LOW-K CALC-ALKALINE GRANITIC SERIES OF SOUTHEASTERN TOCANTINS STATE: CHEMICAL EVIDENCE FOR TWO SOURCES FOR THE GRANITE-GNEISSIC COMPLEXES IN THE PALEOPROTEROZOIC ALMAS-DIANÓPOLIS TERRANE

EMÍLIO LENINE CARVALHO CATUNDA DA CRUZ¹, RAUL MINAS KUYUMJIAN²
& GERALDO RESENDE BOAVENTURA²

Abstract Tonalites, trondhjemites and granodiorites (TTG) compose the major part of Archaean granite-gneiss terranes. These low-K calc-alkaline granitic rocks are divided into low- and high- Al_2O_3 groups. This paper presents whole-rock chemical data displaying that peraluminous and metaluminous low-K calc-alkaline granitoids that constitute the granite-gneiss complexes of Almas-Dianópolis Terrane, central Brazil. These complexes comprise several isotropic to weakly foliated granitoid bodies intruding narrow supracrustal belts. Recent SHRIMP U-Pb geochronology indicates that the granitoid bodies were intruded during the Paleoproterozoic (2.2 to 2.45 Ga). Amphibole-rich granitoids of Suite 1 (2.2 Ga) are dominantly tonalite, but include units of granodiorite, trondhjemite, quartz-diorite and quartz-monzodiorite with lower contents of Al_2O_3 (metaluminous), high #Mg values, high Cr, Ni and V contents, and low Sr/Y and (La/Yb)_n ratios. Mantle partial melting or fractional crystallization of mantle derived magmas yielded these Suite 1 melts. The Ribeirão das Areias Complex (2.45 Ga) and Suite 2 (2.2 Ga) are composed of tonalite, trondhjemite, granodiorite and minor monzogranite units with high- Al_2O_3 contents (peraluminous), low #Mg values; low Cr, Ni, Y and Ybn contents, and high Sr/Y and (La/Yb)_n ratios, which resulted from partial melt of metabasalt, leaving garnet and hornblende as restite. This metabasalt belongs either to subducted oceanic slab or to newly underplated basaltic crust. Oceanic lithosphere subduction is the most suitable geological process to yield both types of low-K calc-alkaline granitic series. If this is so, subduction related processes were active during the building up of the northwestern margin of the São Francisco Craton during Paleoproterozoic times.

Keywords: low-K calc-alkaline granitic series, tonalites, Paleoproterozoic, magmatic arc, Brasília Belt

Resumo Tonalitos, trondhjemitos e granodioritos compõem a maior parte dos complexos granito-gnáissicos arqueanos, as quais pertencem a dois grupos, ou seja, de alto- e baixo- Al_2O_3 . Resultados de análises químicas de rocha total indicam que granitóides calcálicos de baixo-K, peraluminosos e metaluminosos, constituem os complexos granito-gnáissicos do Terreno Almas-Dianópolis, Brasil Central. Estes complexos compreendem vários corpos de granitóides, isotrópicos a fracamente foliados, os quais intrudem estreitas faixas de supracrustais. Recente geocronologia U-Pb (SHRIMP) indica que esses corpos intrudiram no Paleoproterozóico (2,2 a 2,45 Ga). Os granitóides ricos em anfibólio da Suíte 1 (2,2 Ga) são predominantemente tonalito, mais incluem granodiorito, trondhjemito, quartzo-diorito e quartzo-monzodiorito com baixos teores de Al_2O_3 (metaluminosos), elevados valores de #Mg, elevadas concentrações de Cr, Ni e V, e baixas razões Sr/Y e (La/Yb)_n. Fusão parcial do manto, ou cristalização fracionada de magmas de derivação mantélica, produziram os magmas da Suíte 1. O Complexo Ribeirão das Areias (2,45 Ga) e a Suíte 2 (2,2 Ga) são constituídos de tonalito, trondhjemito, granodiorito e, subordinadamente, monzogranito, com altos teores de Al_2O_3 (peraluminosos), baixos valores de #Mg, baixas concentrações de Cr, Ni, Y e Yb, e elevadas razões Sr/Y e (La/Yb)_n, as quais resultaram da fusão parcial de metabasalto deixando granada e hornblenda no restito. Este basalto pertenceu a uma placa oceânica subductada ou a uma crosta basáltica recém formada na crosta inferior. A subducção da litosfera oceânica é o processo geológico mais plausível para produzir os dois tipos de suítes calcálicas de baixo-K. Portanto, processos relacionados a subducção estiveram ativos durante a construção da margem noroeste do Craton São Francisco durante o Paleoproterozóico.

Palavras-chave: séries graníticas calcálicas de baixo-K, tonalitos, Paleoproterozóico, arco magmático, Faixa Brasília.

INTRODUCTION Granite-gneiss terranes of dominant tonalitic and trondhjemitic compositions are exposed in wide areas of Archaean nuclei. In contrast, granitic to granodioritic batholiths constitute most of modern magmatic arc setting (Barker *et al.* 1981). Understanding of generation processes, source rock and tectonic setting of these low-K calc-alkaline melts is fundamental to elucidate Archaean crustal growth processes, as well as the evolution of some Paleoproterozoic terranes. There are several hypotheses to

explain the origin of these magmas: mantle partial melt (Moorbath 1975, Peterman & Barker 1976); mixing of felsic and mafic magmas (Kröner 1986, 1987); sodic metasomatism (Drummond *et al.* 1986); partial melting of immature greywacke (Arth & Hanson 1975); fractional crystallisation of basaltic magmas (Arth *et al.* 1978, Maaloe 1983, Smith *et al.* 1983); partial melt of metabasalts, e.g. amphibolite and garnet amphibolite (Barker & Arth 1976, Barker *et al.* 1981, Martin *et al.* 1983; Martin 1986, 1987, Rapp *et al.* 1991) or

1 - Companhia de Pesquisa de Recursos Minerais, Av. Pasteur n 404, Urca, Rio de Janeiro, RJ, Brasil, 2220-090.

