - \frac{{}^{187}\text{Os}}{{}^{188}\text{Os}}_{measured} \right)}{\frac{{}^{187}\text{Re}}{{}^{188}\text{Os}}_{CHUR}^{t=0}} + 1 \right] \quad (2)$$

This model age has proved to be particularly useful where recent Re addition to xenoliths due to melt infiltration by basalts during eruption has occurred. The Re-depletion model age is particularly robust, as the only mechanism which may alter the Re-depletion model age is further Re-depletion of the original source, which will only have the effect of pushing the minimum age closer to the time of initial depletion of the rock. (Fig. 2). Even the addition of radiogenic Os by fluids or melts as has been proposed to have occurred in some arc peridotites (Brandon et al. 1996; McInnes et al. 1998; McBride et al. 1998), will not compromise the validity of the T_{RD} as a *minimum* model age, although it will yield a younger T_{RD} .

Figure 2. Illustration of the Re depletion model age. A mantle xenolith is depleted in melt at 3.0 Ga, and evolves along path (a) with a ${}^{187}\text{Re}/{}^{188}\text{Os}$ of 0.2 (slope of line) to the present day ${}^{187}\text{Os}/{}^{188}\text{Os} = 0.1170$. The T_{RD} for this sample is 2.26 Ga. Enrichment after the original depletion along path (b) will only make that age appear younger, while further complete depletion along path (c) will only make the apparent age closer to the true depletion age. This demonstrates the robust nature of the T_{RD} as a minimum age for Re depleted rocks.

In a similar fashion to the Sm-Nd isotopic system, Re-Os isotopic data for mantle derived rocks are compared with a model for the Re-Os system. It is customary to use either the “chondritic uniform reservoir” model (CHUR) described above, or a bulk earth model, such as the “primitive upper mantle” model of Meisel (1996). The model is used according to the following equation, presented below for the CHUR model.

$$\gamma_{Os} = \left[\frac{\left(\frac{{}^{187}\text{Os}}{{}^{188}\text{Os}}_{sample} \right)}{\left(\frac{{}^{187}\text{Os}}{{}^{188}\text{Os}}_{CHUR} \right)} - 1 \right] \times 100 \quad (3)$$

Thus the γ_{Os} parameter measures the percent difference between the isotopic composition of a sample at a particular time t and the chondritic uniform reservoir at that time. The analogous parameter in the Sm-Nd isotopic system is the ϵ_{Nd} function, however there is one important difference between the two. The ϵ_{Nd} function measures the difference between the isotopic composition of a sample and the chondritic model reservoir in parts per thousand whereas the γ_{Os} function measures this difference in percent. This highlights the radical difference in the precision of the two techniques. In most situations Os isotopic differences between samples and reservoirs are 100 times larger than those in the Sm-Nd system. The reason for this difference is the fundamentally difference behaviour of Os from Re during mantle melting. Osmium is compatible and is retained in the source whereas Re is generally incompatible and is removed with the melt to the crust, leaving a residue that is depleted in Re.

It is for this reason that the γ_{Os} parameter is particularly useful. Mantle and crustal reservoirs are distinctly different from each other. This is illustrated in the summary table below.

Table 1. γ_{Os} values for present day and ancient reservoirs.

Reservoir	γ_{Os}
SubContinental Lithospheric Mantle (SCLM)	-14 to +1.6 average -11
Primitive Upper Mantle (PUM)	+1.5
Mid Ocean Ridge Basalt- (depleted mantle)	+2 to +160, new average -1.6 (see note)
Plume reservoir	EMI = +3.4 to +38, EMII = -1.3 to +58, HIMU +5.6 to +20
The ancient Plume reservoir	+5.8 to +8
The Precambrian mantle	~ 0

Note: new average for MORB is based on data for abyssal peridotites where sample with <30 ppt Os were excluded due to the likelihood of contamination by radiogenic Os from manganese oxide coatings.

2.1.2 - Molybdenite dating of ore deposits

Molybdenite is a common mineral in many Au-bearing ore deposits. It typically possesses very high levels of Re, coupled with very low common Os concentration. As a result, Molybdenite may be used in a fashion similar to zircon in U-Pb dating to determine very precise ages. In the Re-Os system, however, it is still necessary to determine the proportion of common Os in the mineral to obtain a precise age. This is accomplished by the use of two separate Os spikes. In a typical molybdenite, such as that from the Triassic Huanglongpu deposit in China, the molybdenite contains an average of 284 ppm Re, 659 ppb ^{187}Os derived from the decay of ^{187}Re , and 0.2 ppb common Osmium (Stein et al. 1997). In order to determine these concentrations with accuracy three enriched isotopic spikes are required. Firstly, a highly concentrated ^{185}Re spike for the determination of the Re concentration using the $^{185}Re/^{187}Re$ ratio. Secondly, a very dilute ^{190}Os spike for the determination of the common Os content

using the $^{190}\text{Os}/^{192}\text{Os}$ ratio, and finally a concentrated ^{188}Os spike for the accurate measurement of the ^{187}Os content. While it is, in principle, possible to determine Re-Os ages for molybdenite by conventional analysis using just two (^{190}Os and ^{185}Re) isotopic spikes, it is not generally possible to obtain high precision data by this method. Molybdenite in general will possess a natural $^{187}\text{Os}/^{188}\text{Os}$ ratio of several thousand. The precise analysis of such high ratios is beyond the dynamic range of most, if not all, mass spectrometers. A better plan is to obtain, individually, very precise determinations of the three isotope dilution ratios $^{185}\text{Re}/^{187}\text{Re}$, $^{190}\text{Os}/^{192}\text{Os}$ and $^{187}\text{Os}/^{188}\text{Os}$, and use concentrations to determine the precise age of the sample.

2.1.3 - Re-Os tracing of ore formation processes in magmatic ore deposits

The formation of magmatic ore deposits is dependant on mantle derived melts achieving sulphide saturation (Naldrett 1989). Many models propose that sulphide saturation is a consequence of the assimilation of crustally-derived sulphur into sulphide undersaturated magmas that carried mantle-derived precious metals. The sulphide saturation may be either the result of assimilation of bulk crustal material into an ascending magma as is the case proposed for the Noril'sk-Talnakh deposit (Walker et al. 1994) and the Duluth Complex (Ripley et al. 1998) or by the interaction of a S-undersaturated precious metals bearing mantle-derived magma with a second siliceous magma that has a significant component of crustal material (Irvine et al. 1983). This model has been proposed for the formation of the Merensky Reef in the Bushveld Complex (Walker et al. 1991) and the J-M Reef in the Stillwater Complex (Irvine et al. 1983).

In order to develop efficient exploration and ore deposit formation models for these economically important ore deposits, is it necessary to constrain the sources of both the sulphur and the metals. In this regard, the Re-Os isotopic system is particularly useful, as both Re and Os are strongly partitioned into sulphide phases that separate from a silicate melt.

Recently, Foster et al. (1996), Lambert et al. (1998a,b) and others have demonstrated that the combination of Re-Os isotopes must be coupled with geology and platinum group element data in order to fully explore the genesis of deposits in which sulphide segregation processes play a significant role. The R-factor (mass silicate melt/mass sulphide melt) is a measure of the interaction between a silicate melt and an immiscible sulphide melt. The importance of the R-factor processes in the study of massive sulphide ore deposits has been recognised for some time (e.g. Campbell and Naldrett 1979). It has only recently been coupled with Re-Os isotopic data (Foster et al. 1996; Lambert et al. 1997, 1998a,b; Ripley et al. 1998).

For high R-factors, which imply a turbulent flow regime and efficient interaction of the sulphide and silicate portions of the ore system, the sulphide contains virtually all of the precious metals due to the extremely high sulphide/silicate partition coefficients of precious metals ($D \gg 100$). For low R-factors, implying laminar flow or a stagnant magma chamber regime, the silicate melt retains its precious metals, as the sulphide melt has not interacted with the silicate melt, and has not been given the opportunity to

scavenge the precious metals. As Os and Re are both partitioned strongly into sulphide melts, the R-factor of an ore system will have a profound influence on the resulting Re-Os isotope systematics (Lambert et al. 1998a,b).

Using the R-factor approach to the study of the Kambalda Ni-Cu-PGE magmatic ore deposit, Foster et al. (1996) were able to demonstrate that 1) the silicate melt/sulphide melt distribution coefficients for Re and Os were both very high (~500 and ~10,000, respectively), and 2) at the moderate R-factor calculated for Kambalda ore deposits, sulphide saturation of the komatiite must have occurred prior to or at the time of eruption, and was not the result of incorporation of sediment-derived sulphur into the lava flows. This model, which is somewhat at odds with the conventional ore deposit model (Leshner et al. 1984), must lead to refinements in exploration models for this style of deposit, as the sulphidic sediment association is not a prerequisite for ore formation.

2.2 - Establishment of the Re-Os method at CPGeo

2.2.1 - Making and calibration of Re and Os spikes

The accuracy of Re-Os isotopic data is critically dependant on the accurate calibration of the Os and Re spikes, which is dependant on the use of an accurate primary chemical standard. Producing an Os standard of accurate, precisely known concentration is difficult. Osmium metal may be readily weighed, but in order to obtain a solution it must be fused or acid digested and then distilled. The distillation must be completely quantitative, which is difficult to ensure. Alternatively, the standard may be made up from one of the Os salts, such as ammonium hexachlorosmate, dried to constant weight and then weighed and dissolved. These salts are, however, not completely stoichiometric, as they may retain some water in the structure, which leads to a large uncertainty in the concentration of the standard (6% for Morgan and Walker 1989).

At CPGeo a primary Os standard was prepared using ammonium hexachlorosmate. The salt was dried in an oven at 90°C for several days. During this time, the mass of the vessel was periodically checked after returning the vessel to room temperature. Once the standard had reached constant weight, it was used to make two primary standards in 6 N hydrochloric acid, a concentrated standard at 44.40 ppm, and a dilute at 86.59 ppb.

The primary standard for Re was made using Re metal, which was purchased from Johnson Matthey as a fine powder. Two standards were produced, a concentrated standard at 232.9 ppm and a dilute standard with a concentration of 113.5 ppb.

Osmium and Re isotopic spikes were obtained from Oak Ridge National Laboratories in powdered metal form. The isotopic composition data and error magnification data are presented in Table 2. A solution of the Os metal was obtained by dissolution of 5 mg in aqua regia in a Carius tube at 100°C. The solution was diluted into 6N hydrochloric acid to make a stock solution of approximately 90 ppm. This solution was then diluted for routine use. Two spikes were prepared, a concentrated spike with a concentration of 66.7 ppb and a dilute spike with a concentration of 0.98 ppb. The Re metal was initially

digested in 3 ml aqua regia, and diluted to make a stock solution of approximately 103 ppm. This solution was diluted to make two spikes for routine use, a concentrated spike of 51.0 ppb and a dilute spike of 5.6 ppb.

The Os and Re spikes were calibrated by weighing appropriate amounts of spike and standard into a PTFE vessel. The amounts of each solution were chosen to provide as close to the optimum spike/sample ratio as possible using the estimated concentration of the Os and Re spikes. The mixtures were heated gently overnight to facilitate complete spike-standard equilibration. The ratio of the mixtures was measured by N-TIMS analysis where the Os is measured as OsO_3^- . In order to obtain the most accurate spike concentration possible, the isotopic composition of the primary Os standard was determined precisely by N-TIMS, and this data was used during the calculation of the spike concentration, after correction for the oxygen contribution to the isotopic composition and fractionation correction. A summary of the preliminary calibration data for the Os and Re spikes is presented in Table 3. The Re spike was calibrated in an identical fashion to the Os spike.

Table 2. Oak Ridge certified compositions of enriched Os and Re spikes and spike information.

								Measured Ratio	Ropt	E(Ropt)
^{190}Os spike	^{184}Os	^{186}Os	^{187}Os	^{188}Os	^{189}Os	^{190}Os	^{192}Os			
atomic %	<0.05	<0.05	<0.05	0.50	1.14	97.31	1.04	$^{190}\text{Os}/^{192}\text{Os}$	7.76	-1.18
^{185}Re spike	^{185}Re	^{187}Re								
atomic %	96.74	3.26						$^{185}\text{Re}/^{187}\text{Re}$	4.21	-1.33

*Ropt is the optimum ratio to measure for the chosen measured ratio (eg $^{190}\text{Os}/^{192}\text{Os}$) in order to minimise the propagation of errors due to isotope dilution.

†E(Ropt) is the error magnification factor due to propagation of errors in the isotope dilution calculation. In run statistics (2 sigma) on the measured ratio are multiplied by this factor to obtain realistic 2 sigma errors on the concentration determination.

Table 3. Results for the initial calibration of Os and Re spikes

	Conc. Os	Conc. Re	Dilute Os	Dilute Re
	$\mu\text{Moles/gram Os (x } 10^{-5})$	$\mu\text{Moles/gram Re (x } 10^{-5})$	$\mu\text{Moles/gram Os (x } 10^{-5})$	$\mu\text{Moles/gram Re (x } 10^{-5})$
Calib1	35.39 (34)	17.380 (8)	0.4521 (30)	1.9678(8)
Calib2	33.72 (30)*	17.516 (9)	0.4014 (29)	1.9619 (7)
Calib3	34.88 (36)	16.864(20)*	0.4609 (82)	1.9706 (2)
Calib4	35.05 (19)	17.706 (11)	0.4682 (37)*	1.9464(24)*
Average	35.10 ± 0.26	17.534 ± 0.001	0.438 ± 0.037	1.962 ± 0.011

*excluded from the average. Errors are 2σ on the last two digits shown.

2.2.2 - Sample preparation methods

Re-Os isotope geochemistry in ancient rocks requires the precise determination of both Os isotopic composition and the molecular $^{187}\text{Re}/^{188}\text{Os}$ ratio. This is accomplished by isotope dilution analysis of both Re and Os. Unlike conventional isotope systems, the sample digestion, spike sample equilibration and separation are complicated by the geochemistry of Os. Osmium is both extremely rare in terrestrial rocks, extremely refractory and, under oxidising conditions, extremely volatile.

The problem of ensuring spike equilibration while also preventing spike loss has to the rediscovery of an old technique of digesting samples under oxidising conditions in sealed tubes (Walker and Fassett 1986; Shirey and Walker 1994; 1995). By this method, digestion and spike-sample equilibration is achieved by the extremely oxidising conditions while loss of the volatile Os is prevented.

In detail, the technique involves the digestion, in aqua regia, of a small amount of rock powder (<1g) in a 25 cm³ volume sealed glass tube in the presence of Re and Os spikes. The reagents are frozen before the tube is sealed to inhibit reaction, which may oxidise the sample or spike Os to the volatile OsO₄. The tube is sealed using an oxygen-butane torch, and is then sealed inside a steel bomb to contain failures. The bomb is then placed in an oven at 240°C overnight. Once cool, the tube is removed, frozen in liquid nitrogen which condenses the volatile OsO₄, and opened. This high temperature equilibration step may be combined with an acid digestion procedure under low-temperature and reducing conditions (or desilicification) to reduce the bulk mass of the sample to be introduced into the Carius tube, and assist in the breakdown of silicate phases to release Os to the aqua regia.

2.2.2.1 - Solvent extraction of Osmium

The isobaric overlap of ^{187}Re and ^{187}Os requires complete chemical separation of sample Re and Os for mass spectrometric analysis. Recently, Cohen and Waters (1996) have documented a technique that combines the Carius tube equilibration with an extraction of the equilibrated Os by CHCl₃ or CCl₄. This method has been adopted widely within the Re-Os geochemistry community, and was chosen to be established here at CPGeo. The solvent extraction technique provides high extractive yield coupled with low procedural blanks and at rapid throughput compared with more conventional distillation techniques. The Carius tube is opened after the high temperature equilibration, the contents extracted and mixed with a small amount of solvent. The aqua regia- solvent mixture is agitated to aid the extraction of the Os and then the organic and acidic layers are separated. This procedure is repeated twice to ensure high Os yield. The aqueous layer which contains the sample Re is retained for the separation by ion-exchange column chemistry using the strong anion exchange resin AG- 1 X8. The Os is extracted from the solvent into concentrated hydrobromic acid which is dried and purified by microdistillation, ready for mass spectrometry.

2.2.2.2 - Micro distillation purification of Osmium

The micro distillation procedure was developed by Matthieu Roy Barman (Roy-Barman 1993) to remove organic material and tungsten that are not separated by ordinary distillation and which would inhibit the thermal ionisation of Os. The procedure was only published in the literature in detail in 1997 (Birck et al. 1997), although several laboratories have been using it for some time.

