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# $^{40}$Ar/$^{39}$Ar Cooling Ages of the Paraguay Belt in the Nova Xavantina Region (MT): Tectonic Implications for Western Gondwana Collage

## Idades de Resfriamento $^{40}$Ar/$^{39}$Ar da Faixa Móvel Paraguai na Região de Nova Xavantina (MT): Implicações Tectônicas para a Colagem do Gondwana Ocidental

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## Abstract

$^{40}$Ar/$^{39}$Ar analysis were carried out on biotite crystals from the Paraguay Belt rocks in Nova Xavantina region (Mato Grosso State, Brazil) with the purpose to constrain the age from the regional metamorphic event. The samples are metavolcanic mafic rocks deformed during Brasiliano-Panafrican events. The $^{40}$Ar/$^{30}$Ar plateau ages range from 541.6 ± 0.4 Ma to 531 ± 0.6 Ma and define the cooling period of regional metamorphic event related to the collision between the Amazonian craton and Paranapanema block, the final stages of the western Gondwana assembly. The Paraguay Belt association cropping out in this region comprise metamorphosed sedimentary (chemical and siliciclastic) and volcanic (basic and intermediary) rocks related to an ocean floor geological setting (Xavantina Ocean). This work presents two new ages for two biotite grains and compares with literature data suggesting that the $^{40}$Ar/$^{39}$Ar data here reported and geological evidence indicates that the metabasic rocks present metamorphic ages in the range from 541 Ma to 531 Ma and their protolith about 700-648 Ma or older.

**Keywords:** $^{40}$Ar/$^{39}$Ar; Metamorphism; Paraguay Belt; Western Gondwana

## Resumo

A análise $^{40}$Ar/$^{39}$Ar foi realizada em cristais de biotita das rochas do Cinturão Paraguai na região de Nova Xavantina (Mato Grosso, Brasil) com o objetivo de compreender a idade do evento metamórfico regional. As amostras são rochas máficas meta-vulcânicas deformadas durante eventos Brasiliano-Panafricano. As idades *plateau* $^{40}$Ar/$^{39}$Ar variam de 541,6 ± 0,4 Ma para 531 ± 0,6 Ma e definem o período de resfriamento do evento metamórfico regional relacionado à colisão entre o Cráton Amazônico e o Bloco Paranapanema durante os estágios finais da montagem ocidental do Gondwana. A associação do Cinturão Paraguai que se destaca nesta região compreende as rochas sedimentares metamorfisadas (químicas e siliciclásticas) e vulcânicas (básicas e intermediárias) relacionadas ao ambiente geológico do assoalho oceânico (Oceano Xavantina). Este trabalho apresenta duas novas idades para dois grãos de biotita comparando-os com dados da literatura sugerindo que os dados $^{40}$Ar/$^{39}$Ar aqui relatados, além de evidências geológicas, indicam que as rochas metabásicas apresentam estágios metamórficos no intervalo de 541 Ma e 531 Ma e seus protólitos apresentam idades em torno de 700- 648 Ma ou mais.

**Palavras-chave:** $^{40}$Ar/$^{39}$Ar; Metamorfismo; Cinturão Paraguai; Gondwana ocidental

## 1 Introduction

The Paraguay Belt developed on the border of the Amazonian Craton (Figure 1) and comprises a roughly N-S (southern sector) and E-W (eastern sector) trend of approximately 1500 Km long and 300 Km wide. The origin of this fold belt is related to the Neoproterozoic collision of the Amazonian Craton, the Paranapanema cratonic fragment and the Rio Apa Block during the Gondwana assembly (Trompete, 1994; Campos Neto, 2000; Alvarenga *et al.,* 2000). These Brasiliano orogenies were diachronic, many of which were coeval with taphrogenic processes elsewhere, and the plurality of processes converged to the closure of many oceans and to the collage of the continental fragments (terranes or micro-continents).

Within the Brazilian Platform, this collage continued at least 400 Ma until the Lower Ordovician (Campos Neto, 2000). For example, the closure of the Goianides Ocean probably started at 930 Ma, the Mara Rosa Arc according to Pimentel & Fuck (1992) and the youngest metamorphic event reported in that area is represented by the 520 Ma Buzios Orogeny (Schmitt *et al.,* 2004).

One of the most significant advances in geochronology in the past decade has been the development and dissemination of fully automated laser heating $^{40}$Ar/$^{39}$Ar analysis. The $^{40}$Ar/$^{39}$Ar method is a versatile tool suitable for the study of a diverse range of geological processes, such as thermochronology of metamorphic terrains (Harrinson & McDougall, 1982; McDougall & Harrison, 1999) and thermochronology of shear zones (Goodwin & Renne, 1991; Lee, 1995). The establishment of the metamorphic rocks thermal history requires integrated geological and dating studies, using different chronometers to cover the complex range of processes and temperatures conditions. The $^{40}$Ar/$^{39}$Ar method plays important roles in many aspects of such dating. In low-grade terranes, as in Paraguay Belt rocks, it may be possible to date the cooling time of the regional metamorphism with $^{40}$Ar/$^{39}$Ar method using minerals that have grown or reset during thermal event. This work presents $^{40}$Ar/$^{39}$Ar data determined on the Paraguay Belt metamorphic rocks related to the Brasiliano-Panafrican event, in the Nova Xavantina region, Mato Grosso State, Brazil, focusing on better constrain the timing of metamorphic event and discuss the tectonic implications.