2 - Instituto de Geociências, Universidade de Brasília, Campus Universitário, Brasília, DF, Brasil, 70910-90. E-mail: raulmk@unb.br.

eclogite and basic granulite (Glikson 1976, Jahn *et al.* 1981).

The Almas-Dianópolis Terrane, formerly referred to the Tocantins Terrane (Cruz & Kuyumjian 1998) covers about 7,800 km² in central Brazil (Fig. 1a,b). Over 70% of the exposed rocks from the granite-gneiss complexes are of trondhjemitic, tonalitic and granodioritic composition. The earliest geological mappings of this terrane were those of Costa *et al.* (1976) and Correa Filho & Sá (1980), who regarded the region as composed of greenstone-type linear volcanic-sedimentary belts. This paper discusses whole-rock chemistry of granite-gneiss complexes, based on major, trace and rare earth element contents. To more detailed description of the geological framework of Almas-Dianópolis Terrane the reader should refer to Cruz & Kuyumjian (1998).

REGIONAL GEOLOGY Three main geotectonic units dominate Central Brazil: the Araguaia Belt, the Goiás Massif and the Brasília Belt (Almeida *et al.* 1981, Fig. 1a). The Goiás Massif was first defined as the basement of Proterozoic metasedimentary units, e.g. Araxá Group (Berbert 1980, Almeida *et al.* 1981). This massif comprises granite-greenstone terranes, Paleoproterozoic volcanic-sedimentary belts, granulitic belts and mafic-ultramafic layered complexes, as well as wide areas of granite-gneissic terranes (Danni *et al.* 1981). Recent studies based on geochronological data have indicated that Neoproterozoic arc-related terranes are incorporated in the Goiás Massif (Pimentel & Fuck 1987, Pimentel *et al.* 1993). Also, two granulitic belts broadly coincide with regional gravimetric lows that limit the Goiás Massif and are interpreted as the boundary of tectonic blocks limited by ductile thrust faults (Hasui & Haralvi 1985, Costa *et al.* 1991). Fuck *et al.* (1994) proposed a new tectonic subdivision for the central part of Tocantins Province. In this new interpretation, the Goiás Massif is a smaller block limited with the Western Goiás Magmatic Arc, to the west, and with the Brasília Fold Belt, to the east. In accordance with this new tectonic proposal, Almas-Dianópolis Terrane is part of the basement of the external zone of the Brasília Belt (Fig. 1b). Almeida (1981) and Cruz & Kuyumjian (1993b) proposed that this region composes the partially reworked margins of the São Francisco Craton situated immediately to the east of the Tocantins Province.

The Almas-Dianópolis Terrane is partially covered by Meso-Neoproterozoic metasedimentary units of the Bambuí and Natividade groups (Correa Filho & Sá 1980). Several narrow volcanic-sedimentary belts surround the granite-gneiss complexes (Fig. 2), which are composed of amphibole-bearing granitoids, mostly tonalite, grouped into Suite 1, and granitoids with biotite, mainly tonalite, trondhjemitic and granodiorite, grouped into Suite 2 (Cruz & Kuyumjian 1993a, 1996, Thomsen & Kuyumjian 1994). In the Almas-Dianópolis region, the volcanic-sedimentary belt, named the Riachão do Ouro Group (Costa 1984), comprises the lower Córrego Paiol Formation and the upper Morro do Carneiro Formation (Cruz & Kuyumjian 1998, Fig. 3). The Córrego Paiol Formation includes basaltic flows and rare ultramafic volcanic rocks. These mafic to ultramafic volcanic rocks are divided in a dominant high-Fe metabasalt group and a high-Mg metabasalt group. The ultramafic volcanic rocks that crops out in a small area near the town of Dianópolis are included in the high-Mg group (Cruz & Kuyumjian 1996). The Morro do Carneiro Formation is a monotonous sequence of sericitic phyllites with interlayered beds of banded iron formation, quartzite, chert, conglomerate and felsic volcanic rock (Cruz & Kuyumjian 1998, Borges *et al.* 1998). Metamorphic conditions in the volcanic-sedimentary belts range from amphibolite to greenschist facies. Gneissic-migmatitic rocks,

probable basement of the greenstone belts, are also described (Borges *et al.* 1991, Borges *et al.* 1998, Borges 1993). Zircon and titanite SHRIMP U-Pb data (Cruz 2001) yield ages of 2.45 Ga ($\epsilon_{\text{Nd}(t)} = +0.58$) for the Ribeirão das Areias Complex and 2.2 Ga for the Suite 1 low-K calc-alkaline metaluminous granitoids ($\epsilon_{\text{Nd}(t)} = -0.15$ a -1.37, $T_{\text{DM}} = 2.45$ a 2.54 Ga) and Suite 2 low-K calc-alkaline peraluminous granitoids ($\epsilon_{\text{Nd}(t)} = -0.88$ a -4.95, $T_{\text{DM}} = 2.53$ a 2.76 Ga). Available Rb-Sr and K-Ar data indicate partial isotopic resetting of the basement rocks of the external zone of the Brasília Belt during the Neoproterozoic Brasiliano-Pan-African Cycle (Hasui *et al.* 1980, Tassinari *et al.* 1981).

GRANITE-GNEISS COMPLEXES The granite-gneiss complexes of Almas-Dianópolis region consist of isotropic to weakly foliated granitoid plutons with local gneissic banding (fig. 3), displaying either intrusive or faulted contacts with the volcanic-sedimentary belts. Granitoid bodies have variable foliation pattern, but generally more foliated towards the contacts with volcanic-sedimentary belts. Isotropic to weakly foliated portions of these plutons have euhedral to subhedral plagioclase, amphibole and biotite, interstitial quartz, and poikylitic k-feldspars, which indicate igneous primary textures. Granite-gneiss complexes do not reveal structures related to the D_1 early tectonic phase, which are seen in the volcanic-sedimentary belts. This, and the presence of xenoliths of the supracrustal sequence in the granite-gneiss complexes, strongly suggest that the complexes are intrusive in the Córrego Paiol Formation. Contact relationships with Morro do Carneiro Formation are faults, and intrusive relationships are not evident. Late D_{n+1} vertical shear zones partially obliterate D_n structural features in volcanic-sedimentary belts, although their effects are not penetrative in the granite-gneiss complexes (Cruz & Kuyumjian 1998).