The hexabromo-Os salt obtained from solvent extraction is dissolved in a small amount of hydrobromic acid, transferred to the upturned lid of a 5 ml Savillex TFE conical vial, and dried. A drop of concentrated hydrobromic acid is placed in the bottom of the conical vial, which will remain when upturned due to surface tension. A drop of oxidant is added to the dried Os salt- 8% CrO_3 in 12N H_2SO_4 (Birck et al. 1997), and the vessel sealed in the inverted position. The whole is wrapped in aluminium foil with the very top (or bottom) where the drop of HBr is suspended, and placed on a hotplate for several hours. The HBr drop is then dried down and the rest of the material discarded.

2.2.2.3 - Mass Spectrometric Analysis

Mass spectrometry for Os is performed on a Finnigan MAT 262 N-TIMS. Samples are run on single platinum filaments which are loaded with barium nitrate. The filaments are heated slowly to a running temperature of approximately 800°C (for standards) as measured by an optical pyrometer on the source. Oxygen is introduced into the ion source through a sapphire variable bleed valve, at a pressure of 2×10^{-6} mbar. Samples are run at much higher temperatures than standards due to the presence of impurities in the loaded sample which inhibit the emission of ions. The Os is collected as the negative OsO_3^- ion, which is measured by a single secondary electron multiplier in peak jumping mode.

The heating of the filament to cause ionisation introduces a mass fractionation bias into the measurement, as lighter atoms of Os (or Re) are ionised with a higher efficiency. In addition to this effect, the interference of the three isotopes of oxygen (as it is as the trioxide that Os is measured) must be taken into account.

The oxygen correction for Osmium is achieved by correcting the measured 240/236 (nominally the $^{192}\text{Os}/^{188}\text{Os}$ ratio of the negative trioxide ion) to the value of 240/236 = 3.09219, calculated by Hauri and Hart (1993) using Nier's (1950) revised values for the isotopic composition of oxygen and Luck and Allègre's (1983) value for the ratio of $^{192}\text{Os}/^{188}\text{Os}$.

The data are further corrected for the contribution of the Os spike (if spiked) to the isotopic composition of the other sample isotopes, as the spike does contain significant amounts of the other isotopes, in particular the isotope of interest ^{187}Os . Then, a second round mass fractionation correction is performed to the value of $^{190}\text{Os}/^{188}\text{Os} = 3.08271$ (Luck and Allègre 1983; Reisberg et al. 1991; Horan et al. 1992).

A similar procedure may be adopted for mass fractionation and oxygen correction of the Re data, however, in this case there is no internal mass fractionation possible on the two isotopes of Re. Multiple analyses of the Re isotopic standard indicate that the mass

fractionation involved is negligible at the low temperatures at which Re ionises, and furthermore is within the error of the isotope dilution method used to calculate the abundance of Re.

2.3 - Precision, accuracy, and blanks.

The best way to assess the precision and accuracy of any analytical technique is to compare data obtained on certified reference materials with the certified values and published data. At present there is no certified reference material for the Os isotopic system. In part this must be due to the notorious nugget effect (Potts 1987) which makes the selection and preparation of a suitable material difficult. Isotopic and concentration data have been published for a number of standards that are certified for precious metals concentrations, however, only one of these is likely to be suitable. Several analyses of the Wellgreen massive sulphide precious metals standard WMS-1 have been published (e.g., Dickin et al. 1992) however, due to the very high level of both Re and Os in this sample (252 ppb and 133 ppb, respectively) it is likely to be particularly prone to this problem. As an interim measure, for the purposes of inter-laboratory comparison, the Wellgreen altered peridotite precious metals standard WPR-1 has been used by several laboratories (Table 4). This standard is of a much more moderate concentration. WPR-1 has 16 ppb Os and 12 ppb Re, which is in the same order of magnitude as some of the unknown samples that are routinely analysed. However, there still, remains the difficulty of obtaining a sample with a homogeneous isotopic composition.

Table 4. Os data for WPR-1 precious metals standard.

Method	Os (ppb)	Re(ppb)	$^{187}\text{Os}/^{188}\text{Os}$
OU distillation	15.82 ± 1.14 (n=6)		0.14549 ± 18* (n=6)
OU solvent extraction	16.06 ± 0.80 (n=3)		0.14543 ± 18* (n=3)
Monash	16.801 ± 0.076 (n=11)	11.635 ± 0.045 (n=5)	0.14515 ± 78* (n=11)

Data for OU (Open University) from Cohen and Waters (1996). Errors are external precision. *Errors on the last two digits shown

Table 5. Os data for WPR-1 precious metals standard obtained at CPGeo.

Analysis and spike	Common Os (ppb)	Re(ppb)	$^{187}\text{Os}/^{188}\text{Os}$
1 conc	15.638 ± 0.012	10.937 ± 0.017	0.14188 ± 0.00037
2 conc	15.831 ± 0.018	11.068 ± 0.015	0.14681 ± 0.00045
3 conc	13.002 ± 0.016	11.269 ± 0.011	0.14176 ± 0.00029
4 conc	13.227 ± 0.015	10.819 ± 0.022	0.14320 ± 0.00061
5 dilute	-	11.284 ± 0.018	-
6 dilute	16.510 ± 0.030	11.278 ± 0.021	0.14336 ± 0.00060
7 dilute	16.066 ± 0.032	11.277 ± 0.010	0.14210 ± 0.00039
8 dilute	16.33 ± 0.31	11.022 ± 0.009	0.1536 ± 0.0071
9 conc	18.89 ± 0.25	11.638 ± 0.035	0.1444 ± 0.0011
10 conc	15.824 ± 0.031	10.929 ± 0.033	0.13980 ± 0.00027
11 conc	16.064 ± 0.020	11.069 ± 0.022	0.14092 ± 0.00054
12 dilute	16.302 ± 0.029	11.576 ± 0.018	0.14336 ± 0.00080
Average	$15.79 \pm 1.59^*$	$11.18 \pm 0.25^*$	$0.1437 \pm 0.0037^*$

Data was not obtained for samples where indicated by the dash. All errors are 2 sigma or external precision where marked*.

The data presented in Table 5 is for 12 analyses of the WPR-1 standard. The standard was analysed using both concentrated and dilute spikes in order to test the calibration of each. Analyses 3 and 4 yield anomalously low Os concentrations due to incomplete digestion of chromite during the high temperature digestion step. This was observed as tiny specks of black material in the bottom of the Carius tube. This serves to highlight the importance of complete digestion to the accuracy of the data, and demonstrates the very low Re/Os ratio of chromite.

Bias introduced during the mass spectrometry is assessed by the analysis of a mass spectrometry standard provided by the Department of Terrestrial Magnetism. This standard was made using Johnson-Mathey ammonium hexachlorosmate from the batch 5.56870-A. At CPGeo, this isotopic standard is run with every batch of mass spectrometric analysis. Comparison of DTM, Monash and CPGeo N-TIMS is shown in Tab. 6.

Table 6. Comparison of DTM, Monash and CPGeo N-TIMS data for JM 5.56870-A

	$^{187}\text{Os}/^{188}\text{Os}$
Monash SEM (n = 26)	0.17396 ± 58
Monash FAR static (n = 10)	0.17360 ± 48
DTM pulse (n = 22)	0.17429 ± 55
DTM analog (n = 13)	0.17396 ± 38
CPGeo SEM (n = 5)	0.17165 ± 223

DTM data are from Shirey (1997). DTM data were all acquired in rapid peak hopping mode with a single detector.

Analytical blanks have a significant effect on the usefulness of isotopic analyses. In general, data are only acceptable if the blank is less than 30% of the total element measured. The isotopic composition is extremely important in these circumstances.

Initial blank measurements made at CPGeo were extremely low at 1.5pg for Os and 12 pg for Re. At these levels the blank correction of measured samples is negligible for most rock types.

2.4 - Analysis of real samples

As a part of the establishment of the Re-Os facility at CPGeo, it was decided to analysed some samples that had previous Re-Os isotopic data obtained from the Trace Analysis Laboratory at Monash University, Australia.

The suite of samples represented some of the most challenging rocks that it is possible to analyse by Re-Os isotopes. The suite are mafic to ultramafic samples from the Carajás area, Amazon Craton, Brazil, and the majority of them have both very low concentrations of Os, coupled with a high degree of metamorphic alteration.

Table 6. Re-Os isotopic data for samples analysed at CPGeo and comparison with data obtained at Monash University.

	Os (ppb)	Common Os (ppb)	Re (ppb)	$^{187}\text{Os}/^{188}\text{Os}$	$^{187}\text{Re}/^{188}\text{Os}$
A21	0.0075	0.0023	2.1145	20.408 (66)	4490 (45)
A21*			2.1189		
A3	0.0256	0.0247	0.1071	0.2650 (76)	20.9 (42)
A3*	0.1614	0.1586	0.0841	0.2607 (13)	2.56 (26)
S9	2.9730	1.1992	0.5591	11.133 (22)	2.241 (22)
S9*	2.7778	1.2112	0.4327	9.963 (19)	1.72 (14)
C13	0.0349	0.0296	0.8623	0.6417 (35)	140.0 (14)**
C13*	0.0089	0.0072	0.7127	1.842 (10)	478 (48)**

Note: Analyses marked * were performed at CPGeo. ** See comments in text

While the analysis itself can not be considered a success in that the samples were too strongly altered to obtain any useful information, the comparison between the CPGeo and the previously analysed data are interesting. There are several points to notice. Firstly, for the sample A21, while no Os data were obtained, the agreement between the Monash and CPGeo Re determinations is excellent. For the sample A3, while we see little agreement in either the Os or Re concentrations, there is remarkable agreement in the determined isotopic composition of the sample. This is not intuitively possible, as all samples (or mineral grains within samples) that possess different Re and Os concentrations should therefore have different Re/Os ratios, and will evolve to different present day isotopic compositions from a common initial isotopic composition. However in this sample, we must have complete and recent Os isotopic homogenisation in order for samples with differing Re/Os ratios to possess identical isotopic composition. This homogenisation is in this case a small scale event, since these analyses were of the same sample powder. Moreover, this is not an unlikely scenario given the complete sericitisation that is present in this sample.

The sample S9 exhibits the level of reproducibility that is typical of osmium isotopic analyses, particularly between different laboratories. We cannot expect osmium isotopic determinations to be reproducible on the same levels that we expect from Rb-Sr and Sm-Nd analyses. Chiefly this is because these elements are present in most rocks at the ppm level, as opposed to the ppt to ppb levels for Re and Os. Furthermore, neither Os nor Re is able to partition into the silicate phases in rocks. Therefore these elements will be present in trace phases, and the distribution of these in rocks is not uniform.

This effect, called the nugget effect, is strongly apparent in the difference between the analyses of the sample C13. The Monash determination yielded a common Os concentration of 29.6 ppt, whereas the CPGeo determination yielded just 7.2 ppt of common Os. Unfortunately this is a common occurrence in the analyses of crustal rocks. Moreover, at this level we can have but little confidence in the isotopic composition determination as the corrections that are required for the isotopic composition of the spike and the isotopic composition of the blank are significant factors in the final isotopic composition of the sample. However, Os isotopic analyses at this level have been performed successfully under extremely low blank conditions (Alves et al. 1999).

2.5 - Conclusions

The Re-Os isotopic system is ideally suited to the study of mantle derived rocks, ore deposits and mantle xenoliths. In these systems it may be used as both a geochronological tool, and as a tracer of mantle processes. The newly established facility at CPGeo has the capability to provide a valuable contribution to the research of timing, origin and history of many metallogenic prospects as well as to cooperate together with other isotope methods to improve the knowledge of regional geology, petrology and tectonic evolution in South America.

Acknowledgements

This research was supported by PRONEX (41.96.0899.00) and FAPESP (Thematic project 97/00640-5). Louise Frick was supported by FAPESP grant number 98/13426-4. Thanks are given to all the staff at CPGeo for assistance during the course of this work. Thanks particularly to Sandra Andrade for somehow always being able to provide the required reagents at very short notice.

Imagem do sensor ETM+ do satélite Landsat 7, do Complexo de Niquelândia, Goiás. Composição colorida/falsa cor com razões de banda de modo a destacar a textura. Notar que a forma e a estrutura estratiforme do complexo destacam-se em relação às rochas encaixantes. Escala aproximada 1: 290.000. Em preto têm-se as águas do lago da usina de Serra da Mesa e o limite da imagem no canto inferior direito.

CAPÍTULO 3

2.0 Ga U-Pb and Re-Os ages for the Niquelândia basic-ultrabasic layered intrusion, Central Goiás, Brazil

Abstract

The Niquelândia ultrabasic layered intrusion, central Brazil, has been analysed by U-Pb and Re-Os methods in an attempt to constrain its age, origin and evolution. Zircons from an evolved gabbro display a wide range of U-Pb ages, from 1981 ± 52 Ma to 778 ± 16 Ma, suggesting a 2.0 Ga emplacement age and a protracted history of isotopic disturbances during later episodes of metamorphism. Seven samples define two preliminary Re-Os isochrons. One gabbro with igneous textures and very high $^{187}\text{Re}/^{188}\text{Os}$ and two chromitites with very low $^{187}\text{Re}/^{188}\text{Os}$ together yield an isochron age of 2066 ± 69 Ma in close agreement with the oldest concordant zircon age. The near-chondritic initial γ_{Os} for this isochron suggests that the parental magmas were subjected to only limited amounts of crustal contamination. Four samples with metamorphic fabrics define a separate, ca. 800 Ma Re-Os isochron, consistent with the youngest concordant zircon ages, and reflecting later disturbance to the Re-Os isotopic system.

Keywords: Geochronology, Niquelândia, Stratiform Complex, Re-Os, U-Pb, SHRIMP.

3.1 - Introduction

The Niquelândia complex (NQC) in central Brazil is an anorogenic, stratiform layered igneous intrusion, one of the largest of its type in the world, whose layers dip from 30° to 50° NW. It belongs to a 300 km long, discontinuous, north-trending chain of mafic-ultramafic massifs which also includes the southern Barro Alto (BAC) and the northern Cana Brava (CBC) complexes (Figure 1). These bodies are of great economic significance to Brazil. The Niquelândia complex is the principal mining area of laterite-hosted nickel in Brazil, and the Barro Alto complex has huge reserves of laterite-hosted nickel. The Cana Brava complex hosts the largest asbestos mine in Brazil. All three bodies have been investigated for their potential to host platinum group element mineralization.

There is considerable debate as to the true age of emplacement of these layered intrusions and to their post-emplacement tectonic history. Previous isotopic data for the complexes consist mainly of K-Ar and Rb-Sr analyses of the BAC and CBC or their country rocks. While these systems record various aspects of the post-magmatic history of these units, they do not record primary emplacement ages. A recent conventional U-Pb study of Niquelândia (Ferreira Filho et al., 1994) produced a lower concordia intercept age of 770-795 Ma from zircons, consistent with metamorphic disturbance during the Brasiliano tectonic event, and an upper intercept age of 1560-1600 Ma that was interpreted as the age of igneous crystallization. However, these zircons were >70% discordant, suggesting that the upper intercept age is poorly constrained.

Drawn by: Thelma Samara / 98.

New SHRIMP-II (Sensitive High-Resolution Ion Microprobe) U-Pb zircon data from an evolved gabbro from the Niquelândia complex and TIMS (thermal ionisation mass spectrometry) Re-Os data for seven whole rock samples from the complex have been obtained in order to set better limits on the crystallization age of these intrusions, to trace the source of their parental magmas, and to verify how similar they are in terms of tectonic evolution.

3.2 – Geologic setting of the NQC

The NQC and the two other associated complexes are now recognized as stratiform intrusions (Rivalenti et al., 1982; Girardi et al., 1986; Feininger et al., 1991; Ferreira Filho et al., 1992, 1994; Correia, 1994). The NQC comprises, from base to top: 1) a lower sequence (LS) comprising a basal gabbro zone (BGZ); a basal peridotite zone (BPZ); a layered ultramafic zone (LUZ); and a layered gabbro zone (LGZ); and 2) an upper sequence (US) comprising an upper gabbro-anorthosite zone (UGAZ) and an upper amphibolite zone (UA) (Rivalenti et al. 1982) (Figs 2 and 3). Based on the relatively constant dip and the absence of stratigraphic repetition, the total thickness of the NQC is estimated at 14.5 km. Relative proportions of the zones are as follows: BGZ 2%, BPZ 6%, LUZ 13%, LGZ 44%, UGAZ 33%, and UA 2%.

The ultramafic units (BGZ, BPZ, and LUZ) are composed of mylonitic metagabbro at their base grading into layers of Cr-spinel-bearing gabbro, websterite, and peridotite. Two chromitite horizons (cm to dm thick) are found within the LUZ.

LGZ is composed of melanocratic to leucocratic gabbros (plagioclase, augite, hypersthene, with minor and variable amounts of ilmenite, magnetite, sulphide and apatite), and some thin layers of websterite and peridotite close to the base of the zone. Cumulate igneous textures are locally well preserved. Mylonitic textures are common, associated with discrete shear zones. Amphibole appears before the middle of LGZ and increases in proportion upwards. At the top of LGZ where it meets UGAZ is a more evolved gabbro ('hydrous LGZ top'), tens of meters thick. At this level biotite appears together with quartz, hornblende and orthopyroxene as major mineral phases, whilst apatite and zircon appear and in some samples are significant components.

UGAZ is composed of gabbro, anorthosite and some clinopyroxenite layers near its top. Cumulate textures (plagioclase and olivine cumulus, orthopyroxene intercumulus) and ophitic textures are quite common, as are corona textures derived from reaction between plagioclase and primary mafic phases. In the anorthosites, hornblende is the main mafic phase.

UA lithotypes are layered amphibolite (hornblende, plagioclase, clinopyroxene, opaque minerals, $\pm$ garnet), and some anorthosite at its base.

Correia et al. (1997a) considered the NQC together with BAC and CBC as part of a Palaeoproterozoic rift system preserved within Archaean blocks of eastern and central Brazil, or emerging within Meso- and Neoproterozoic supracrustal rocks inside the Goiás Massif (Nilson et al., 1994; Pimentel et al., 1996). In the east, the basal NQC unit (BGZ) is in tectonic contact with a narrow slice of tonalitic granite-gneiss rocks

supposed to belong to the Goiás Massif. Further to the east these rocks overthrust metasedimentary rocks of the Serra da Mesa Group (Marini et al. 1977). In the west, the top NQC units come into contact with metavolcano-sedimentary rocks of the Indaianópolis Sequence (Ribeiro Filho & Teixeira, 1981). Metamorphosed xenoliths supposedly derived from these country rocks are found inside the US gabbros showing that, in a Cana Brava-like scenario, the west border country rocks of these complexes were already metamorphosed at the time of the intrusions.

Notwithstanding important improvements made during the last few years to understanding the geology of these ultramafic bodies, some important aspects still remain under debate. As illustrated by Ferreira Filho et al. (1994), these issues include: a) the extent of post-magmatic deformation due to tectonism; b) the extent to which recrystallization patterns exhibited by NQC rocks were caused by subsolidus re-equilibration during cooling (Girardi et al., 1996) as opposed to later high grade metamorphism (Danni et al., 1982); c) the chronological and tectonic relationship between the complex and its country rocks.

3.3 - Geochronology

The first geochronological data for the region consists of K–Ar and Rb–Sr data for BAC and its country rocks presented by Hasui and Almeida (1970) and in the PhD thesis of Souza (1973), discussed and summarized by Cordani and Hasui (1975). The spread of obtained ages was very large (4,000 to 500 Ma) and their significance remains controversial due to analytical and sampling uncertainties. Based on these ages, various authors have placed the formation of the mafic-ultramafic complexes anywhere from the early Archaean to the Brasiliano/Panafricano tectonic cycle (800-500 Ma, Almeida, 1968).

Later, Matsui et al. (1976) and Girardi et al. (1978) published Ar/Ar, K–Ar and Rb–Sr data from the Cana Brava region. Both studies produced conventional K–Ar ages distributed over the range 3,950 to 480 Ma, similar to the earlier studies of BAC. In addition, Matsui et al. (1976) reported two K/Ar whole-rock isochron ages of $1,925 \pm 110$ Ma and 475 ± 15 Ma, and Girardi et al. (1978) reported two Rb–Sr isochron ages for country rocks bordering the CBC. The older isochron, comprising samples from the western border of the complex, yielded an age of $1,157 \pm 150$ Ma, while the younger isochron, including samples of the eastern border of the complex, yielded an age of 644 ± 27 Ma. Girardi et al. (1978) interpreted the 1,157 Ma Rb–Sr age as the age of amphibolite facies metamorphism of the western border of CBC (a metavolcano-sedimentary sequence similar to those occurring on the western borders of BAC and NQC).

Fuji (1989) obtained two precise whole rock Sm–Nd isochrons for samples of CBC and the Serra da Bota Gabbro, a satellite body to the CBC, which intrudes its eastern country rocks (Figure 1). The CBC data yielded an isochron age of $1,970 \pm 69$ Ma, while the data from the satellite body defined an age of $1,088 \pm 18$ Ma. Fuji (1989) interpreted these ages as corresponding to the time of igneous crystallization of the CBC and SBB bodies, respectively.

Fuck et al. (1989) determined two Rb-Sr isochron ages for BAC rocks, the first being from gneissic country rocks of its western border ($1,266 \pm 17$ Ma) and the second from felsic granulites found inside the complex ($1,330 \pm 66$ Ma). Fuck et al. (1989) suggested that these ages were related to metamorphism of those units, probably due to the continental collision between Goiás massif and the Neoproterozoic metamorphic units forming its eastern border, during the Uruaçuano cycle (ca. 1,300-1,400 Ma, Hasui and Almeida 1976).

Suita et al. (1994) presented the first U-Pb conventional zircon data for BAC. They interpreted an U-Pb upper concordia intercept age of 1.72-1.73 Ga as the minimum igneous age for the Barro Alto complex. They also reported U-Pb ages of 1.29-1.35 Ga (upper intercept) and 0.77-0.82 Ga (lower intercept) for a pegmatitic gabbro from the Barro Alto complex. The upper intercept age was interpreted as a period of mafic magmatism related to the Uruaçuano cycle, or perhaps post-Barro Alto magmatism. The lower intercept age was attributed to the last metamorphic event during Brasiliano times.

Ferreira Filho et al. (1994), again using conventional U-Pb geochronology, obtained lower concordia intercept ages of 770-795 Ma for different zircon samples from the Niquelândia complex, consistent with a Brasiliano metamorphic disturbance, and upper concordia intercepts of 1560-1600 Ma. Based on the agreement of the upper intercepts of their samples they interpreted this as the igneous crystallization age for the Niquelândia complex. They further suggested that there was no metamorphic event in the region between 1,600 and 790 Ma, and that if 1,560-1,600 Ma intrusion ages are assumed for the BAC and CBC, the younger ages could indicate extensive basic magmatism at this time.

Lastly, Correia et al. (1997a) presented new Rb-Sr and Sm-Nd data for CBC. They obtained a Rb-Sr isochron age of 1350 ± 35 Ma, and a Sm-Nd mineral/whole-rock isochron age of 770 ± 43 Ma. Based on these and other available data, including ϵ_{Nd} considerations, the data appear to support Fugii's (1989) first proposal that the CBC formed around 2.0 Ga. However, Correia et al. (1997a) attributed the old Rb-Sr age to Uruaçuano metamorphism in the region, and the young Sm-Nd age to the most recent Brasiliano overprint, disagreeing with the regional interpretations proposed by Ferreira Filho et al. (1994) as mentioned above.

3.3.1 - Sample Information

The samples selected are located in Figure 2 and their coordinates are given in Table 3.

NQ 1564 is a fresh, weakly foliated metagabbro from BGZ with less than 1% of opaque minerals. Among its minerals, the plagioclase shows granoblastic textures in some domains and some sulphide grains display secondary remobilization into cracks and boundaries with surrounding phases (Figure 6).

Modified from V.A.V. Girardi et al., 1986

Figure 2 – Niquelândia geology and units with sample locations.

NQ1563 is a highly sheared olivine websterite from BPZ (Figure 7). 10% of the sample volume corresponds to secondary serpentine. The other 90% are porphyroclasts (0.5-1.5 cm) of orthopyroxene, olivine and minor spinel inside a matrix with grains around 0.5-1.5 mm.

Chromitites occur in two horizons parallel to the main layering at the base of LUZ (Figure 3). NQ210 comes from the lower horizon and NQ1000 from the upper. Both horizons consist of several discontinuous cm to dm-sized layers or lenses of massive chromitite. Their compositions are chromite (38-45%), olivine (35-45%), brown spinel (13-18%), orthopyroxene (5-10%) and minor clinopyroxene, opaque minerals (magnetite and sulfides) and secondary serpentine. Chromite displays cumulus texture with the other main phases as intercumulus material.

NQ1560 and NQ1561 are LUZ gabbros. The first is a medium grained clinopyroxene norite. This sample is the one with better preserved igneous texture, without foliation or shear overprints. Its sulfides, too, show no evidence of later remobilization (Figure 8) as shown by the other samples (Figure 6 and 7). NQ1561 is a medium grained orthopyroxene gabbro with granoblastic domains, weak foliation and also cracks due to shear action.

NQ1557 is a medium to coarse grained websterite from LUZ with equals amounts of orthopyroxene and clinopyroxene and less than 1% of opaque minerals (mainly sulfides). NQ1549 comes from the top hydrous layer of LGZ. It is a medium grained clinopyroxene norite with primary hornblende, biotite and minor amounts of rutile, opaque minerals, apatite and prismatic zircons (Figure 9). Its mineralogy shows no signs of alteration. The pyroxenes exhibit igneous characteristics while the plagioclases are mainly granoblastic.

NQ1552 is an medium grained anorthosite (>95% labradorite) with minor hornblende, epidote, scapolite and titanite.

3.3.2 – Analytical Procedures

3.3.2.1 - U-Pb SHRIMP II Analysis

All zircon analyses refer to zircons separated from a 2kg sample NQ1549. Mineral separation and zircon mounting procedures were performed at VIEPS Department of Earth Sciences, Monash University, Victoria. About 300 colourless to pale yellow or pink zircons were recovered from the gabbro sample using standard heavy liquid techniques. The majority could be grouped into two morphological populations: one group of small ($\leq 100 \mu\text{m}$) rounded grains and another of euhedral prismatic grains or fragments of grains (50 to 250 μm in size).

Backscattered and cathodoluminescence (CL) images of the sectioned zircons were done at the Centre for Microscopy and Microanalysis, University of Western Australia. CL images reveal that simple, continuous zonation from core to rim is characteristic of the rounded zircons. The prismatic grains, in contrast, generally displayed different types of complex zonation whereby a zoned core is overgrown by one or two outer

Modified from V.A.V. Girardi et al., 1986

Figure 3 - Niquelândia stratigraphic column with sample locations.

rings (with or without truncation of the interior), the outer rings themselves displaying fine-scale euhedral zoning, with generally the outermost zone being wider and more brightly luminescent. The majority of isotopic analyses were taken from cores of grains least affected by later overgrowths and interpreted to represent the primary igneous zircon.

U-Th-Pb isotopic ratios and elemental abundances in ca. 20 μm diameter areas of zircons were determined using the SHRIMP II at the Western Australia Isotope Science Research Centre, Curtin University of Technology, Perth. A 2.0 nA primary ionizing O_2^- beam was employed, and mass resolution set at 5000, resulting in a sensitivity for Pb isotopes of 15 counts per second per ppm Pb per nA. Pb isotope ratios were corrected for common Pb based on the measured $^{204}\text{Pb}/^{206}\text{Pb}$, typically <1% correction to ^{206}Pb . Pb/U isotope ratios were corrected for interelement discrimination using data obtained concurrently from Perth standard zircon CZ3 ($^{206}\text{Pb}/^{238}\text{U} = 0.0914$). Ages were calculated using standard decay constants.

3.3.2.2 - Re-Os Isotopic Analysis

To avoid potential Re contamination from steel and tungsten carbide crushing equipment, all whole rock powders were prepared using a ceramic jaw crusher and an agate mill. The jaw crusher and mill were thoroughly cleaned between samples by crushing multiple aliquots of clean quartz and pre-contaminated with an aliquot of the sample. The contaminated sample was discarded prior to preparation of a clean aliquot of rock powder.

The Carius tube isotope dilution procedure employed in our laboratory for the measurement of Re and Os concentrations and Os isotopic compositions is similar to that developed by Shirey and Walker (1995), the details of which are described in Lambert et al. (1998). During this study, total chemistry and mass spectrometry blanks were 26 pg for Re and 2 pg for Os, with a $^{187}\text{Os}/^{188}\text{Os}$ of 0.183. Blank corrections were insignificant for all samples analysed in this study. Analyses over a period of three years of an Os isotopic mass spectrometry standard provided by the Carnegie Institution of Washington - Department of Terrestrial Magnetism (DTM), made using Johnson-Matthey ammonium hexachlorosmate batch 5.56870-A, yielded a mean $^{187}\text{Os}/^{188}\text{Os} = 0.17367 \pm 0.00058$ (external reproducibility at the 2σ level, $n = 24$), within error of the DTM value of 0.17429 ± 0.00055 (Shirey, 1997; Lambert et al., 1998). Thus, there is no measureable bias introduced into the data from this mass spectrometer (Finnigan MAT 262 N-TIMS) relative to DTM. Comparable external reproducibility was obtained on measured $^{189}\text{Os}/^{188}\text{Os}$ and $^{190}\text{Os}/^{188}\text{Os}$ for all samples after spike subtraction and blank correction.

At present, there is no accepted international rock standard for Re and Os concentrations and Os isotopic composition to permit laboratories to monitor overall analytical accuracy. We have attempted to assess our analytical accuracy by measuring Re and Os concentrations and Os isotopic composition in the proposed peridotite PGE standard "WPR-1" provided by the Canadian Certified Reference Materials Project. Our average concentrations are 16.8 ppb Os and 11.7 ppb Re, and

our measured $^{187}\text{Os}/^{188}\text{Os} = 0.14559 \pm 0.00073$ (external reproducibility at the 2σ level, $n=7$). Our Os isotopic result compares well with the limited number of published Re-Os isotopic analyses available for WPR-1: $^{187}\text{Os}/^{188}\text{Os} = 0.14543 \pm 0.00018$ ($n=3$; Cohen, 1996) and $^{187}\text{Os}/^{188}\text{Os} = 0.14549 \pm 0.00018$ ($n=6$; G. Pearson data from DTM, quoted in Cohen, 1996).

In Table 3, we have provided an assessment of uncertainties in $^{187}\text{Re}/^{188}\text{Os}$ and $^{187}\text{Os}/^{188}\text{Os}$ at 2 standard errors of the mean (SEM), including error magnification and uncertainties in spike calibration.

3.3.3 - Results and Discussion

Table 1 and 2 present the U-Pb SHRIMP II data for zircons from NQ1549. The concordia diagram for these data is shown in Figure 4. One highly discordant determination, spot 63, has a minimum $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2794 ± 32 Ma (offscale Figure 4), here interpreted as an inherited grain preserved inside Niquelândia's magmatic chamber. The remainder of zircon domains display a large range of U-Pb ages, from 778 ± 16 Ma (mean $^{206}\text{Pb}/^{238}\text{U}$ age of 13 analyses) to 1981 ± 52 Ma ($^{207}\text{Pb}/^{206}\text{Pb}$ age of near-concordant spot 66), with intermediate groupings of data approximately in the age ranges 1000-1400 and 1600-1880 Ma.

We believe that this complex age distribution reflects the polycyclic metamorphic/deformational history of the environment in which NQC has settled and evolved. The mean value for the lower concordia intercept is in close agreement with values of 770-795 Ma, 770-820 Ma and 770 ± 43 Ma obtained respectively for Niquelândia (U-Pb, Ferreira Filho et al., 1994), Barro Alto (U-Pb, Suita et al., 1994) and Cana Brava (Sm-Nd, Correia et al., 1997a). The other age clusters displayed by the NQ1549 zircons, probably the result of more than one episode of Pb loss, also correspond well to the regional geochronology.

The 1000-1400 Ma age cluster fits well with the Rb-Sr isochron age of $1,157 \pm 150$ Ma for samples from the western country rocks of CBC (Girardi et al., 1978), with Rb-Sr ages of $1,266 \pm 17$ Ma and $1,330 \pm 66$ Ma for BAC rocks (Fuck et al., 1989), and with the U-Pb zircon ages of 1.29-1.35 Ga (upper intercept) for a pegmatitic gabbro from Barro Alto (Suita et al., 1994), all interpreted as related to compressive tectonism during the Uruaçuano Cycle.