Tonalite, trondhjemitic and granodiorite are dominant units, which characterize these complexes as TTG terranes. These granitoids are grouped into Suite 1, Suite 2, and the Ribeirão das Areias Complex. Very deformed granite-gneiss complexes crop out to the south of the towns of Almas and Porto Alegre. To date, tonalite and monzogranite are dominant to west and tonalite, trondhjemitic and granodiorite are dominant to east of a quartzite stripe. These complexes have been more recently included in Suite 2 due the dominance of biotite over amphibole as the main mafic mineral.

Ribeirão das Areias Complex The Ribeirão das Areias Complex (RAC) consists of tonalite and trondhjemitic and embodies units of granodiorite. These granitoids are medium- to coarse-grained, equigranular, white-with-light-green-tone, and progressively foliated towards greenstone contacts. Subhedral to anhedral plagioclase (40-47%) is totally altered. Quartz (35-47%) is interstitial and exhibits undulose extinction or recrystallisation along foliation. Microcline is interstitial and has inclusions of plagioclase and quartz crystal. Brown greenish biotite flakes (0-2%) include zircon crystals. Titanite, apatite and allanite are accessory phases. RAC granitoids present xenoliths of mafic schists from the Córrego Paiol Formation.

SUITE 1 Amphibole bearing granitoids are exposed in central and eastern parts of study area. Eastern outcrops are mainly of tonalite, but units of granodiorite, trondhjemitic, quartz-monzodiorite and quartz diorite also occur. They differ from one to another in the plagioclase, quartz, amphibole and K-feldspar contents. Crosscutting relations among different granitoid types

Figure 1 - a) Brazilian structural provinces (simplified from Almeida et al. 1977); b) Tectonic compartments of Tocantins Province central sector (simplified from Fuck et al. 1994).

Figure 2 - Geological map of Almas-Dianópolis Terrane (simplified from Padilha 1984)

are not observed. Differences between them consist in the different proportions of main minerals, e.g. plagioclase, quartz and amphibole. These granitoids are isotropic to faintly foliated, equigranular, and medium grey with scattered spots of dark green prismatic amphibole. Centimetric amphibole-rich clots and metabasalt xenoliths are common. Light grey monzogranite dykes crosscut these rocks. Plagioclase (40-48%) is euhedral to subhedral, tabular and generally is altered to albite, white mica, zoisite and clinozoisite. The compositions of the least altered rims show compositional zonation in some mantled plagioclase crystals. Quartz (27-40%) is interstitial and shows undulose extinction. Amphibole is euhedral to subhedral, twinned and includes inclusions of zircon, apatite and quartz. It alters to penine along cleavage planes. Apatite is the common accessory phase as euhedral elongated crystal. Zircon and opaque minerals are the other accessory phases.

In the central part of the study area, amphibole granitoids are mainly tonalite with units of quartz-diorite. They are equigranular, medium-grained and light grey, have gneissic banding marked by amphibole-rich schlierens and embody meter-scale layers of dark green amphibolite. Plagioclase crystals (45-55%) are anhedral to subhedral, rarely euhedral, lies along foliation planes and is altered to epidote group minerals and white mica. Interstitial quartz (35-39%) may have undulose extinction or be divided in subgrains. Amphibole (8-15%) is anhedral, twinned, and alters to penine along rims. Opaque minerals and euhedral to subhedral apatite and zircon are accessory phases.

SUITE 2 São Martins, Ponta da Serra and Manto Verde plutons

Figure 3 - Geologic sketch of Almas-Dianópolis region (modified from Correa Filho & Sá 1980).

and a small leucotonalite stock are grouped into Suite 2. Some of the plutons include amphibole granitoid xenoliths. The São Martins Pluton is composed of biotite-rich tonalite and granodiorite units. In the eastern part of the pluton, these granitoids are weakly foliated, equigranular, medium-grained, white-grey and include xenoliths of greenstone mafic units. Westward, they are medium- to coarse-grained, have millimeter-scale plagioclase phenocrysts, are more foliated with local gneiss banding and include enclaves of biotite-plagioclase schist. From east to west, mafic xenoliths became biotite-rich and plagioclase crystals mark the foliation that contours mafic enclaves. Tabular plagioclase (37-55%) is euhedral to subhedral, and corrosion gulfs and biotite and quartz inclusions are common. Biotite (3-15%) occurs as isolated flakes and anhedral poikilitic aggregates. Quartz, orthoclase and microcline are interstitial. Apatite, zircon and opaque minerals are accessory.

The Pluton Ponta da Serra is composed of medium-grained, equigranular, faintly foliated and light grey tonalite and granodiorite. Apophyses of these leucocratic magmas are intrusive in the São Martins pluton. Plagioclase (37-55%) is euhedral to subhedral, includes rare orthoclase and quartz crystals and is totally altered to albite, white mica and zoisite/clinozoisite. Quartz (45-55%) has undulose extinction and recrystallised rims. Dark brown pleochroic biotite (4-7%) has zircon inclusions and partly alters to moscovite (0-3%). Orthoclase (0-4%) is interstitial or occurs as smaller sparse crystals. Fibroradiated actinolite and epidote group minerals are the alteration phases.