The 1600-1800 time interval also broadly covers the range of ages showed by the upper concordia intercepts of 1560-1600 Ma and 1.72-1.73 Ga found respectively for NQC and BAC (Ferreira Filho et al., Suita et al., op. cit.) and interpreted together with other isotopic data by Nilson et al. (1994) and Brito Neves et al. (1995) as a period of magmatic activity related to continental rifting in Central Brazil. Alternatively, the 1981 ± 52 Ma age displayed by the highest, concordant spot 66 is within error of the 1925 ± 110 Ma Ar/Ar (Matsui et al., 1976) and the 1970 ± 69 Ma Sm-Nd isochron ages for CBC (Fugii, 1989) interpreted by Fugii as corresponding to the igneous crystallization of the CBC body.

In order to provide better constraints on the magmatic source for the NQC, and to assess the model proposed by Girardi et al. (1986) for the petrologic evolution of the NQC, we carried out a pilot Re-Os isotopic study of the NQC. The Re-Os isotopic data, which are presented in Table 3 and in Figure 5, reinforce the U-Pb results. Figure 5 displays two Re-Os isochrons. The NQ1560 gabbro, which has a well preserved igneous texture (see Figure 8), has a very high $^{187}\text{Re}/^{188}\text{Os}$ ratio. This gabbro and two chromitites with very low $^{187}\text{Re}/^{188}\text{Os}$ yield a Model 1 isochron with an age of 2073 ± 70 Ma but with a large MSWD (88) indicating that there is excess geological scatter about the isochron. However, the Model 3 isochron yields essentially the same age. Both isochrons yield near-chondritic initial γ_{Os} values of +4 to +6. This Re-Os isochron age agrees well with the SHRIMP data for Niquelândia and with the Sm-Nd age for Cana Brava, confirming a 2 Ga emplacement age for these intrusions. The near-chondritic initial γ_{Os} value is in agreement with the behavior of other trace elements in Niquelândia which, according to Girardi et al. (1986), exhibit trace element ratios with near-chondritic (mantle-like) values. These data together indicate that, during emplacement and crystallization, the Niquelândia parental magma suffered limited amounts of crustal contamination.

A second and much younger isochron with an age of ca. 800 Ma is defined by samples with textural evidence of later metamorphic/tectonic reequilibration. This age is consistent with the youngest zircon ages and illustrates that the Re-Os system was deeply affected and has locally suffered complete rehomogenization during Brasiliano times. Data from Correia et al. (1997b) indicate that the Sm-Nd system for Niquelândia has been affected in a similar way. They obtained a 10 sample whole rock isochron (MSWD = 68) of 776 ± 25 Ma ($R_0 = 0.51157 \pm 0.00004$) with an initial ϵ_{Nd} value of -13. These data together support the regional importance of the last metamorphic episode during Neoproterozoic time (Brasiliano cycle).

Together, these data provide evidence that the NQC, BAC and CBC were generated by the same event and underwent the same geologic evolution. Moreover, it is well known that Niquelândia, the best exposed and preserved of these intrusions, presents many petrogenetic similarities with other layered basic intrusions, such as the Bushveld and Stillwater Complexes. The Bushveld Complex in particular occurs in a similar tectonic context and displays a similar age of ca. 2.0 Ga (2095 ± 24 Ma, Hamilton, 1977).

Based on global geological evidence many authors (Condie, 1989; Hoffman, 1989; Goodwin, 1991; Brito Neves et al., 1996) agree that the Rhyacian (2.3-2.05 Ga) and Orosirian (2.05-1.8 Ga) periods were mainly characterized by the aggregation of continental crustal blocks and were followed by extensive rifting during the next period (Statherian, 1.8-1.6 Ga). However, since the production of voluminous basaltic magma such as is required to form huge magmatic complexes like Bushveld and Niquelândia suggests an extensional regime related to crustal rifting, this implies that, contrary to the above, major extension occurred at about the time of the Orosirian/Rhyacian transition.

Figure 4 - NQ1549 zircons U-Pb concordia diagram

Figure 5 - Re-Os diagram

Figure 6 - Photomicrograph of NQ1564. BZG Metagabbronorite displaying metamorphic texture and remobilized sulfides. Transmitted light, Polarizer //, Ocular 10X. Picture sides 1.00X0.66mm.

Figure 7 - Photomicrograph of NQ1563. BPZ sheared olivine websterite exhibiting metamorphic texture and remobilized sulfides. Reflected light, Polarizer //, Ocular 10X. Picture sides 1.00X0.66mm.

Figure 8 - Photomicrograph of NQ1560. LUZ gabbro showing igneous texture and well-preserved sulfides. Transmitted light, Polarizer //, Ocular 4X. Picture sides 2.50X1.66mm.

Figure 9 - Photomicrograph of NQ1549. Clinopyroxene norite, from the top of the LZG hydrous layer. Note the evolved mineralogy with biotite and zircon. Transmitted light, Polarizer //, Ocular 10X. Picture sides 1.00X0.66mm.

Table 1 - NQ1549 U-Pb zircon's results

Spot	Age $^{206}\text{Pb}/^{238}\text{U} \pm 2\sigma$	Core/Border	Shape/Size	Obs.
1	1117 $\pm$ 23	Core	Prism./ $\approx$ 200 μm	Complex zonation
2	761 $\pm$ 16	Core	Prism./ $\approx$ 200 μm	Simple zonation
3	780 $\pm$ 16	Core	Prism./ $\approx$ 100 μm	Simple zonation
4	756 $\pm$ 16	Core	Prism./ $\approx$ 100 μm	Simple zonation
5	1393 $\pm$ 28	Core	Prism./ $\approx$ 200 μm	Complex zonation
6	798 $\pm$ 17	Core	Rounded./ $\approx$ 100 μm	Simple zonation
7	792 $\pm$ 17	Border of 6	Rounded./ $\approx$ 100 μm	Simple zonation
8	1604 $\pm$ 32	Core	Prism./ $\approx$ 300 μm	Complex zonation
9	859 $\pm$ 18	Core	Prism./ $\approx$ 150 μm	Simple zonation
10	1780 $\pm$ 35	Core	Prism./ $\approx$ 200 μm	Complex zonation
11	807 $\pm$ 17	Core	Prism./ $\approx$ 200 μm	Simple zonation
16	1050 $\pm$ 21	Core	Prism./ $\approx$ 200 μm	Complex zonation
17	785 $\pm$ 16	Core	Prism./ $\approx$ 200 μm	Simple zonation
18	779 $\pm$ 16	Core	Prism./ $\approx$ 200 μm	Simple zonation
20	1014 $\pm$ 21	Core	Prism./ $\approx$ 200 μm	Complex zonation
57	1641 $\pm$ 42	Core	Prism./ $\approx$ 200 μm	Complex zonation
58	778 $\pm$ 21	Core	Prism./ $\approx$ 200 μm	Simple zonation
59	1548 $\pm$ 39	Core	Prism./ $\approx$ 200 μm	Complex zonation
60	759 $\pm$ 20	Core	Prism./ $\approx$ 200 μm	Simple zonation
61	778 $\pm$ 21	Core	Prism./ $\approx$ 200 μm	Simple zonation
62	1037 $\pm$ 27	Core	Prism./ $\approx$ 200 μm	Complex zonation
63	2457 $\pm$ 59	Core	Prism./ $\approx$ 200 μm	Complex zonation
64	1589 $\pm$ 40	Core	Prism./ $\approx$ 200 μm	Complex zonation
65	766 $\pm$ 20	Border of 63	Prism./ $\approx$ 200 μm	Complex zonation
66	1991 $\pm$ 49	Core	Prism./ $\approx$ 200 μm	Complex zonation
67	1263 $\pm$ 32	Core	Prism./ $\approx$ 200 μm	Complex zonation
68	1256 $\pm$ 32	Core	Prism./ $\approx$ 200 μm	Complex zonation
69	1211 $\pm$ 31	Core	Prism./ $\approx$ 200 μm	Complex zonation
70	777 $\pm$ 21	Core	Prism./ $\approx$ 200 μm	Complex zonation
71	855 $\pm$ 23	Core	Prism./ $\approx$ 100 μm	Simple zonation

Table 2. NQ1549 SHRIMP(II) zircons's data.

Grain No.	U ppm	Th ppm	Th/U	Pb ppm	%com ^{206}Pb	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{207}\text{Pb}/^{206}\text{Pb}$ Age
63	89	58	0.65	49	0.51	0.1961 ± 20	0.464 ± 13	12.54 ± 40	2794 ± 16
66	98	62	0.63	40	0.68	0.1217 ± 18	0.362 ± 10	6.07 ± 20	1981 ± 26
10	399	531	1.33	165	0.10	0.1129 ± 07	0.3181 ± 71	4.95 ± 12	1847 ± 12
57	81	72	0.90	29	1.38	0.1116 ± 29	0.2898 ± 83	4.46 ± 18	1826 ± 47
8	176	152	0.87	59	0.46	0.1058 ± 15	0.2826 ± 64	4.12 ± 12	1728 ± 26
64	128	126	0.99	43	0.45	0.1040 ± 17	0.2795 ± 79	4.01 ± 14	1697 ± 29
59	215	143	0.67	67	0.56	0.1024 ± 12	0.2714 ± 77	3.83 ± 12	1668 ± 22
67	333	64	0.19	72	0.46	0.0952 ± 11	0.2165 ± 61	2.840 ± 90	1531 ± 21
5	133	72	0.54	35	0.27	0.0930 ± 20	0.2411 ± 54	3.09 ± 10	1488 ± 40
69	302	262	0.87	75	0.81	0.0915 ± 13	0.2067 ± 58	2.609 ± 86	1458 ± 26
68	199	67	0.34	44	0.35	0.0864 ± 14	0.2151 ± 61	2.563 ± 88	1347 ± 32
62	103	62	0.61	20	1.04	0.0811 ± 28	0.1746 ± 50	1.953 ± 93	1225 ± 68
1	269	123	0.46	54	0.35	0.0805 ± 14	0.1893 ± 42	2.100 ± 63	1208 ± 34
16	638	293	0.46	120	0.34	0.0778 ± 09	0.1768 ± 39	1.897 ± 50	1142 ± 24
20	128	48	0.38	23	0.44	0.0768 ± 23	0.1704 ± 38	1.803 ± 71	1116 ± 59
7	70	25	0.36	10	0.84	0.0694 ± 49	0.1308 ± 30	1.252 ± 97	911 ± 146
9	832	238	0.29	119	0.17	0.0689 ± 06	0.1426 ± 32	1.354 ± 34	894 ± 19
71	206	78	0.38	30	0.55	0.0688 ± 18	0.1418 ± 40	1.345 ± 56	893 ± 56
18	383	225	0.59	53	0.10	0.0669 ± 11	0.1284 ± 28	1.184 ± 34	833 ± 33
70	394	174	0.44	53	0.53	0.0662 ± 13	0.1281 ± 36	1.169 ± 42	812 ± 40
60	306	37	0.12	37	0.44	0.0656 ± 14	0.1250 ± 35	1.131 ± 42	795 ± 45
17	615	286	0.47	83	0.21	0.0655 ± 10	0.1295 ± 29	1.170 ± 33	792 ± 31
58	465	137	0.30	60	0.39	0.0651 ± 10	0.1283 ± 36	1.152 ± 38	779 ± 31
6	229	90	0.39	31	0.35	0.0651 ± 16	0.1317 ± 29	1.182 ± 41	778 ± 51
4	292	74	0.25	37	0.87	0.0648 ± 21	0.1243 ± 28	1.111 ± 46	768 ± 67
3	230	58	0.25	30	0.78	0.0642 ± 21	0.1286 ± 29	1.138 ± 47	749 ± 68
11	491	188	0.38	68	0.44	0.0639 ± 12	0.1333 ± 30	1.175 ± 36	740 ± 39
65	267	98	0.37	35	0.68	0.0638 ± 16	0.1262 ± 35	1.110 ± 45	735 ± 54
2	240	123	0.51	32	0.86	0.0634 ± 21	0.1253 ± 28	1.094 ± 46	721 ± 70
61	94	27	0.28	13	1.84	0.0622 ± 43	0.1282 ± 37	1.099 ± 85	680 ± 147

Errors are quoted at the 1 σ level.

Table 3. Sample location coordinates and Re-Os isotopic data for the Niquelândia Complex, Brazil.

Sample Number	Location Coordinates	Stratigraphic Location	Lithology	Re (ppb)	Os (ppb)	Common Os (ppb) ^a	¹⁸⁷ Re/ ¹⁸⁸ Os ^b	¹⁸⁷ Os/ ¹⁸⁸ Os ^c
NQ 1552	14°22'03" W 48°31'38" S	Upper gabbro-anorthosite zone	anorthosite	0.0534	0.0147	0.0141	18.28 ± 0.55	0.23612 ± 0.00575
NQ 1549	14°21'48" W 48°29'55" S	Lower gabbro zone (hydrous top)	norite	0.0062	0.0270	0.0193	1.548 ± 0.046	1.1855 ± 0.0287
NQ 1557	14°22'02" W 48°25'34" S	Layered ultramafic zone	websterite	5.066	0.209	0.165	147.3 ± 4.4	2.0577 ± 0.0142
NQ 1561	14°20'30" W 48°24'29" S	Layered ultramafic zone	gabbro	0.339	0.0832	0.0543	30.04 ± 0.90	3.4853 ± 0.0639
NQ 1560	14°20'43" W 48°24'31" S	Layered ultramafic zone	norite	0.738	0.0193	0.0061	579 ± 17	20.093 ± 0.0927
NQ 1000	14°20'42" W 48°23'17" S	Layered ultramafic zone	chromitite	0.786	63.1	62.7	0.0602 ± 0.0018	0.12777 ± 0.00091
NQ 210	14°20'40" W 48°23'08" S	Layered ultramafic zone	chromitite	0.452	154	154	0.0141 ± 0.0004	0.12598 ± 0.00046
NQ 1563	14°17'18" W 48°22'59" S	Basal peridotite zone	olivine websterite	4.76	0.817	0.754	30.35 ± 0.91	0.54294 ± 0.00304
NQ 1564	14°17'11" W 48°22'49" S	Basal gabbro zone	gabbro-norite	3.06	0.354	0.324	45.24 ± 1.36	0.70628 ± 0.00227

^aOs concentration at time of intrusion, using an age = 2000 Ma. ^bUncertainty ≤ 4% at 2 standard error of the mean (SEM), including error magnification and spike calibration. ^cUncertainties for Os isotopic composition at 2SEM.

3.4 – Concluding Remarks

New U–Pb and Re–Os isotopic data set the time for igneous intrusion and crystallization of Niquelândia at about 2.0 Ga. These determinations together with other geochronological information for Niquelândia and the associated complexes of Barro Alto and Cana Brava indicate that they all represent singular manifestations of the same event and suffered a similar and complex evolution. Evidence of compressive tectonism are found for the periods ca. 780 Ma and 1000–1400 Ma, while the time of emplacement and the 1600–1880 Ma time interval probably represent times of tensional relaxing due to extensional rifting in the area. Petrogenetic characteristics and initial γ_{Os} values indicate chondritic affinities for the Niquelândia magma and suggest that no significant crustal contamination occurred during emplacement. Geochronological, petrogenetic and tectonic characteristics indicate that Niquelândia and Bushveld could represent different manifestations correlated in time and in terms of global tectonic regime.

Acknowledgments - To Cia. Niquel Tocantins, particularly Drs. J.A. Branquinho, Z. Rosado and R. Landigraf, for the permission to carry out the field works and for the facilities offered during the field seasons, to FAPESP (Thematic Proj. 95/4652-2 and 97/00640-5) and to CNPq for financial support. Financial support for Re–Os isotopic studies by the *Ore Genesis Research Group* at Monash University was derived from the Monash University Research Fund; the Australian Geodynamics Cooperative Research Centre; an Australian Research Council (ARC) Research Infrastructure (Equipment & Facilities) grant to D. Lambert and the VIEPS consortium; an ARC Research Infrastructure (Special Allocations) grant to D. Lambert and I. Nicholls; and ARC Large Grant A39131595 to D. Lambert, I. Nicholls and R. Keays.

CAPÍTULO 4

Resultados analíticos U-Pb em amostras dos complexos de Barro Alto e Cana Brava e nas seqüências metavulcano-sedimentares de Juscelândia e Indaianópolis.