Tonalite and granodiorite dominate in the Manto Verde Pluton, but trondhjemite and monzogranite units also occur. They are isotropic to faintly foliated, equigranular, medium-grained and light

grey. Monzogranite units have orthoclase phenocrysts up to 1cm. Dark-green amphibolitic enclaves occur mostly along pluton margins. Subhedral to euhedral plagioclase (33-38%) is partially or totally altered to white mica and epidote group minerals. Interstitial quartz (40-45%) has undulose extinction. Orthoclase (5-25%) has graphic texture and occurs as poikilitic crystals with inclusions of plagioclase and quartz; as euhedral phenocrysts with biotite, quartz and euhedral plagioclase inclusions; and as subhedral to anhedral crystal in the matrix. Dark brown pleochroic biotite (1-12%) composes irregular aggregates or is interstitial. Portions richer in amphibolitic enclaves have dark green hornblende (0-4%).

The leucotonalite stock is oval-shaped, 2 km long, equigranular, medium-grained, light grey and weakly foliated. The stock embodies amphibole-bearing xenoliths. Rare biotite is the only mafic mineral.

SAMPLING AND ANALYTICAL TECHNIQUES Selected samples for analysis were those showing no hand specimen or petrographic evidences of weathering and hydrothermal alteration. Most of granitoid samples are isotropic to weakly foliated. Rock samples were cut in diamond saw to get rid off the outer and possible weathered rims and then were reduced to fragment size smaller than 1cm using a hydraulic jack and grinded to powder with a tungsten mill. Major and trace elements were determined by inductive coupled plasma-atomic spectrometry (ICP-AES) at the Laboratório de Geoquímica do Instituto de Geociências, Universidade de Brasília, with a spectrometer SPECTROFVMO3. The elements S, Al, Fe, Ca, Mg, and Ti were determined through fusion with lithium metaborate (LiBO_2) in platinum crucibles. The other elements were determined through acid digestion with HF/HClO_4 .

HNO₃ and HCl. Rare earth elements were determined by GEOSOL Laboratory using Plasma Emission Spectrometry. Abbreviations used are: Large Ion Lithophile Elements (LILE), Rare Earth Elements (REE), Light Rare Earth Elements (LREE), Heavy Rare Earth Elements (HREE), High Field Strength Elements (HFSE), and Mg/(Mg+Fe)_{mol} (#Mg). The REE normalized to chondritic values of Nakamura (1974) are referred to as REEn.

Whole-Rock Chemical Data Most of Suite 1 samples displays a coherent chemical behavior, however, two SiO₂-rich samples (EL-27A, EL-167B) have some chemical characteristics of both Suite 1 and Suite 2 (Table 1). As these two samples are amphibole-rich and crops out amongst other Suite 1 amphibole granitoids, they are believed to belong to Suite 1. Notwithstanding, these samples are always referred apart to make things clearer. Data from the various plutons of Suite 2 (Table 2) are always discussed together, unless some small differences demand separate discussion. In figure 4a, most of Suite 1 granitoids are classified as tonalites and granodiorites, sample EL-27A as trondhjemite and sample EL-167B as tonalite, while Suite 2 granitoids scatter over tonalite, trondhjemite, granodiorite and granite fields. In spite of some scattering of the data, Suite 1, Suite 2 and RAC plot close to trondhjemitic trend (or low-K calc-alkaline trend) on Ab-Qz-Or diagram (Fig. 4b), moreover K/Na ratios are lower than 1. Although all the granitoids show a trondhjemitic affinity, Suite 1 is metaluminous, with Al/(Ca+K+Na) molar ratio ranging from 0.58 to 0.97, whereas Suite 2 and RAC are mostly peraluminous with that ratio varying from 0.95 to 1.23 and 1.35 to 1.65, respectively (Fig. 5). This distinction is corroborated by Al₂O₃ vs. SiO₂ variation diagram, where Suite 1 has a low-Al₂O₃ trend and Suite 2 and RAC describe a high-Al₂O₃ trend (Fig. 6). Another distinctive difference is the most primitive chemical signature of Suite 1, which has #Mg values spanning from 0.49 to 0.75 (0.56 in average), whereas Suite 2 #Mg varies from 0.29 to 0.66 (from 0.41 to 0.50, in average for each pluton) and RAC from 0.29 to 0.37. Regarding other major elements, there is no significant contrast between Suite 1, Suite 2 and RAC. Although Suite 1 samples always display a more scattered pattern, they align on the same trend (Fig. 6). High-SiO₂ Suite 1 samples are peraluminous and have #Mg values in the same range of Suite 2 (0.47-0.53), however, these #Mg values are higher to the same SiO₂ content when compared to Suite 2 and RAC samples.

The Na₂O and K₂O vs. SiO₂ diagrams show a more scattered pattern. For the Suite 1, apart high SiO₂ samples, K₂O does not vary while Na₂O diminishes when SiO₂ increases. For the Suite 2, each pluton has its own differentiation trend: Pluton Manto Verde has an initial enrichment in Na₂O and K₂O, then Na₂O decreases while K₂O continuously increases; CaO decrease in São Martins pluton whereas K₂O diminishes and Na₂O content does not vary; and Pluton Ponta da Serra has a flat trend to K₂O and Na₂O. RAC has a consistent more Na₂O-rich trend. The relations between Na₂O and K₂O are illustrated in figure 8, and it can be seen that all the individual Suite 2 plutons Na₂O has an antipathetic relation with K₂O. The undistinction of each pluton own differentiation trend would lead the reader to an erroneous interpretation that the scattering of these oxides would result from some degree of mobilization.