4.1 - Introdução

Com objetivo de melhor compreender o padrão isotópico do sistema U-Pb nos grandes complexos máficos-ultramáficos de Goiás, bem como de procurar estabelecer de forma mais precisa as relações desses complexos com as seqüências metavulcano-sedimentares situadas em seus limites Oeste (figura 2.1), foram realizadas análises complementares via SHRIMP (laboratório e condições analíticas conforme descrito no cap. anterior), em amostras dessas unidades. Apenas da seqüência de Palmeirópolis ainda não foi possível obter esse tipo de resultado. Em todas as amostras os pontos escolhidos para análise foram feitos com base em imagens de cátodo-luminescência (CL) e/ou de elétrons retroespalhados (BS). Infelizmente porém, nem de todas as amostras foi possível transformar as imagens obtidas em arquivos digitalizados, como os que serão apresentados a seguir. Os dados completos inéditos dessas análises encontram-se respectivamente nas tabelas 4.1, 4.2 e 4.3.

4.2 – Resultados U-Pb no Complexo de Barro Alto e Seqüência de Juscelândia.

Os dados aqui tratados encontram-se compilados na Tabela 4.1.

A amostra BA1540 corresponde a um ortognaisse das rochas encaixantes da Borda Leste do complexo, de composição tonalítica, que aflora nas imediações da Cidade de Goianésia. Imagens CL dos zircões dessa amostra revelam na maioria cristais prismáticos, idiomórficos, com zoneamento simples (a semelhança da imagem da Figura 4.15), onde bordas de sobrecrecimento são raras. Os diagramas da Figura 4.1(A e B), revelam idades que se distribuem entre o intercepto superior sobre a concórdia ao redor de 2,1 Ga, até idades ao redor de 700 Ma nas vizinhanças do intercepto inferior. O agrupamento superior data em 2125 ± 14 Ma (idade $^{207}\text{Pb}/^{206}\text{Pb}$, média ponderada de 13 análises) o evento de cristalização ígnea dos zircões desse ortognaisse.

A amostra BA 1546 provém de um metagranito de granulação média à grossa, intrusivo na porção central do complexo de Barro Alto a Noroeste de Goianésia. Esse metagranito apresenta claras evidências de metamorfismo de alto grau, que determina formação da associação biotita vermelha, mesopertita, cordierita e silimanita. Os zircões são abundantes e prismáticos. Imagens de CL revelam zonamento simples bem definido sendo que muitos grãos apresentam bordas sobrecrecidas (mais escuras nesse tipo de imagem: razões U/Th mais elevadas) sobre núcleos que sofreram reabsorção/dissolução após a cristalização ígnea, a semelhança do padrão revelado na Figura 4.5. Na Figura 4.2 nota-se que o principal agrupamento de idades distribui-se entre 1,2 e 1,3 Ga. Na verdade, esses resultados parecem corresponder a dois grupos (Figura 4.2B), um com idade ao redor de 1,2 Ga, enquanto o outro,

superior, apresenta idade $^{207}\text{Pb}/^{206}\text{Pb}$ de 1302 ± 32 Ma (média ponderada de 6 análises). Como a maioria dos resultados mais antigos correspondem aos núcleos dos grãos, a idade de 1,3 Ga é interpretada como a da cristalização ígnea do granito, e a mais recente, ao redor de 1,2 Ga, como provavelmente correspondente aos processos de reequilíbrio/recristalização mineral durante evento de metamorfismo de grau alto que gerou a paragênese metamórfica da rocha. O mesmo padrão também é sugerido pelas idades da amostra TC2 que será discutida a seguir. As demais análises, próximas da concórdia entre 800-1000 Ma, são de difícil explicação, podendo corresponder a eventos tectônicos ainda não bem definidos como será discutido no próximo capítulo.

A Amostra TC2 provém de um dos vários corpos de granulitos ácidos que se localizam encaixados nas unidades superiores do complexo de Barro Alto. Possui granulação fina à média, textura granoblástica, com assembléia metamórfica principal constituída pela associação: quartzo, cordierita, silimanita, plagioclásio, mesopertita e bitotita vermelha, além das demais fases acessórias (opacos, apatita, clinozoizita-epítoto e zircão). Essa assembléia mineral é a mesma do corpo granítico da amostra BA1546, porém a provável textura ígnea original não mais encontra-se preservada. Está localizada na estrada que liga Goianésia a Juscelândia, no limite superior do complexo de Barro Alto, a algumas centenas de metros do contato com os xistos e metabásicas da respectiva seqüência metavulcano-sedimentar. Essa amostra possui grande quantidade de zircões, muito límpidos e com aspecto cristalino bem definido. Na sua maioria apresentam hábitos prismáticos (Figura 4.3 e 4.4) mas, grãos arredondados também encontram-se presentes, como normalmente ocorre em zircões metamórficos. Tantos nos grãos prismáticos como nos demais, é comum a presença de núcleos preservados em meio a bordas recristalizadas que revelam maiores teores em U, em função do padrão mais escuro nas imagens de CL.

A distribuição de idades na Figura 4.5, é bastante complexa e interessante. São encontrados valores desde cerca de 800 Ma, até 2100 Ma, com agrupamentos localizados sobre a concórdia no intervalos entre 830-870, 1040-1080, 1180-1310 Ma. Para o agrupamento principal a melhor estimativa de idade corresponde a 1286 ± 13 Ma ($^{207}\text{Pb}/^{206}\text{Pb}$, média ponderada de 13 análises). Novamente (como no padrão da amostra BA1546) é possível que esse agrupamento corresponda a dois grupos, com o segundo relacionando-se a um evento por volta de 1200 Ma.

Tassinari et al. (1999) concluem que as idades apresentadas pelos zircões metamórficos dos granulitos ácidos do complexo de Anápolis-Itauçu (Marini et al., 1984; Lacerda Filho e Oliveira, 1995) de 640 ± 13 Ma, não correspondem a condições de pico do metamórfico regional (cerca de 780 Ma: Ferreira Filho et al., 1994; Correia et al., 1997), mas ao evento de exumação dessas rochas para níveis crustais superiores da crosta, nas fases tardias do evento compressivo regional do Neoproterozóico na área. Os dados apresentados para as amostras BA1546 e TC2, podem ter explicação semelhante e representem as primeiras assinaturas isotópicas U-Pb da ainda controversa (Fuck et al., 1989; Ferreira Filho et al., 1994; Suita et al., 1996; Correia et

al., 1997) orogênese do Mesoproterozóico (aglutinação de Rodinia?) nas unidades da porção central de Goiás.

As Figura 4.6, 4.7 e 4.8 referem-se às análises da amostra TC3, um granada biotita xisto (com rutilo) da seqüência de Juscelândia, coletado a algumas centenas de metros do afloramento da amostra TC2, portanto também próxima do contato com as rochas do complexo de Barro Alto. A amostra exhibe textura granolepdoblástica, com nítidas evidências de cisalhamento dútil (domínios com foliação mais intensa, onde os minerais apresentam contatos cerrilhados e granulação reduzida por cominuição dos grãos; além de ser possível observar por toda a lâmina, a presença de fraturamento generalizado nas granadas, cianitas e no quartzo) que denuncia a natureza tectônica do contato entre as unidades da seqüência e as unidades superiores de Barro Alto, no local. Os zircões mostram-se bem formados e com bordas recristalizadas sobre núcleos pré-existentes. Na Figura 4.6, a grande maioria dos pontos concentra-se sobre a concórdia ao redor de 800 Ma (Idade $^{207}\text{Pb}/^{206}\text{Pb}$ de 794 ± 14 Ma, média ponderada de 15 análises). Esse valor corresponde justamente aos atribuídos ao evento principal de metamorfismo compressivo do Neoproterozóico na região, conforme mencionado no parágrafo anterior, sendo interpretados, em função das características da amostra, como geradas por esse evento metamórfico ao invés de refletirem o momento da cristalização primária desses zircões.

Os pontos mais antigos da Figura 4.6, correspondem as análises da porção intermediária e central do grão da Figura 4.8 (resultados tc3.121 e tc3.124 da Tabela 4.1).

4.3 - Resultados U-Pb na Seqüência de Indaianópolis.

Na tabela 4.2 encontram-se os resultados analíticos relativos às amostras de Indaianópolis, coletadas nas proximidades do contato dessa unidade com os litotipos do topo de Niquelândia, a aproximadamente 2 km ao Norte da localidade de Indaianópolis. As análises foram feitas em amostras de hornblenda biotita(verde) gnaisses, de granulação fina a média, de origem provavelmente parametamórfica, dada suas relações transicionais com xistos e quartzitos. Ambas as amostras forneceram grandes quantidades de zircões prismáticos e bem formados porém muito escuros tanto à observação em luz natural como nas imagens de CL. Essa feição é comum em zircões com altos teores de urânio, compatíveis com os revelados pelas respectivas análises. As imagens de CL, da amostra NQ1577 ficaram prejudicadas uma vez que os altos teores de U determinam matizes escuras que não se distinguem adequadamente da resina dos suportes. As Figura 4.9 e 4.10, correspondem aos zircões das amostra NQ1575, que ostentam padrões reveladores de avançado estágio de destruição reticular por conta de processos de metamictização.

Na Figura 4.11(A e B), têm-se os resultados analíticos para essas amostra no diagrama concordia. A amostra NQ1577 apresenta um conjunto significativo de pontos sobre a concórdia ao redor de 1290 Ma, com idade $^{207}\text{Pb}/^{206}\text{Pb}$ de 1273 ± 16 Ma. Essa idade corresponde perfeitamente ao limite superior dos agrupamentos principais de idades Mesoproterozóicas das amostras BA1546 e TC2, conforme visto no item anterior.

Interpreta-se que definam, como nos casos anteriores o evento de cristalização ígnea desses zircões, ao contrário da procedência metamórfica conforme preliminarmente sugerido por Correia et al (1999).

Na Figura 4.11B, as análises da amostra NQ1575, distribuem-se ao redor de 800 Ma, refletindo o evento principal do Neoproterozóico. Provavelmente, esse comportamento possa ser explicado em função das transformações reticulares sofridas por esses zircões em função da metamictização que, ao facilitar o acesso de fluidos ao interior dos grãos, tenha zerado o sistema U-Pb nessa amostra durante o Neoproterozóico.

4.4 - Resultados U-Pb no Complexo de Cana Brava.

As análises de Cana Brava (Tabela 4.3) encontram-se nas Figura 4.12(A à D). Correspondem a gabros/grabronoritos das unidades superiores PICB4 (CB1075) e PICB5 (demais amostras) do complexo, conforme subdividido por Correia et al. (1997).

Nas Figura 4.13 e 4.14 encontram-se representados zircões exibindo padrões onde é possível reconhecer núcleos sobrecrecidos por bordas posteriores. Esse comportamento é o mais freqüente nas amostras de Cana Brava embora, estejam também presentes indivíduos que ostentam padrão com zonamento simples e contínuo (Figura 4.15). Em ambos conjuntos, medidas nos núcleos dos grãos distribuem-se sobre a concórdia no intervalo entre 670 e 820 Ma e correspondem a idades $^{207}\text{Pb}/^{206}\text{Pb}$ de 794 ± 52 Ma ($n = 12$), 782 ± 69 Ma ($n = 12$), e 759 ± 29 Ma ($n = 10$), respectivamente para as amostras CB1100, CB1382 e CB1030. Foram registradas apenas 3 análises (Figura 4.12 B e C) com idades fora da concórdia, mais antigas que o agrupamento principal compatível com o Neoproterozóico.

Novamente fica evidente a importância desse evento do Neoproterozóico sobre a sistemática U-Pb das rochas de Cana Brava. A explicação para a ausência de idades U-Pb mais antigas, como em Barro Alto e Niquelândia, permanece em aberto, uma vez que estudos Rb-Sr (Correia et al., 1997) e Sm-Nd (Fugui et al., 1989), registram os eventos do Meso e Paleoproterozóico na origem e evolução desses litotipos.

Tabela 4.1 – Resultados U-Pb (SHRIMP II) para amostras do complexo de Barro Alto (BA1540, BA1546 e TC2) e sequência metavulcano-sedimentar de Juscelândia (TC3).