Despite of the anomalous samples EL-166 (52ppm Cr) and EL-105A (48ppm Cr), Suite 1 has a high Ni, Cr and V contents (57, 199 and 117ppm in average respectively), moderately high Y contents ranging from 10 to 28 (19ppm in average) and low to moderately

Figure 4 - a) The classification of granitoids in the albite-anorthite-orthoclase normative diagram of O'Connors 1965; b) Albite-orthoclase-quartz ternary plot showing the trondhjemitic (Tdj) and calc-alkaline differentiation trends. Symbols: Suite 1 (filled circles); high-SiO₂ Suite 1 samples, empty circle; Suite 2: Ribeirão das Areias complex, empty square; Manto Verde pluton, cross; São Martins pluton, empty diamonds; Ponta da Serra Pluton, asterisk; and leucotonalite, x.

high Sr content (228-902 ppm, 457ppm in average). Concerning the high-SiO₂ Suite 1 samples, EL-167B has high Sr (698ppm) and Y (24ppm) and low Cr (50ppm) and Ni (27ppm) contents, while sample EL-27A has low Sr (253ppm) contents (no determinations of Y, Ni and Cr are available). Suite 2 contents are lower regarding Cr (6-154ppm), Ni (3-64ppm) and V (8-70ppm). The Sr contents are moderately higher (404 to 1132ppm), while Y contents range from 2 to 50ppm. RAC has trace element concentrations similar to Suite 2 (5-11ppm Cr, 3-9ppm Ni, 22-42ppm V, and 399-1112ppm Sr).

Suite 1 has moderate REE enrichment ($\Sigma=94.56-143.12$ ppm, table 4) with moderate fractionating between LREE and HREE, (La/Yb)_n ranging from 12.05 to 18.58. REE enrichment is mainly due to LREE ($\Sigma=85.22-128.999$ ppm) than to HREE ($\Sigma=8.34-13.04$ ppm). Both LREE and HREE increase with SiO₂ content, although, LREE enrichment is more remarkable. HREE pattern is flat and Eu anomalies are slightly negative (Fig. 7a).

Suite 2 has low to moderate REE contents (36.49-153.63ppm)

Figure 5 - $Al_2O_3/(Na_2O+K_2O)$ mol vs. $Al_2O_3/(CaO+Na_2O+K_2O)$ mol diagrams (Shand's index). Symbols as in Fig. 4.

with a high to moderate fractionated pattern, $(La/Yb)_n$ ranging from 11.62 to 44.59. Apart from sample EL-265 (33.57ppm), LREE contents are similar to Suite 1 (68.65-146.33ppm), while HREE are lower (2.22-6.19ppm). Eu anomalies are slightly negative to strongly positive. Suite 2 HREE pattern is concave with a strong Yb depletion with Yb_n varying from 1.61 to 2.20, whereas Suite 1 values range from 4.47-5.88. Again, sample EL-265 has a distinct behavior, with a stronger depletion on middle rare earth elements (Fig. 7b). For the Suite 2, REE contents have no coherent relationship with SiO_2 contents. Again, RAC shows the same pattern of Suite 2, with depletion in Yb ($Yb_n=1.27$) and highly fractionated REE pattern ($(La/Yb)_n=64.25$).

The multielemental plots (Fig. 8) show some differences between both suites and RAC. Regarding the HFSE, Suite 1 is depleted in Y and Yb, whereas Suite 2 and RAC are richer in these elements. In addition, Suite 1 tends to be more depleted in Zr whereas Suite 2 and RAC are more depleted in Ti. Suite 2 tends also to be systematically more depleted in P. All samples are enriched in LILE, however, Suite 2 and RAC are always enriched in Sr, whereas Suite 1 can have either positive or negative Sr anomalies.

DISCUSSION ON CHEMICAL DATA AND THEIR TECTONIC IMPLICATIONS

The studied rocks have a trondhjemitic affinity. According to Barker & Arth (1976), tonalite and trondhjemite are divided, at 70% of SiO_2 , into two groups: the low- Al_2O_3 group and the high- Al_2O_3 group. The first group has low Rb and Sr contents, moderate LREE enrichment, negative Eu anomalies, and flat HREE pattern. The second group has low Rb, moderate Sr, moderate LREE enrichment, HREE depletion, and small either positive or negative Eu anomalies. The dominantly metaluminous Suite 1 with its low- Al_2O_3 trend, moderate LREE enrichment, flat HREE pattern and slightly negative Eu anomalies may be compared to the low- Al_2O_3 group, although higher Sr contents and more mafic units such as quartz-monzodiorite and quartz-diorite. In contrast, the dominantly peraluminous Suite 2 and RAC have a high Al_2O_3 trend, higher Sr contents, HREE depletion, and either negative or positive Eu anomalies, fitting very well on the high- Al_2O_3 group. Other distinctive characteristic between low- and high- Al_2O_3 groups is the $(La/Yb)_n$ ratio. High- Al_2O_3 group has higher $(La/Yb)_n$ and low Yb_n , whereas low- Al_2O_3 group has lower $(La/Yb)_n$ and high Yb_n (Drummond and Defant 1990). On $(La/Yb)_n$ vs. Yb_n diagram (Fig. 9), Suite 1 samples plot in the overlapping field,

although the HREE flat pattern is typical of the low- Al_2O_3 group, and Suite 2 and RAC samples plot on the high- Al_2O_3 field. We do not have definitive explanation, or a better one, to high- SiO_2 Suite 1 samples ambiguous behavior, but we suggest that they are going toward minimum melt composition. According to Battler & Bowed (1985) granite melts from different granite series tend to converge to the same composition at high SiO_2 contents, the so-called minimum melt composition. Inasmuch as these samples are not the centerpiece of the ongoing discussion, we consider that explanation acceptable for the moment.

Petrogenesis of high- Al_2O_3 TTG has been more discussed than the low- Al_2O_3 group (Drummond & Defant 1990 and references there in). However, our data allows to draw some constraints on the origin of metaluminous low-K calc-alkaline granitoids of Almas-Dianópolis Terrane. The more mafic Suite 1 amphibole granitoids have a primitive chemical signature, with high Cr and Ni, up to 365 and 87ppm respectively, and high #Mg values, reaching 0.62 to the less fractionated member. These high Cr and Ni contents and #Mg values are unlikely to be derived from melting of metabasalt. High-Fe metabasalts have Cr (170 ppm), Ni (102ppm) and #Mg (0.49) (Cruz 1993) average values lower than Suite 1. On the other hand, high-Mg metabasalts crop out in a small area near Dianópolis and, therefore, cannot produce large volumes of amphibole granitoids of the the study area. The flat HREE pattern, high Y and Yb contents suggest that hornblende and garnet were not present as residual phases. Retention of both minerals on restite would imply in Y and Yb depleted melts (Hanson 1978, Culler & Graf 1984). Flat HREE pattern are more akin to a pyroxene and olivine-rich restite (Hanson 1978). It seems that an ultramafic source is the most probably one to produce these high-MgO granitic melts.

On Sr/Y vs. Y diagram, Suite 1 plots in the island-arc andesite-dacite-riolite suite field (Fig. 10). Along with low $(La/Yb)_n$ it makes the amphibole bearing quartz-diorite, quartz-monzodiorite, tonalite, granodiorite and trondhjemite similar to modern volcanic arc andesite-dacite-riolite suites. Basaltic magmas fractional crystallisation has been proposed as a TTG forming process (Arth *et al.* 1978, Maaloe 1983, Smith *et al.* 1983). This process would yield gabbro-diorite-tonalite-trondhjemite suite or ophiolite plagiogranites (Coleman & Donato 1979, Aldis 1981). The scanty or lack of intermediate components of fractional crystallisation series led some authors to consider this process secondary in the Archaean (Arth 1979, Glikson 1979). Suite 1 has SiO_2 poor components (54.36%) that can correspond to this intermediate link. Moreover, mantled plagioclase crystals indicate that fractional crystallisation of plagioclase was important to produce quartz-diorites to trondhjemite series.

To sum up, Suite 1 amphibole granitoids have Sr/Y and $(La/Yb)_n$ ratios and Sr and Yb contents that are similar to those of metaluminous low-K calc-alkaline rocks and modern andesite-dacite-riolite volcanic arc suites; their more mafic members (high Cr, Ni and #Mg) were derived from an ultramafic source; hornblende and garnet were not important as restite minerals; fractional crystallisation (e.g. mantled plagioclase) was present to form the quartz-diorite to trondhjemite series.

Suite 2 and RAC have a smaller SiO_2 content variation (59.80-73.81%), which results in the lack of intermediate granitoids. Trondhjemite, tonalite and granodiorite are dominant, but units of monzogranite also occur. As stated before, Suite 2 and RAC are classified as high- Al_2O_3 TTG. The highly fractionated REE pattern, HREE enrichment, Yb and Y depletion and concave HREE pattern of high- Al_2O_3 TTG melts have been explained by amphibole and

Figure 6 - Variation diagrams for the Suite 1 and Suite 2. Symbols as in figure 5.

Table 1 - Range and average major (wt%) and trace element (ppm) analyses of granitic rocks from Almas-Dianópolis region, TO.

	Amphibole Granitoid (Suíte 1)		Ribeirão das Areias Complex		Manto Verde Pluton (Suíte 2)		São Martins Pluton (Suíte 2)		Ponta da Serra Pluton (Suíte 2)		High-SiO ₂ Amphibole Granitoid*		Leuco- Tonalite*
	Range	Average	Range	Average	Range	average	Range	Average	Range	Average	EL-27A	EL-167B	EL-247
SiO ₂	54.36-64.10	59.21	68.85-73.81	70.63	65.80-73.48	70.02	59.80-72.50	66.24	65.02-75.12	71.30	73.98	68.88	70.22
TiO ₂	0.52-0.90	0.72	0.25-0.39	.30	0.08-0.51	.26	0.27-0.66	.45	0.17-0.49	.31	.10	.36	.30
Al ₂ O ₃	13.69-18.13	14.83	12.83-15.80	14.62	13.98-15.95	15.15	14.81- 17.50	16.11	13.60-15.15	14.52	14.58	14.53	15.79
Fe ₂ O ₃	0.46-2.93	1.79	0.98-2.00	1.63	0.49-1.06	.64	0.20-0.93	.48	0.00-1.44	.87	.42	.69	1.15
FeO	3.14-5.84	4.93	0.69-1.53	1.06	0.69-3.16	1.75	1.71-3.86	2.79	0.66-3.63	2.17	.49	2.06	1.08
MnO	0.07-0.15	0.12	0.03-0.05	.04	0.02-0.06	.04	0.02-0.08	.04	0.00-0.07	.02	.02	.09	.00
MgO	3.44-7.35	4.73	0.60-0.89	.69	0.55-1.89	1.06	0.75-4.43	1.97	0.53-3.02	1.30	.44	1.71	.99
CaO	4.48-7.45	5.71	1.63-3.05	2.51	1.21-4.69	2.66	3.14-5.47	3.78	2.51-4.60	3.23	1.21	3.48	3.48
Na ₂ O	2.38-5.78	3.19	4.16-4.90	4.52	3.24-3.98	3.71	3.57-4.15	3.83	2.89-4.18	3.42	5.40	3.81	4.39
K ₂ O	0.95-2.46	1.56	1.09-2.64	2.05	1.71-3.67	2.59	1.12-2.44	1.92	1.76-2.29	1.94	1.58	1.77	1.60
P ₂ O ₅	0.14-0.22	0.18	0.07-0.11	.10	0.04-0.14	.09	0.06-0.46	.19	0.05-0.15	.09	.05	.12	.04
LOI	1.93-5.75	2.82	1.14-1.98	1.41	0.30-1.54	1.09	0.69-2.35	1.29	0.24-2.04	1.29	.98	1.60	1.49
TOTAL	98.73-100.83	99.78	99.01-100.42	99.54	98.55-99.47	99.05	98.26-100.98	99.08	100.06-100.61	100.46	99.25	99.10	100.53
Zn	71-100	86	43-60	51	23-112	62	39-82	66	23-158	54	11	59	27
Co	71-142	96	72-177	109	86-109	101	66-111	89	80-103	92	88	129	100
Ni	30-87	57	3-9	6	10-37	25	8-47	21	3-64	18	-	27	5
Cr	48-365	199	5-11	7	6-55	28	18-71	42	7-154	48	-	50	13
V	74-257	117	22-42	33	12-67	34	36-70	47	-	-	5	38	-
Be	1-3	2	1-2	1	1-3	2	1-3	2	1-2	2	1	2	1
Cu	9-42	22	4-20	9	3-27	12	4-40	14	-	-	-	6	-
Zr	24-117	49	58-88	64	28-72	45	25-51	37	4-87	46	42	59	58
Y	14-28	19	6-8	7	3-8	6	6-50	15	2-9	5	-	24	3
Sr	228-902	457	399-1112	675	504-948	713	500-1132	605	473-492	516	253	698	-
Ba	371-1428	656	412-1732	1034	640-2896	1766	372-1242	644	25-929	506	697	849	-
K/Na	0.13-0.64	0.36	0.15-0.40	.30	0.31-0.75	.47	0.18-0.46	.33	0.29-0.52	.38	.19	.31	.24
Al'	0.58-0.97	0.87	1.01-1.10	1.03	0.97-1.23	1.12	0.95-1.18	1.06	1.02-1.16	1.07	1.14	1.00	1.03
#Mg	0.49-0.75	0.56	0.29-0.37	.33	0.33-0.52	.44	0.40-0.66	.50	0.37-0.52	.41	.47	.53	.45
Sr/Y	8-64	24	49-185	98	63-237	113	6-189	42	55-154	112	-	29	-