Amostra	U ppm	Th ppm	Th/U	Pb total	206Pb %	207Pb/ 206Pb	Erro (1 Sig.)	206Pb/ 238U	Erro (1 Sig.)	207Pb/ 235U	Erro (1 Sig.)	Idade (Ma) 207/206	Erro (1 Sig.)
ba1540.31	189	156	0.8	97	0.19	0.1628	0.0012	0.4268	0.0223	9.58	0.51	2485	12
ba1540.32	388	79	0.2	138	0.13	0.1302	0.0008	0.3487	0.0182	6.26	0.33	2100	10
ba1540.33	419	144	0.3	135	1.39	0.1373	0.0015	0.2801	0.0146	5.30	0.29	2193	18
ba1540.34	261	31	0.1	75	0.88	0.1220	0.0015	0.2780	0.0145	4.68	0.26	1986	22
ba1540.35	642	118	0.2	123	0.10	0.1071	0.0007	0.1917	0.0100	2.83	0.15	1750	12
ba1540.36	172	52	0.3	75	0.78	0.1498	0.0016	0.4029	0.0211	8.32	0.46	2343	19
ba1540.37	242	45	0.2	93	0.35	0.1299	0.0011	0.3741	0.0195	6.70	0.36	2097	15
ba1540.38	401	88	0.2	153	0.13	0.1325	0.0007	0.3755	0.0196	6.86	0.36	2131	9
ba1540.39	184	0	0.0	22	1.99	0.0929	0.0045	0.1198	0.0063	1.53	0.12	1486	92
ba1540.40	176	44	0.3	70	0.23	0.1344	0.0013	0.3774	0.0197	6.99	0.38	2156	16
ba1540.41	271	53	0.2	100	0.08	0.1320	0.0010	0.3602	0.0188	6.55	0.35	2124	14
ba1540.42	132	18	0.1	46	0.45	0.1321	0.0021	0.3399	0.0178	6.19	0.35	2125	28
ba1540.43	186	116	0.6	77	0.45	0.1344	0.0013	0.3612	0.0189	6.70	0.36	2157	17
ba1540.44	231	33	0.1	74	1.59	0.1227	0.0019	0.3013	0.0158	5.10	0.29	1996	28
ba1540.45	55	6	0.1	21	0.96	0.1309	0.0034	0.3595	0.0190	6.49	0.40	2110	46
ba1540.46	163	22	0.1	60	0.14	0.1343	0.0013	0.3585	0.0187	6.64	0.36	2155	17
ba1540.47	274	50	0.2	104	0.14	0.1322	0.0009	0.3702	0.0193	6.75	0.36	2128	11
ba1540.48	235	4	0.0	84	0.15	0.1341	0.0011	0.3649	0.0191	6.75	0.36	2153	14
ba1540.49	942	49	0.1	159	4.69	0.0946	0.0019	0.1476	0.0077	1.92	0.11	1519	38
ba1540.50	1308	33	0.0	157	1.77	0.0753	0.0012	0.1195	0.0062	1.240	0.070	1076	33
ba1540.148	91	68	0.7	51	0.88	0.1600	0.0017	0.4603	0.0064	10.15	0.19	2456	18
ba1540.149	222	33	0.2	85	1.01	0.1292	0.0011	0.3646	0.0046	6.50	0.11	2087	16
ba1540.150	340	47	0.1	101	1.79	0.1213	0.0014	0.2803	0.0035	4.690	0.083	1976	20
ba1540.151	109	15	0.1	40	3.15	0.1304	0.0027	0.3244	0.0044	5.83	0.15	2103	36
ba1546.51	433	1133	2.6	208	0.47	0.0796	0.0011	0.2073	0.0108	2.27	0.13	1187	28
ba1546.52	355	43	0.1	48	0.34	0.0649	0.0014	0.1427	0.0074	1.277	0.075	771	46
ba1546.53	109	54	0.5	25	0.20	0.0878	0.0022	0.2141	0.0112	2.59	0.16	1379	48
ba1546.54	323	93	0.3	37	0.27	0.0847	0.0016	0.1139	0.0059	1.016	0.062	765	53
ba1546.55	317	182	0.6	70	0.51	0.0840	0.0013	0.2023	0.0106	2.34	0.13	1292	30
ba1546.56	355	324	0.9	95	0.49	0.0801	0.0011	0.2090	0.0109	2.31	0.13	1199	27
ba1546.135	380	217	0.6	81	0.68	0.0801	0.0011	0.1928	0.0024	2.130	0.043	1200	28
ba1546.136	194	129	0.7	49	0.97	0.0830	0.0018	0.2228	0.0030	2.548	0.069	1268	43
ba1546.137	48	38	0.8	19	1.64	0.1082	0.0035	0.3303	0.0054	4.93	0.19	1770	59
ba1546.138	379	107	0.3	54	1.23	0.0636	0.0015	0.1405	0.0018	1.232	0.035	729	50
ba1546.139	322	104	0.3	67	0.53	0.0801	0.0010	0.2001	0.0025	2.210	0.041	1199	24
ba1546.140	482	109	0.2	79	1.36	0.0738	0.0014	0.1577	0.0019	1.805	0.038	1036	38
ba1546.141	238	118	0.5	59	0.75	0.0846	0.0013	0.2256	0.0029	2.630	0.055	1306	30
ba1546.142	126	77	0.6	33	1.79	0.0885	0.0028	0.2195	0.0031	2.679	0.096	1394	60
ba1546.143	130	82	0.6	35	2.38	0.0856	0.0026	0.2288	0.0031	2.699	0.093	1328	58
ba1546.144	562	145	0.3	86	1.32	0.0711	0.0012	0.1473	0.0018	1.445	0.031	961	34
ba1546.145	315	192	0.6	79	0.40	0.0843	0.0009	0.2262	0.0028	2.630	0.047	1300	22
ba1546.146	143	63	0.4	31	0.92	0.0825	0.0019	0.2015	0.0027	2.292	0.065	1257	46
ba1546.147	285	135	0.5	72	0.48	0.0842	0.0010	0.2339	0.0029	2.714	0.049	1296	23
tc2.82	685	128	0.2	114	0.13	0.0738	0.0005	0.1757	0.0024	1.787	0.028	1035	13
tc2.83	714	790	1.1	192	0.06	0.0836	0.0004	0.2212	0.0031	2.550	0.039	1284	10
tc2.84	431	78	0.2	58	0.46	0.0679	0.0009	0.1367	0.0019	1.281	0.026	867	27
tc2.85	104	54	0.5	25	3.08	0.0959	0.0039	0.1988	0.0032	2.629	0.119	1547	76
tc2.86	96	38	0.4	21	0.78	0.0839	0.0021	0.2073	0.0033	2.399	0.075	1291	49
tc2.87	584	88	0.2	82	0.23	0.0678	0.0007	0.1457	0.0020	1.363	0.024	863	20
tc2.88	64	23	0.4	12	3.10	0.0755	0.0049	0.1656	0.0029	1.725	0.118	1083	129
tc2.89	153	101	0.7	35	0.58	0.0800	0.0015	0.2018	0.0030	2.227	0.057	1197	38
tc2.90	209	73	0.4	47	0.24	0.0835	0.0009	0.2176	0.0032	2.505	0.049	1281	22
tc2.91	229	87	0.4	54	0.23	0.0857	0.0010	0.2253	0.0033	2.660	0.052	1330	22
tc2.92	821	767	0.9	206	0.13	0.0832	0.0004	0.2132	0.0029	2.447	0.037	1275	10
tc2.93	485	39	0.1	64	0.33	0.0863	0.0008	0.1378	0.0019	1.260	0.025	816	27
tc2.94	416	273	0.7	96	0.26	0.0839	0.0007	0.2078	0.0029	2.405	0.041	1291	16
tc2.95	314	224	0.7	78	0.48	0.0823	0.0009	0.2206	0.0031	2.502	0.048	1252	22
tc2.96	165	136	0.8	76	0.46	0.1229	0.0011	0.3872	0.0057	6.56	0.12	1998	15
tc2.97	183	58	0.3	42	0.51	0.0840	0.0012	0.2233	0.0033	2.587	0.057	1293	29
tc2.98	366	168	0.5	88	0.37	0.0848	0.0008	0.2240	0.0032	2.619	0.048	1311	19
tc2.99	114	53	0.5	34	1.91	0.0948	0.0024	0.2610	0.0040	3.41	0.11	1523	48
tc2.100	191	129	0.7	43	0.44	0.0821	0.0012	0.1996	0.0029	2.259	0.051	1248	30
tc2.101	152	69	0.5	29	0.74	0.0762	0.0018	0.1752	0.0027	1.841	0.054	1101	46
tc2.102	305	84	0.3	45	0.76	0.0673	0.0014	0.1438	0.0021	1.335	0.035	848	42
tc2.103	109	64	0.8	24	0.85	0.0826	0.0020	0.2009	0.0032	2.287	0.069	1260	46
tc2.104	189	110	0.6	47	0.40	0.0837	0.0012	0.2252	0.0033	2.599	0.056	1286	27
tc2.105	150	75	0.5	36	0.66	0.0866	0.0017	0.2181	0.0033	2.604	0.068	1351	38
tc2.106	295	104	0.4	63	0.44	0.0809	0.0011	0.2048	0.0030	2.286	0.048	1220	26
tc2.107	50	19	0.4	10	2.56	0.0717	0.0051	0.1762	0.0033	1.74	0.13	978	145
tc2.108	250	132	0.5	108	0.21	0.1334	0.0008	0.3865	0.0055	7.11	0.12	2143	10
tc2.109	640	195	0.3	118	0.21	0.0761	0.0006	0.1794	0.0025	1.882	0.031	1088	15
tc2.110	389	3506	9.0	515	0.41	0.0895	0.0007	0.3286	0.0047	4.057	0.070	1416	16
tc2.111	338	44	0.1	56	0.90	0.0730	0.0013	0.1669	0.0024	1.680	0.040	1014	35
tc2.112	249	61	0.3	72	0.37	0.1124	0.0009	0.2795	0.0041	4.333	0.076	1839	15
tc2.113	938	391	0.4	175	0.13	0.0777	0.0005	0.1785	0.0025	1.912	0.030	1139	12
tc2.114	46	25	0.6	12	2.62	0.0785	0.0054	0.2258	0.0044	2.45	0.18	1160	137
tc3.27	2475	1267	0.5	336	0.04	0.0657	0.0003	0.1291	0.0033	1.170	0.031	797	10
tc3.28	125	75	0.6	17	1.44	0.0628	0.0032	0.1239	0.0033	1.072	0.064	700	107
tc3.29	489	30	0.1	57	0.32	0.0854	0.0011	0.1239	0.0032	1.118	0.036	788	34
tc3.30	203	204	1.0	31	0.74	0.0658	0.0022	0.1285	0.0033	1.147	0.051	800	69
tc3.32	201	113	0.6	28	1.00	0.0630	0.0020	0.1291	0.0034	1.121	0.049	708	69
tc3.33	2408	114	0.1	302	0.24	0.0655	0.0004	0.1342	0.0034	1.212	0.032	791	12
tc3.121	421	155	0.4	67	0.54	0.0800	0.0009	0.1529	0.0025	1.687	0.035	1188	23
tc3.122	170	68	0.4	23	0.60	0.0646	0.0016	0.1315	0.0022	1.171	0.037	761	51
tc3.123	152	57	0.4	21	1.56	0.0671	0.0023	0.1293	0.0022	1.196	0.048	840	71
tc3.124	438	234	0.5	156	0.20	0.1232	0.0006	0.3205	0.0051	5.444	0.095	2003	9
tc3.125	485	16	0.0	60	0.44	0.0653	0.0008	0.1318	0.0021	1.187	0.025	784	25
tc3.126	217	133	0.6	33	1.64	0.0669	0.0021	0.1320	0.0022	1.218	0.045	836	64
tc3.127	202	182	0.9	31	0.78	0.0691	0.0015	0.1266	0.0021	1.205	0.036	800	46
tc3.12													

Tabela 4.2 – Resultados U-Pb (SHRIMP II) para amostras da seqüência metavulcano-sedimentar de Indaianópolis (borda oeste de Niquelândia).

Amostra	U ppm	Th ppm	Th/U	Pb total	206Pb %	207Pb/ 206Pb	Erro (1 Sig.)	206Pb/ 238U	Erro (1 Sig.)	207Pb/ 235U	Erro (1 Sig.)	Idade (Ma) 207/206	Erro (1 Sig.)
nq1575.115	255	759	3.0	52	0.86	0.0663	0.0015	0.1271	0.0021	1.161	0.034	815	46
nq1575.116	398	195	0.5	55	0.97	0.0674	0.0012	0.1318	0.0021	1.225	0.031	849	36
nq1575.117	134	35	0.3	18	1.31	0.0658	0.0025	0.1327	0.0023	1.204	0.052	800	78
nq1575.118	141	168	1.2	22	1.01	0.0676	0.0022	0.1236	0.0021	1.152	0.045	856	68
nq1575.119	83	11	0.1	11	1.18	0.0683	0.0036	0.1274	0.0023	1.199	0.070	877	109
nq1575.120	162	62	0.4	19	0.68	0.0699	0.0022	0.1096	0.0019	1.056	0.040	925	66
nq1577.13	1999	1542	0.8	504	0.03	0.0837	0.0003	0.2229	0.0056	2.571	0.067	1285	6
nq1577.14	1587	873	0.6	333	0.46	0.0804	0.0005	0.1839	0.0047	2.039	0.055	1207	12
nq1577.15	1620	1411	0.9	421	0.03	0.0840	0.0003	0.2249	0.0057	2.606	0.068	1293	6
nq1577.16	1533	1057	0.7	378	0.04	0.0833	0.0003	0.2220	0.0056	2.549	0.066	1275	7
nq1577.17	2126	1747	0.8	544	0.02	0.0831	0.0003	0.2240	0.0057	2.566	0.066	1272	6
nq1577.18	1399	129	0.1	276	0.02	0.0817	0.0003	0.2063	0.0052	2.325	0.061	1239	8
nq1577.19	2057	1586	0.8	420	0.09	0.0779	0.0003	0.1878	0.0048	2.018	0.053	1145	7
nq1577.10	1626	807	0.5	306	0.08	0.0793	0.0003	0.1793	0.0045	1.960	0.051	1180	8
nq1577.20	2016	780	0.4	377	0.12	0.0816	0.0003	0.1797	0.0046	2.022	0.053	1236	8
nq1577.22	1514	987	0.7	314	0.03	0.0810	0.0003	0.1906	0.0048	2.130	0.056	1222	8
nq1577.23	2848	3084	1.1	804	0.02	0.0822	0.0002	0.2280	0.0058	2.582	0.066	1249	5
nq1577.24	2650	2380	0.9	670	0.01	0.0832	0.0002	0.2158	0.0055	2.477	0.064	1275	5
nq1577.25	157	117	0.7	19	0.00	0.0654	0.0011	0.1057	0.0028	0.953	0.032	787	36
nq1577.26	1893	358	0.2	341	0.05	0.0783	0.0003	0.1848	0.0047	1.994	0.052	1154	8

Tabela 4.3 – Resultados U-Pb (SHRIMP II) para amostras do Complexo de Cana Brava.

Amostra	U ppm	Th ppm	Th/U	Pb total	206Pb %	207Pb/ 206Pb	Erro (1 Sig.)	206Pb/ 238U	Erro (1 Sig.)	207Pb/ 235U	Erro (1 Sig.)	Idade (Ma) 207/206
cb1100.72	80	38	0.5	26	3.14	0.1161	0.0042	0.2723	0.0079	4.381	0.213	1898
cb1100.73	57	20	0.3	9	8.18	0.0657	0.0144	0.1152	0.0037	1.043	0.235	796
cb1100.74	264	140	0.5	34	0.53	0.0625	0.0017	0.1198	0.0034	1.032	0.043	692
cb1100.75	235	89	0.4	31	2.02	0.0664	0.0032	0.1211	0.0034	1.108	0.065	818
cb1100.76	132	30	0.2	24	9.31	0.0642	0.0076	0.1307	0.0038	1.157	0.148	747
cb1100.77	66	26	0.4	11	4.31	0.0788	0.0077	0.1401	0.0041	1.518	0.160	1163
cb1100.84	162	30	0.2	23	1.69	0.0723	0.0031	0.1349	0.0038	1.344	0.074	993
cb1100.85	80	31	0.4	12	3.15	0.0749	0.0068	0.1254	0.0037	1.295	0.129	1066
cb1100.86	193	93	0.5	27	2.57	0.0660	0.0033	0.1248	0.0035	1.136	0.069	807
cb1100.50	292	187	0.6	42	1.32	0.0652	0.0015	0.1304	0.0015	1.172	0.032	780
cb1100.51	59	23	0.4	10	5.83	0.0618	0.0073	0.1299	0.0021	1.108	0.135	689
cb1100.52	223	54	0.2	31	1.54	0.0662	0.0018	0.1331	0.0016	1.214	0.038	812
cb1100.53	165	47	0.3	22	0.81	0.0645	0.0018	0.1301	0.0016	1.157	0.038	758
cb1100.54	185	93	0.5	27	1.70	0.0631	0.0023	0.1303	0.0016	1.133	0.046	711
cb1100.55	117	63	0.5	18	1.57	0.0675	0.0028	0.1325	0.0017	1.233	0.056	853
cb1100.56	132	59	0.5	20	2.91	0.0620	0.0033	0.1319	0.0017	1.127	0.063	673
cb1100.57	54	22	0.4	9	6.16	0.0701	0.0074	0.1346	0.0023	1.301	0.142	932
cb1100.58	98	44	0.4	15	3.02	0.0697	0.0045	0.1337	0.0019	1.285	0.086	920
cb1100.59	100	44	0.4	15	2.69	0.0684	0.0039	0.1316	0.0018	1.204	0.075	817
cb1030.78	136	61	0.5	18	2.47	0.0559	0.0048	0.1219	0.0035	0.940	0.088	450
cb1030.79	493	108	0.2	63	0.98	0.0639	0.0015	0.1279	0.0036	1.126	0.043	737
cb1030.80	81	20	0.2	12	4.02	0.0725	0.0070	0.1269	0.0037	1.269	0.132	1000
cb1030.81	69	21	0.3	10	4.48	0.0602	0.0087	0.1293	0.0038	1.073	0.162	611
cb1030.82	1166	473	0.4	149	0.89	0.0634	0.0010	0.1215	0.0034	1.062	0.038	720
cb1030.83	237	150	0.6	34	1.03	0.0663	0.0021	0.1280	0.0038	1.153	0.052	817
cb1030.84	154	79	0.5	23	3.28	0.0604	0.0035	0.1280	0.0016	1.065	0.065	618
cb1030.35	446	35	0.1	56	1.46	0.0646	0.0013	0.1272	0.0014	1.132	0.027	760
cb1030.36	81	31	0.4	12	3.24	0.0721	0.0052	0.1319	0.0019	1.312	0.099	990
cb1030.37	260	157	0.8	38	1.28	0.0631	0.0017	0.1313	0.0015	1.142	0.035	711
cb1030.38	1769	328	0.2	228	0.37	0.0648	0.0004	0.1325	0.0014	1.184	0.015	768
cb1030.39	62	27	0.4	11	6.77	0.0688	0.0073	0.1310	0.0021	1.243	0.136	893
cb1075.132	225	64	0.3	30	1.33	0.0634	0.0021	0.1278	0.0017	1.118	0.042	723
cb1075.133	1473	441	0.3	182	0.16	0.0666	0.0005	0.1223	0.0014	1.124	0.016	826
cb1075.134	160	45	0.3	22	1.45	0.0647	0.0029	0.1292	0.0018	1.153	0.057	766
cb1382.40	82	79	1.0	15	5.73	0.0658	0.0059	0.1298	0.0019	1.18	0.11	800
cb1382.41	66	36	0.5	17	3.56	0.0867	0.0042	0.2125	0.0030	2.54	0.13	1354
cb1382.42	138	134	1.0	22	2.89	0.0659	0.0033	0.1268	0.0016	1.152	0.062	802
cb1382.43	121	96	0.8	18	1.52	0.0639	0.0026	0.1272	0.0016	1.121	0.049	739
cb1382.44	180	119	0.7	53	0.91	0.1087	0.0014	0.2606	0.0031	3.906	0.071	1777
cb1382.45	108	108	1.0	20	4.90	0.0610	0.0047	0.1340	0.0018	1.127	0.090	838
cb1382.46	225	240	1.1	38	2.01	0.0628	0.0021	0.1317	0.0016	1.140	0.043	701
cb1382.47	200	244	1.2	33	0.22	0.0672	0.0012	0.1317	0.0016	1.220	0.028	843
cb1382.48	135	128	1.0	23	2.94	0.0684	0.0034	0.1300	0.0017	1.191	0.064	820
cb1382.70	88	71	0.8	15	5.98	0.0557	0.0057	0.1251	0.0018	0.96	0.10	441
cb1382.71	120	101	0.8	21	4.42	0.0682	0.0043	0.1302	0.0017	1.188	0.080	811
cb1382.72	165	48	0.3	26	5.41	0.0588	0.0042	0.1305	0.0017	1.057	0.078	558

Figura 4.1 – (A) Diagrama concórdia com os resultados U-Pb (SHRIMP II) para as amostras BA 1540 (gnaisse tonalítico). Complexo de Barro Alto, embasamento leste. **(B)** Detalhe do embasamento principal sobre a concórdia.

Figura 4.2 – (A) Diagrama concórdia com os resultados de U-Pb (SHRIMP II) para a amostra BA 1546 (granito intrusivo no Complexo de Barro Alto). **(B)** Detalhe da distribuição principal sobre a concórdia.

Figura 4.3 – Imagem de CL dos zircões, na maioria prismáticos e bem formados da amostra TC2 (granulito ácido) do Complexo de Barro Alto. Observar as bordas e terminações sobrecrecidas sobre núcleos com padrão diferente de zoneamento.

Figura 4.4 – Imagem de CL de Zircão da amostra TC2 (granulito ácido) do Complexo de Barro Alto. Observar a complexidade dos diferentes domínios no interior do mineral.

Figura 4.5 – (A) Diagrama concórdia com os resultados U-Pb (SHRIMP II) para a amostra TC2 (granulito ácido) do Complexo de Barro Alto. **(B)** Detalhe dos agrupamentos principais sobre a concórdia. Notar que em todos os conjuntos encontram-se tanto determinações no núcleo como nas bordas dos grãos.

Figura 4.6 – Diagrama concórdia com os resultados U-Pb (SHRIMP II) para a amostra TC3 (xisto) da seqüência metavulcano-sedimentar de Juscelândia (borda oeste do Complexo Barro Alto).

Figura 4.7 – Imagem de CL dos zircões da amostra TC3 (xisto) da seqüência metavulcano-sedimentar de Palmeirópolis. Notar multiplas fases de sobrecrecimentos na maioria dos grãos.

Figura 4.8 - Imagem de CL de um dos zircões da amostra TC3 (xisto) com mais de um episódio de sobrecrecimento. Os pontos 1, 2 e 3 correspondem respectivamente às análises tc3.124, tc3.121 e tc3.123, da tabela 4.1.

Figura 4.9 – Imagem de CL dos zircões da amostra NQ1575 (gnaisse da seqüência metavulcano-sedimentar de Indaianópolis, borda oeste do Complexo de Niquelândia). Notar a ausência de padrão regular de zoneamento interno como consequência de processo de metamictização.

Figura 4.10 – Imagem de CL de zircão da amostra TC3 (gnaisse da seqüência metavulcano-sedimentar de Indaianópolis). Detalhe da estrutura interna afetada por processo de metamictização.

Figura 4.11 – Diagramas concórdia para os gnaisses da seqüência metavulcano-sedimentar de Indaianópolis. Borda oeste do Complexo de Niquelândia

Figura 4.12 – Diagramas concórdia com os resultados U-Pb (SHRIMP II) para as amostras do Complexo de Cana Brava. Apenas nos diagramas (B) e (D) encontram-se determinações que não correspondem ao evento neoproterozoico.

Figura 4.13 – Imagem de CL dos zircões da amostra CB1030, da unidade superior do Complexo de Cana Brava.

Figura 4.14 – Imagem de CL, revelando múltiplas bordas de sobrecrecimento em zircão da amostra CB1100, da unidade superior do Complexo de Cana Brava.

Figura 4.15 – Imagem de CL de zircão com zoneamento simples. Amostra CB1100, unidade superior, Complexo de Cana Brava.

CAPÍTULO 5

Origem e evolução tectônica dos grandes complexos máficos-ultramáficos da porção central do Brasil.

O conjunto de informações atualmente disponíveis sobre a estratigrafia interna, características geoquímicas, petrologia e dados isotópicos permitiu estabelecer de modo amplamente aceito que os grandes complexos máficos-ultramáficos de Barro-Alto, Niquelândia e Cana Brava classificam-se como complexos estratiformes anarogênicos (Girardi et al., 1981 e 1986; Girardi e Kurat, 1982; Rivalenti et al., 1982; Mazzucchelli et al., 1983; Fugl, 1989; Feininger et al., 1991; Anete e Jost, 1992; Ferreira Filho et al., 1992 e 1994, Suita, 1996; Correia et al., 1997 e 1998, Lima, 1997), formados por processos de fracionamento magmático a partir de magma basáltico de composição toleítica.

Quanto à petrologia, Girardi et al. (1986) e Correia e Girardi (1998), apresentam, respectivamente, para os complexos de Niquelândia e Cana Brava modelos que suportam a hipótese de cristalização a partir do fracionamento contínuo de um único pulso de colocação do magma progenitor. De modo oposto, estudo e publicações preliminares de Ferreira Filho (1994) e Ferreira Filho et al. (1995 e 1998) propõem que o complexo de Niquelândia seria constituído por dois sistemas magmáticos distintos, sendo o superior de composição diferente e mais novo que as unidades basais do complexo. De forma análoga, Lima (1997) sugere que as unidades superiores de Cana Brava não teriam a mesma filiação e seriam mais jovens que os litotipos da sua porção basal.

Pimentel et al. (2000) consideram que as isócronas Sm-Nd em rocha total obtidas em gabros e anortositos das unidades superiores de Niquelândia (Ferreira Filho e Pimentel, 1999) com cerca de 1.3 Ga e, principalmente, os valores positivos de ϵ_{Nd} (+4) dessas rochas, sustentam as propostas de Ferreira Filho, mencionadas acima.

Em relação a essa questão, é necessário que os estudos geoquímicos e modelos petrológicos sugeridos por Ferreira Filho et al. (1995 e 1998) e Lima (1997) sejam publicados de forma completa para permitir a devida confrontação com os modelos previamente divulgados por Girardi et al. (1986) e Correia e Girardi (1998). É preciso também verificar se os valores juvenis de ϵ_{Nd} se encontram presentes de forma abrangente nas unidades superiores de Niquelândia ou se têm caráter restrito, podendo representar alguma intrusão menor, desvinculada do episódio principal de formação do complexo.

No diagrama da Figura 5.1, encontram-se tabulados de forma conjunta todos os resultados isotópicos Pb/Pb que constam das tabelas 4.1, 4.2 e 4.3. A distribuição desses dados permite algumas conjecturas a respeito da evolução tectônica da região. Não apenas fica em evidência a importância do evento compressivo inicial do Neoproterozóico, na configuração da Faixa Brasília, conforme descrito por Dardenne (2000), como também é colocado em destaque a presença marcante do Mesoproterozóico (1300 Ma), enquanto as idades do Paleoproterozóico referem-se

provavelmente aos litotipos remanescentes do Paleocôntinente Atlântica (Rogers, 1996) que teria se desintegrado durante os processos tafrogenéticos do Estateriano (Brito Neves, et al. 1995), vindo posteriormente a se reaglutinar no Mesoproterozóico (Rodínia).

Figura 5.1 – Histograma de distribuição de freqüência do conjunto das idades Pb/Pb, das Tabelas 4.1, 4.2 e 4.3 (139 análises). Em destaque os picos de freqüência que registram os eventos vinculados ao Paleo-, Meso- e Neoproterozóico nas unidades do Maciço de Goiás (conforme dispostas na Fig. 3.1).

Nesse contexto, as publicações preliminares (Correia et al., 1996, 1997b e 1999) dos dados apresentados nos capítulos 3 e 4, contribuíram para dar suporte ao modelo de evolução geodinâmica do Maciço de Goiás, de acordo com o proposto por Brito Neves et al. (1999) e Campos Neto (2000). Para esses autores essa unidade tectônica se encontrava vinculada à placa da Amazônia (Figura 5.2) e não à placa do São Francisco Congo, durante o intervalo do Paleo- ao Mesoproterozóico. Essa proposição decorre da constatação de que é no entorno da placa da Amazônia e não na placa do São Francisco-Congo que se encontram registros de sucessivos terrenos acrecionais durante o Mesoproterozóico (Teixeira et al., 1989; Sadowski e Bettencourt, 1996; Bettencourt et al., 1999 e Tassinari et al., 1999, Tassinari et al., 2000).

A modified view for the Rodinia reconstruction (from Weil et al, 1998).
The shape of Amazonas, São Francisco, Rio de la Plata and Western Africa continental segments of plates is modified.
Speculative position of the postulate Hoggar-Potiguar plate and Cariris Velhos terrane.

1. Grenvillian orogens; 2. Continental plate segments; 3. Tonian rift lines.

AM - Amazonas, BA - Baltica, C - Congo, CV - Cariris Velhos, CMG - Coates Land-Maudheim-Grune-Hogna Province, E - Ellworth-Withmore Mountain block, G - Greenland, H-P - Hoggar-Potiguar, K - Kalahari, LAU - Laurentia, RP - Rio de la Plata, WA - Western Africa. AN - Arabian-Nubian Ocean, CG - Central Goiás terrane, CV - Cariris Velhos terrane, G - Goianides Ocean, LA - Luis Alves terrane, PhB - Pharusian-Borborema Ocean, SP - South Pole.

Figura 5.2 – Ilustração de Campos Neto (1999, Figura 4.5, pg. 55) onde o terreno de “Goiás Central” aparece associado à placa do Amazonas no período Toniano, imediatamente após a separação por rifteamento das placas do Amazonas e do São Francisco-Congo.

Especificamente quanto às relações mútuas entre os Complexos de Barro Alto, Niquelândia e Cana Brava e das seqüências metavulcano-sedimentares a eles adjacentes, é preciso ainda obter informações mais robustas que permitam estabelecer com maior segurança a idade da cristalização ígnea de Barro Alto, e o caráter compressivo ou distensivo do evento responsável pelo registro do Mesoproterozóico em praticamente todas as unidades referidas.

Nesse sentido, constituem evidências significativas em favor do caráter colisional do evento Mesoproterozóico no Centro-Oeste do Brasil os dados Rb-Sr para rochas da seqüência de Palmeirópolis de 1157 ± 150 Ma (Girardi et al, 1978), interpretada como idade do metamorfismo; as idades modelo Pb/Pb que se distribuem no intervalo de 1,17-1,27 Ga, obtidas em galenas das mineralizações de Cu-Pb-Zn de Palmeirópolis (Araújo et al., 1996a e b) e as determinações U-Pb para as rochas metagranitoides a cordierita e silimanita (BA1546 e TC2) intrusivas em Barro Alto.

CAPÍTULO 6

Referências Bibliográficas

- Almeida, F.F.M. de., 1968. Evolução tectônica do Centro Oeste Brasileiro no Proterozóico Superior. *Anais da Acad. Bras. de Ciências*, **40**(supl.):285-295.
- Alves S., Schiano P. and Allegre C.J., 1999. Rhenium-osmium isotopic investigation of Java subduction zone lavas. *Earth and Planetary Science Letters*, **168**:65-77.
- Anete, M. de O. & Jost, H., 1992. Estratigrafia da seqüência granulítica do Complexo de Barro Alto na região de Goianésia, Goiás. 37 Congr. Bras. de Geol. - SBG/SP, **1**:446-447.
- Araújo, S.M.; Longstaffe, F.J. and Scott, S.D., 1996a. Effects of high grade metamorphism on the oxygen isotope composition of the alteration zones associated with the Palmeirópolis volcanogenic massive sulfide deposit, Tocantins state, Brazil. *Anais, XXXIX Cong. Bras. Geol.*, Salvador, SBG, **7**:339-342.
- Araújo, S.M.; Scott, S.D. and Longstaffe, F.J. 1996b. Oxygen isotope composition of the alteration zones of highly metamorphosed volcanogenic massive sulfide deposits, Geco, Canada and Palmeirópolis, Brazil. *Economic Geology*, **91**:697-712.
- Bettencourt, J.S.; Tosdal, R.M.; Leite, W.B. and Payolla Jr., B.L., 1999. Mesoproterozoic rapakivi granites of the Rondônia Tin Province, southwestern border of the Amazonian craton, Brazil-I: Reconnaissance U-Pb geochronology and regional implications. *Precambrian Research*, **95**:41-67.
- Birck J. L., Roy Barman M., and Capmas F., 1997. Re-Os isotopic measurements at the femtomole level in natural samples. *Geostandards Newsletter*, **20**:19-27.
- Brandon A. D., Creaser R. A., Shirey S. B., and Carlson R. W., 1996. Osmium recycling in subduction zones. *Science*, **272**:861-864.
- Brito Neves, B.B.; Sá, J.M. de.; Nilson, A.A. and Botelho, 1995. A tafrogênese Estateriana nos blocos paleoproterozóicos da América do Sul e processos subsequentes. *Geonomos*, **3**(2):1-21.
- Brito Neves, B.B.; Winge, M and Carneiro, M.A., 1996. Orogeneses precedendo e tafrogêneses sucedendo Rodínia na América do Sul. *Bol.IG-USP, Sér. Cient.*, **27**:1-40.
- Brito Neves, B.B.; Campos Neto, M.C. and Fuck, R.A., 1999, From Rodinia to Western Gondwana: an approach to the Brasiliano-Pan Africano Cycle and orogenic collage. *Episodes*, **22**(3):155-166.
- Campos Neto, M.C., 1999. Extensão sul do sistema orogênico Tocantins no contexto Geodinâmico da Aglutinação do Gondwana: exercício de tectônica. Tese de Livre-docência, USP, São Paulo, 101p. Inédito.

- Campos Neto, M.C., 2000. Orogenic Systems from Southwestern Gondwana: an approach to Brasiliano-Pan African Cycle and orogenic collage in Southeastern Brazil. In: Tectonic Evolution of South America. Ed. by Cordani, U.G.; Milani, E.J.; Thomaz Filho and Campos, D.A. . Rio de Janeiro: 31st International Geological Congress, 2000. 856p. (335-368).
- Cohen A. S. and Waters F. G., 1996. Separation of osmium from geological materials by solvent extraction for analysis by thermal ionisation mass spectrometry. *Analytica Chimica Acta*, **332**:269-275.
- Condie, K.C., 1989. Plate Tectonics and Crustal Evolution 3rd ed., Pergamon Press, 476p.
- Correia, C.T., 1994. Petrologia do complexo máfico-ultramáfico de Cana Brava, Goiás. Unpublished Doctorate thesis, IG-USP, São Paulo, Brazil. 151p., 1 map.
- Correia, C.T.; Girardi, V.A.V.; Lambert, D.D.; Kinny, P.D. and Reeves, S.J., 1996. 2 Ga U-Pb (SHRIMP II) and Re-Os ages for the Niquelândia basic-ultrabasic layered intrusion, Central Goiás, Brazil. In: Cong. Bras. Geol., 39, Salvador, anais, SBG, **6**:187-189.
- Correia, C.T.; Girardi, V.A.V.; Tassinari, C.G. and Jost, H., 1997a. Rb-Sr and Sm-Nd geochronology of the Cana Brava layered mafic-ultramafic intrusion, Brazil, and considerations regarding its tectonic evolution. *Revista Brasileira de Geociências*, **27**(2):163-168.
- Correia, C.T.; Tassinari, C.C.G.; Lambert, D.D.; Kinny, P.D. and Girardi, V.A.V., 1997b. U-Pb (SHRIMP), Sm-Nd and Re-Os systematics of the Cana Brava, Niquelândia and Barro Alto layered intrusions in central Brazil, and constraints on the tectonic evolution. In: South Amer. Symp. on Isotope Geol., Brazil, Extended Abstracts:88-89.
- Correia, C.T.; Girardi, V.A.V., 1998. Geoquímica e Petrologia das Rochas Máficas e Ultramáficas do Complexo Estratiforme de Cana Brava-GO, e das suas Encaixantes. *Boletim do IG-USP, Série Científica*, **29**:1-37
- Correia, C.T.; 1998. O Método Isotópico Re-Os: Características e Potencialidade. *Boletim do Instituto de Geociências da USP* *Boletim do IG-USP, Série Científica*, **29**:219.
- Correia, C.T., Jost, H., Girardi, V.A.V. and Kinny, P.D., 1999. Ectasian Mesoproterozoic U-Pb Ages (SHRIMP II) for the metavolcano-sedimentary sequences of Juscelândia and Indaianópolis and for high grade metamorphosed rocks of Barro Alto Stratiform igneous complex, Goiás State, Central Brazil. In: II South Amer. Symp. on Isotope Geol., Cordoba, Argentina, Actas:31-33.
- Cordani, U.G. and Hasui, Y., 1975. Comentários sobre os dados geocronológicos disponíveis para a Folha Goiás. In: Brasil, DNPM. Carta Geológica do Brasil ao Milionésimo, Folha Goiás (SD 22). DNPM, DGM:85-94.