Al' = Al₂O₃/(CaO+Na₂O+K₂O)molar; #Mg = MgO/(MgO+FeO)molar.

* Major (%) and trace element (ppm) analyses.

Table 2 - Rare earth element data (ppm) of granitic rocks from Suíte 1 and Suíte 2.

Sample	Suíte 1			Suíte 2			
	EL-18	EL-105A	DI-09	RAC EL-76	SMP EL-117	MVP EL-134	PPS EL-265
La	30.150	18.710	27.250	36.570	13.780	37.940	9.077
Ce	63.380	44.090	60.600	59.890	30.030	74.070	17.280
Nd	29.400	19.020	25.720	21.240	14.930	29.520	6.200
Sm	6.0600	3.396	4.833	3.270	3.490	4.900	1.008
Eu	1.090	1.006	1.014	.670	1.200	1.010	.706
Gd	4.600	2.662	3.631	1.850	2.400	2.870	.709
Dy	3.880	2.347	3.155	.980	1.450	1.650	.533
Ho	.780	.481	.611	.180	.280	.310	.118
Er	2.090	1.359	1.550	.440	.670	.780	.377
Yb	1.490	1.329	1.161	.280	.350	.490	.399
Lu	.200	.161	.152	.060	.070	.090	.081
ΣREE	143.116	94.561	129.677	125.430	68.650	153.629	36.488
ΣLREE	128.994	85.216	118.403	120.968	62.230	146.433	33.565
ΣHREE	13.036	8.339	10.260	3.794	5.222	6.181	2.217
La/Lu	11.085	7.091	8.724	3.226	4.440	5.256	1.885
La/Yb	15.705	12.046	18.584	64.251	21.643	44.691	11.616
Eu/Eu*	.606	.991	.713	.761	1.201	.763	2.434

Eu* = (Sm+Gd)/2

Figure 7 - Chondrite-normalised (Nakamura 1974) rare earth elements for the Suite 1 (a) and Suite 2 and RAC (b). SiO_2 contents displayed.

Figure 8 - Chondrite-normalised (Nakamura 1974) multi-element diagram for the Suite 1(a) and Suite 2 and RAC (b).

Figure 9 - Chondrite-normalised Yb_n vs. $(\text{La}/\text{Yb})_n$ diagram (Jahn et al. 1981) showing three times tectonic fields of Martin (1986). Samples are plotted against the Archaean trondhjemite-tonalite-granodiorite (TTG) field (shaded), post-Archaeon granitic rocks (unpatterned), and the range of MORB values (dark shading). Four partial melting curves from Drummond and Defand (1990) are displayed. Percent partial melt values are listed on each of the model curves.

garnet retention in the restite (Cullers & Graf 1984, Drummond & Defand 1990). On the other hand, amphibole and garnet may contribute to form positive Eu anomalies (Hanson 1978). The partial retention of plagioclase in the restite or its further removal by fractional crystallisation compensates positive Eu anomalies. Plagioclase incorporation in the melt also leads to Sr enrichment (Hanson 1978). Several source rocks were proposed to yield granitoids with low K/Na and high Al_2O_3 , Sr/Y and La/Yb, nevertheless, some experimental data have shown that partial melting of metabasalts seems to be the most likely process to produce this unique chemical characteristic (Rapp et al. 1991, Winther 1996). Subaluminous hornblende in restite would yield Al_2O_3 -rich melts and hornblende absence would yield low- Al_2O_3 melts (Feng & Kerrich 1992).