- Danni J.C.M; Fuck, R.A. and Leonardos O.H., 1982. Archaean and lower Proterozoic units in Central Brazil. *Geol. Rundschau*, **71**:291-317.
- Dardenne, M.A., 2000. The Brasília Fold Belt. In: *Tectonic Evolution of South América*. Ed. by Cordani, U.G.; Milani, E.J.; Thomaz Filho and Campos, D.A. . Rio de Janeiro: 31st International Geological Congress, 2000. 856p. (231-264).
- Dickin A. P., Richardson J. M., Crocket J. H., McNutt R. H., and Peredery W. V., 1992. Osmium isotope evidence for crustal origin of platinum group elements in the Sudbury nickel ore, Ontario, Canada. *Geochimica et Cosmochimica Acta*, **56**:3531-3537.
- Feininger, T.; Dantas, J.J. and Girardi, V.A.V., 1991. Gravity interpretation and possible regional significance of the Niquelândia layered basic-ultrabasic complex, Goiás, Brazil. *Journal of South American Earth Sciences*, **4(4)**:343-350.
- Ferreira Filho, C.F.; Nilson, A.A. and Naldrett, A.J., 1992. The Niquelândia mafic-ultramafic complex, Goiás, Brazil: A contribution to the ophiolite x stratiform controversy based on new eological and structural data. *Precambrian Research*, **59**:125-143.
- Ferreira Filho, C.F.; Kamo, S.L.; Fuck, R.A.; Krogh, T.E. and Naldrett, A.J., 1994. Zircon and rutile U-Pb geochronology in the Niquelândia layered mafic-ultramafic intrusion, Brazil: constraints for the timing of magmatism and high-grade metamorphism. *Precambrian Research*, **68(3-4)**:241-256.
- Ferreira Filho, C.F.; Naldrett, A.J. and Gorton, M.P., 1995. Petrology of the Mesoproterozoic Niquelândia layered mafic-ultramafic complex, central Brazil: evidence for a composite intrusion in an intracontinental rift system. *Actas, International Field Conference and Symposium, Duluth*:45.
- Ferreira Filho, C.F.; Naldrett, A.J. and Gorton, M.P., 1998. REE and pyroxene compositional variation across the Niquelândia layered intrusion, Brazil: petrological and metallogenetic implications. *Transactions of the Institution of Mining and Mettallurgy*, **107(B)**:1-22.
- Foster J. G., Lambert D. D., Frick L. R., and Maas R., 1996. Re-Os isotopic evidence for genesis of Archaean nickel ores from uncontaminated komatiites. *Nature*, **382**:703-706.
- Fuck, R.A.; Brito Neves, B.B.; Cordani, U.G. and Kawashita, K., 1989. Geocronologia Rb-Sr no complexo de Barro Alto, Goiás: Evidências de metamorfismo de alto grau e colisão continental há 1300 Ma no Brasil central. *Geochimica Brasiliensis*, **3(2)**:125-140.
- Fuji, M.Y., 1989. REE geochemistry and Sm/Nd geochronology of the Cana Brava Complex, Brazil. Unpublished Master Thesis. Kobe Univ., Japan, 55p..
- Girardi V. A. V., Kawashita, K., Basei, M.A. S. ; Cordani, U., 1978. Algumas considerações sobre a evolução geológica da região de Cana Brava, a partir de

- dados geocronológicos. In: Cong. Bras. Geol., 30, Recife, Anais, SBG, 1:337-348.
- Girardi, V.A.V.; Rivalenti, G., Siena, F., & Sinigoi, S., 1981. Precambrian Barro Alto Complex of Goiás, Brazil: bulk geochemistry and phase equilibria. *Neues Jb. Miner. Abh.* **142**:270-91.
- Girardi, V.A.V. & Kurat, G., 1982. Precambrian mafic and ultramafic rocks of the Cana Brava Complex, Brazil-mineral compositions and evolution. *Rev.Bras.Geoc., SBG*, **12(1-3)**:313-323, São Paulo.
- Girardi, V.A.V., Rivalenti, G.; Sinigoi, S., 1986. The petrogenesis of the Niquelândia layered basic-ultrabasic complex, Central Goiás, Brazil. *Journ. Petrol.*, **27(3)**:715-744.
- Goodwin, A.M., 1991. *Precambrian Geology. The Dynamic evolution of the continental crust.* London, Academic Press, 666p.
- Hamilton, J., 1977. Sr isotope and trace element studies of the Great Dyke and Bushveld mafic phase and their relation to early proterozoic magma genesis in Southern Africa. *Journal of Petrology*, **18(1)**:24-52.
- Hasui, Y. and Almeida, F.F.M. de, 1970. Geocronologia do Centro-Oeste Brasileiro. *Bol. Soc. Bras. Geol.*, **19(1)**:5-26.
- Hasui e Almeida, 1976. A faixa de dobramentos Uruaçu no Brasil Central. In: Congr. Latino Americano de Geol., México, Resúmenes, **3**:62-63.
- Hauri E. K. and Hart S. R., 1993. Re-Os isotope systematics of HIMU and EMII oceanic island basalts from the south Pacific Ocean. *Earth and Planetary Science Letters*, **114**:353-371.
- Hoffman, P.F., 1989. Speculations on Laurentia's first gigayear (2.0 to 1.0 Ga). *Geology*, **17(2)**:135-138.
- Horan M. F., Morgan J. W., Walker R. J., and Grossman J. N., 1992. Rhenium-osmium isotope constraints on the age of iron meteorites. *Science*, **255**:1118-1121.
- Lacerda Filho, J.V. e Oliveira, C.C., 1995. Geologia da região centro-sul de Goiás. *Bol. de Geociências do Centro-Oeste*. **18(1/2)**:3-19.
- Lambert, D.D., Foster, J.G., Frick, L.R., Hoatson, D.M., and Purvis, A.C., 1998a, Application of the Re-Os isotopic system to the study of Precambrian magmatic sulfide deposits of Western Australia: *Australian Journal of Earth Sciences*, **45**:265-284.
- Lambert D. D., Foster J. G., Frick L. R., Ripley E. M., and Zientek M. L., 1998b. Geodynamics of magmatic Cu-Ni-PGE sulfide deposits: New insights from the Re-Os isotope system. *Economic Geology*, **93**:121-136.
- Lima, T.M., 1997. Geologia, estratigrafia e petrologia da porção sul do complexo máfico-ultramáfico de Cana Brava, Goiás. Tese de Mestrado, UNB, Brasília, 312p. Inédito.

- Luck J.-M. and Allegre C. J., 1983. ^{187}Re - ^{187}Os systematics in meteorites and cosmochemical consequences. *Nature*, **302**, 130-132.
- Marini, O. J.; Fuck, R. A. ; Dardenne, M. A. ; Faria, A. de., 1977. Contribuição à geologia do pré-cambriano da porção central de Goiás. *Rev. Bras. Geoc.*, **7**:304-324.
- Marini, O.J.; Fuck, R.A.; Danni, J.C.M.; Dardenne, M.A.; Loguercio, S.O.C. and Ramalho, R., 1984. As faixas de dobramentos Brasília, Uruaçu e Paraguai-Araguaia e o Maciço Mediano de Goiás. In: Schobbenhaus, C.; Campos, D.A.; Derze, R. and Asmus, H.E. (coords.) *Geologia do Brasil*. MME/DNPM, Brasília, 501 p. .
- Matsui, K.; Girardi, V.A.V.; Basei, M. A. S. ; Hasui, Y., 1976. Geocronologia do complexo básico-ultrabásico de Cana Brava, Goiás. In: *Cong Bras Geol.*, **29**, Ouro Preto. *Anais*, SBG, **4**:279-288:
- Mazzucchelli, M., Siena, F., & Girardi, V.A.V., 1983. Textural features and olivine fabrics as petrogenetic indicators in the Niquelândia complex of central Goiás (Brazil). *Neues Jb. Miner. Abh.* **148**:50-57
- McBride J. S., Lambert D. D., McInnes B. I. A., and Evans N. J., 1998. Re-Os isotope evidence for fluid-peridotite interactions in sub-arc mantle xenoliths, Lihir Island, Papua New Guinea. *American Geophysical Union, Fall Meeting*.
- McInnes B. I. A., Evans N. J., McBride J. S., and Lambert D. D., 1998. Osmium isotope and noble metal enrichment of the mantle source region of the Ladolam gold deposit, Lihir Island, PNG. *Geological Society of America, Abstracts with programs*, **A**:302.
- Meisel T., Walker R. J., and Morgan J. W., 1996. The osmium isotopic composition of the Earth's primitive upper mantle. *Nature*, **383**:517-520.
- Morgan J. W. and Walker R. J., 1989. Isotopic determinations of rhenium and osmium in meteorites by using fusion, distillation and ion-exchange separations. *Analytica Chimica Acta*, **222**:291-300.
- Nier A. O., 1950. A redetermination of the relative abundances of the isotopes of carbon, nitrogen, oxygen, argon and potassium. *Physics Reviews*, **77**:789-793.
- Nilson, A.A. Botelho, N.F. and Ferreira Filho, C.F., 1994. Riftingamento crustal mesoproterozóico no Centro-Oeste de Goiás. In: *Congr. Bras. Geol.*, **38**, Camboriu, SC, Brazil, *Resumos Expandidos*, **1**:258-259.
- Pearson D. G., Carlson R. W., Shirey S. B., Boyd F. R., and Nixon P. H., 1995. Stabilisation of Archaean lithospheric mantle; A Re-Os isotope study of peridotite xenoliths from the Kaapvaal craton. *Earth and Planetary Science Letters*, **134**:341-357.
- Pearson D. G., Shirey S. B., Carlson R. W., Boyd F. R., Pokhilenko N. P., and Shimizu N., 1995. Re-Os, Sm-Nd, and Rb-Sr isotope evidence for thick Archaean

- lithospheric mantle beneath the Siberian craton modified by multi-stage metasomatism. *Geochimica et Cosmochimica Acta*, **59**(5):959-977.
- Pearson D. G., Snyder G. A., Shirey S. B., Taylor L. A., Carlson R. W., and Sobolev N. V., 1995. Archaean Re-Os age for Siberian eclogites and constraints on Archaean tectonics. *Nature*, **374**:711-713.
- Pimentel, M.M.; Fuck, R.A. and Del'Rey Silva, L.J.H, 1996. Dados Rb-Sr e Sm-Nd da região de Jussara-Goiás-Mossâmedes (GO), e o limite entre terrenos antigos do maciço de Goiás e o arco magmático de Goiás. *Rev. Bras. Geoc.*, **26**(2):61-70.
- Pimentel, M.M.; Fuck, R.A.; Jost, H.; Ferreira Filho, C.F. and Araújo, M., 2000. The basement of the Brasília Fold Belt and the Goiás Magmático Arc. In: *Tectonic Evolution of South América*. Ed. by Cordani, U.G.; Milani, E.J.; Thomaz Filho and Campos, D.A. . Rio de Janeiro: 31st International Geological Congress, 2000. 856p. (195-230).
- Reisberg L. C., Allegre C. J., and Luck J.-M., 1991. The Re-Os systematics of the Rhonda Ultramafic Complex of southern Spain. *Earth and Planetary Science Letters*, **105**:196-213.
- Ribeiro Filho, W.; Teixeira, N. A., 1981. Sequência vulcano-sedimentar da borda oeste dos complexos de Niquelândia e Cana Brava. *Bol. Inf. Núcleo Centro-Oeste*, **10**:157-177.
- Righter K., Chesley J. T., Geist D., and Ruiz J., 1998. Behavior of Re during magma fractionation: an example from Volcan Alcedo, Galapagos. *Journal of Petrology*, **39**, 785-795.
- Rivalenti, G.; Girardi, V.A.V.; Sinigoi, S.; Rossi, A. and Siena, F., 1982. The Niquelândia mafic-ultramafic complex of Central Brazil: petrological considerations. *Rev. Bras. Geoc.*, **12**:380-391.
- Rogers, J.J.W., 1996. A history of the continents in the past three bylions years: *Journal of Geology*, **104**:91-107.
- Roy-Barman M., 1993. Mesure du rapport $^{187}\text{Os}/^{186}\text{Os}$ dans les basalts et les péridotites: Contribution a la systématique ^{187}Re - ^{187}Os dans le manteau, PhD Thesis, Paris 7.
- Sadowski, G.R. and Bettencourt, J.S., 1996. Mesoproterozoic tectonic correlations between eastern Laurentia and the western border of the Amazon Craton. *Precambrian Research*, **76**:123-227.
- Shirey S. B., 1997. Re-Os isotopic compositions of Midcontinent rift system picrites: implications for plume-lithosphere interaction and enriched mantle sources. *Canadian Journal of Earth Sciences*, **34**:489-503.
- Shirey S. B. and Walker R. J., 1994. Carius tube digestions for Re-Os Chemistry: An old technique applied to new problems. *EOS*, **75**(16):355.

- Shirey S. B. and Walker R. J., 1995. Carius tube digestion for low-blank rhenium-osmium analysis. *Analytical Chemistry*, **67**(13):2136-2141.
- Smoliar M. I., Walker R. J., and Morgan J. W., 1996. Re-Os ages of group IIa, IIIA, IVA, and IVB iron meteorites. *Science*, **271**:1099-1102.
- Souza, A., 1983. Aspectos geológicos e geocronológicos do complexo de Barro Alto, Goiás. Unpublished Doctorate thesis, FFCLRP-USP, Ribeirão Preto, São Paulo, Brazil. 112p. .
- Suita, M.T.F.; Kamo, D.L.; Krogh, T.E.; Fyfe, W.S. and Hartmann, L.A., 1994. U-Pb ages from the high-grade barro Alto mafic-ultramafic complex (Goiás, Central Brazil): Middle Proterozoic continental mafic magmatism and Upper Proterozoic continental collision. Abstracts of the Eighth Int. Conf. Geochr. Cosmochr. And Isotope Geol. (ICOG8), U.S. Geol. Survey. Circ., **1107**:309.
- Suita, M.T.F., 1996. Geoquímica e metalogenia dos elementos do grupo da platina (EGP + Au) em complexos máficos-ultramáficos do Brasil: critérios e guias com ênfase no complexo máfico-ultramáfico acamadado de grau alto de Barro Alto. Doctorate Thesis, UFRGS, Porto Alegre, 600p. Inédito.
- Tassinari, C.C.G.; Cordani, U.G.; Correia, C.T.; Nutman, A.; Kinny, P. and Dias Neto, C., 1999. Dating of granulites by SHRIMP U-Pb systematics in Brazil: constrains for the age of the metamorphism of Proterozoic orogenies. In: South Amer. Symp. on Isotope Geol., Brazil, Actas:371-375.
- Tassinari, C.C.G.; Bettencourt, J.S.; Geraldes, M.C.; Macambira, M.J.B. and Lafon, M., 2000. The Amazonian Craton. In: Tectonic Evolution of South América. Ed. by Cordani, U.G.; Milani, E.J.; Thomaz Filho and Campos, D.A. . Rio de Janeiro: 31st International Geological Congress, 2000. 856p. (19-40).
- Teixeira, W.; Tassinari, C.C.G.; Cordani, U.G. and Kawashita, K., 1989. A review of the geochronology of the Amazonian Craton: tectonic implications. *Precambrian Research*, **42**:213-227.
- Weil, A.B.; Van der Voo, R.; Niocail, C.M. and Meert, J.g., 1998. The proterozoic supercontinent Rodinia: paleomagnetically derived reconstructions for 1100 to 800 Ma. *Earth and Planetary Science Letters*, **154**:13-24.
- Walker R. J. and Fassett J. D., 1986. Isotopic measurement of subnanogram quantities of rhenium and osmium by resonance ionization mass spectrometry. *Analytical Chemistry*, **58**:2923-2927.
- Walker R. J. and Morgan J. W., 1989. Rhenium-osmium isotope systematics of carbonaceous chondrites. *Science*, **243**:519-522.

AGRADECIMENTOS

Às agências de fomento, FAPESP e CNPq, cujo suporte financeiro através do projeto Temático 97/00640-5 e PRONEX 41.96.0899.00, respectivamente, viabilizaram essa pesquisa.

Aos colegas, técnicos, alunos, amigos e familiares que das mais variadas formas colaboram para que esse trabalho fosse realizado e concluído; os nossos mais sinceros agradecimentos.