Figure 10 displays, on the Sr/Y vs. Y diagram, partial melting curves to Archaean mafic rocks and mid ocean ridge basalts (MORB), either leaving eclogite or garnet amphibolite restite. Suite 2 and RAC samples plot mostly close to Archaean mafic rocks partial melting curves and MORB source with eclogitic restite. Suite 2 and RAC derivation from fractional crystallisation of a basaltic magma (Arth et al. 1978, Maaloe et al. 1983, Smith et al. 1983) is improbable due to the absence of intermediate magmas. Suite 1 fractional crystallisation is not regarded as a possible genetic process to yield Suite 2 because Suite 1 has lower Al_2O_3 to similar SiO_2 contents, and Suite 2 becomes HREE richer, rather than HREE

Figure 10 - Y (ppm) vs. Sr/Y diagram with basalt partial melting curves leaving either 10% garnet amphibolite or eclogite restite assemblages (Drummond & Defant 1990). Percent partial melt values are listed on each of the model curves.

depleted, with increasing SiO_2 content. The varied trace and major element behavior of Suite 2 plutons, K/Na ratios for instance, may be devoid to a range of factors. According to Rapp *et al.* (1991), higher K_2O contents depend on smaller partial melting rates of source rock (i.e. metabasalts). Besides that, field description of granulite and gneiss enclaves near the study area (Correa Filho & Sá 1980, Costa 1984) may indicate the existence of an older sialic basement, as suggested by Borges *et al.* (1991). It is possible that crustal assimilation, continental crust partial melting and some degrees of fractional crystallisation (De Paolo 1981, Hildreth & Moorbath 1988) were effective processes during Suite 2 evolution. In summary, Suite 2 and RAC have low K/Na and high Al_2O_3 , Sr/Y and $(\text{La}/\text{Yb})_n$ typical of high- Al_2O_3 TTG suites. The most likely process to produce these melts is metabasalts partial melting, leaving either eclogitic or garnet amphibolite restite. Secondary processes as varied partial melting rate, crustal assimilation, continental crust partial melting and fractional crystallisation may have resulted in the small differences among Suite 2 plutons.

TECTONIC IMPLICATIONS Chemical data indicate that two different sources contributed to form the granite-gneiss complexes. Suite 1 amphibole granitoids (2.2Ga) were derived from an ultramafic, and pyroxene was a more important restite mineral than hornblende or garnet. From these, we infer that direct mantle partial melting or fractional crystallisation of mantle derived basaltic magmas produced Suite 1 metaluminous melts. Drummond and Defant (1990) proposed that mantle edge above subduction zones as the source of low- Al_2O_3 calc-alkaline granitoids. Tonalites and granodiorites generated by mantle derived monzodiorite fractional crystallisation are described in Superior Province, Canada (Sutcliffe *et al.* 1990, Stern & Hanson 1991, Feng & Kerrich 1992). Late Archaean granitoids are also associated with mantle derived basic magmatism (Sutcliffe 1989), therefore, mantle derived granitoids are found since Archaean to present times. We propose that Suite 1 amphibole granitoids were derived from a mantelic source as proposed to other Archaean high-Mg amphibole bearing-granitoids (Stern & Hanson 1991).

Partial melting of basic rocks has been proposed as the most

likely process to produce high- Al_2O_3 TTG melts (Barker & Arth 1976, Barker *et al.* 1981, Martin *et al.* 1983, Rapp *et al.* 1991, Glikson 1976, Jahn *et al.* 1981). However, contrasting tectonic settings can be suitable to this process. The partial melting of subducted oceanic lithosphere has been proposed as the most efficient process to allow continuous recycling of the basaltic source (Martin 1987, Arkani-Hamed & Jolly 1989, Drummond & Defant 1990). According to this idea, during the Archaean, the subducted lithosphere was young and hot, thus partial melting of subducted slab was possible at lower temperature before dehydration occurred (Martin 1993). Trace element data from garnet and clinopyroxene inclusions in diamond were interpreted as consistent with eclogite forming in equilibrium with Archaean tonalitic and trondhjemitic magmas (Ireland *et al.* 1994). On the other hand, some writers argued that partial melting of newly underplated basaltic crust might have produced high- Al_2O_3 TTG in subduction zones (Atherton & Petford 1993, Wolde *et al.* 1996). Figueiredo *et al.* (1997), studied high alumina basalt of the Santa Catarina granulitic complex and concluded that subduction of cold, hydrated ocean crust followed by its dehydration, invasion of the overlying mantle prism by the released fluids and partial melting of mantle peridotite to yield mafic magmas with very high Al contents could have occurred during the late Archaean, when the more common process was direct melting of the hot, anhydrous subducted slab to yield tonalities and related magmas.

Apart from the diverse source rocks and processes proposed to yield low-K calc-alkaline melts, there is a convergence in the fact that volcanic arcs are the tectonic setting where these sodic granitoids are generated. From our data we propose that two source rocks contributed to build the wide granite-gneiss complexes of Almas-Dianópolis region at 2.2Ga and 2.46 Ga. Furthermore, we infer that a subduction zone is the suitable tectonic setting to yield these rocks from partial melting of mantle wedge over subduction zones, in the case of Suite 1, and from either subducted oceanic slab or newly underplated basaltic crust, in the case of Suite 2 and RAC. Magma generation sites in modern volcanic arcs occur since subducted oceanic slab to the bottom of continental crust, passing through overlying mantle wedge (Wyllie 1988), and our data indicate that these processes may have also operated in the Paleoproterozoic.

CONCLUSIONS Field and petrological data on granite-gneiss complexes of Almas-Dianópolis region indicate that they are composed of isotropic to weakly foliated granitoid plutons with local gneissic banding and that tonalite, trondhjemitic, and granodiorite are dominant units. Localized gneiss banding occurs, though. The relatively high Mg, Cr and Ni contents, low-Al trondhjemitic trend (i.e. low-Al TTG), and relatively low Sr/Y and $(\text{La}/\text{Yb})_n$ ratios of Suite 1 amphibole granitoids strongly suggest that they were derived from partial melting of a ultramafic source living a restite of pyroxene and olivine. As proposed to other low-Al TTG melts (Drummond & Defant 1990), we infer that mantle wedge over subduction zone was the most likely source. On the other hand, the high-Al trondhjemitic trend (high-Al TTG) and higher Sr/Y and $(\text{La}/\text{Yb})_n$ of Suite 2 and RAC granitoids indicate a basaltic source living a garnet amphibolite or eclogite restite. This basaltic source could be either a subducting oceanic lithosphere or a newly underplated basaltic crust. Thus, these chemical data imply that subduction-related process were operating in the northwestern margin of São Francisco Craton since very late Archaean through Paleoproterozoic.

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