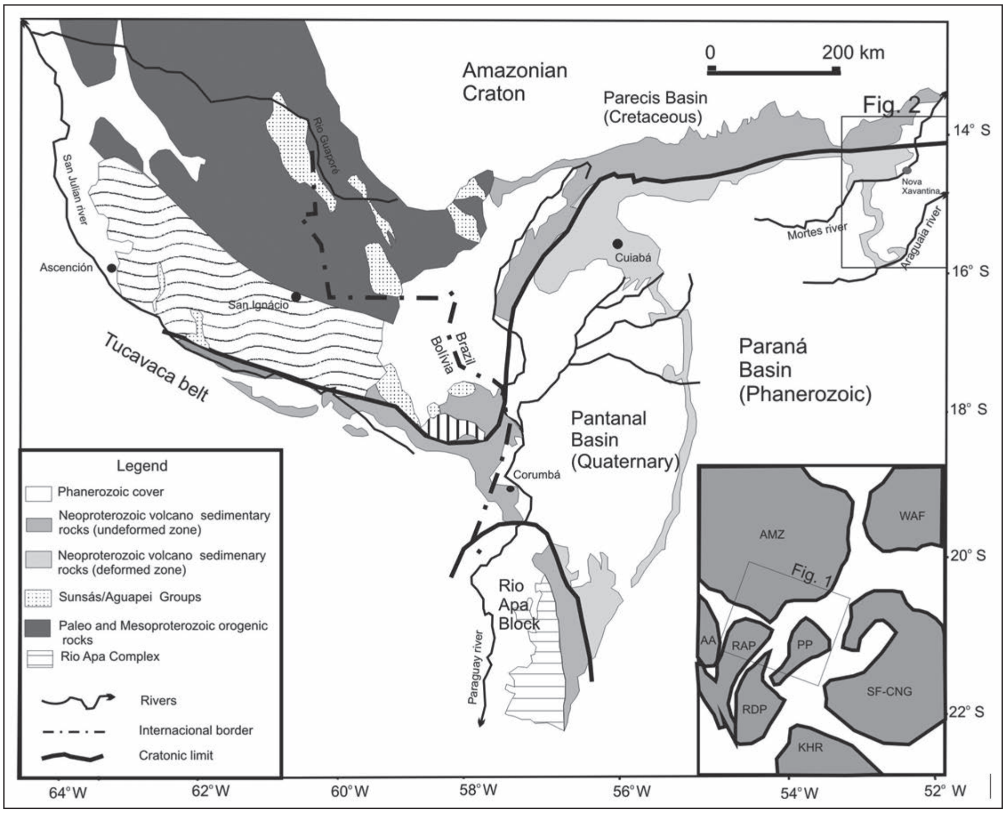

Figure 1 Regional setting of the Paraguay Belt. The Paraguay Belt rocks may be divided into undeformed sedimentary rocks (Amazonian Craton cover) and deformed sedimentary rocks, corresponding to the orogenic external and internal zones, respectively (modified from Geraldes *et al*., 2008).

## 2 Geological Settings

The Neoproterozoic Paraguay Belt and its corresponding cratonic cover were formed on the southern margin of the Amazonian Craton (Figure 1) deposited and subsequently metamorphosed at greenschist facies conditions (Almeida, 1984). The sedimentary sequences deposited on the southeastern and southern portion of the Amazonian craton comprise limestones, laminated siltstones and sandstones (Cuiabá Group), carbonates (Corumbá Group), and siliciclastic rocks (Boquira and Alto Paraguay Groups). Bonhomme *et al.* (1982) reported a Rb-Sr isochron at 568 ± 20 Ma for shales from the top of the Alto Paraguay Group, interpreted as diagenetic age.

Deformation in the belt increases from west to east. In the Craton, the sedimentary rocks are gently folded with open folds on the border and within the belt the rocks are tight folds with associated cleavage. Hasui & Almeida (1970) reported a K-Ar age of 549 Ma for this metamorphic event determinated on metasedimentary rock from the Cuiabá Group. Martinelli (1998) suggested that the metamorphic evolution characterized by the greenschist facies was synchronous with the main deformational phase, in agreement with Alvarenga *et al.* (2000). The regional vergence of the belt is towards the Amazonian Craton, as observed in the Cuiabá Group (NE-verging folds) and the Alto Paraguay Group. According to Alvarenga *et al.* (2000), this belt represents a young Brazilian tectonic unit formed by Vendian to Early Cambrian sediments, which were deformed between 550 Ma and 500 Ma and intruded by post-orogenic granites ca. 500 Ma (Bonhomme *et al.,* 1982).

## 3 Local Geology

In the Nova Xavantina Region (Figure 2), the Paraguay Fold Belt is comprised of a volcanic sequence that some authors correlate it to the Cuiabá Group (Silva *et al.,* 1974; Pinho, 1990). The sequence is composed of mafic to ultramafic rocks affected by low-grade metamorphism, related to the Brasiliano (Pan African) event (Pinho & Pinho, 1990). However, the stratigraphic position of the metavolcanics observed in the studied area is still debatable, and has being considered as representative of the Cuiabá Group basement by Almeida (1984) and Ruiz & Santos (1999). The lack of geochronological data from this unit does not allow better age constraint.

The metamorphosed volcano-sedimentary rocks in the studied area crop out in a structural window characterized by thrust fault-contact with sediments of Alto Paraguay Group (Martinelli & Batista, 1990). This sequence consists of glaciomarine beds and sediments of turbidite character with glacial affinities overlain by the carbonate unit, followed by a pile of siliciclastic rocks (Alvarenga, 1990). In the western area, the Ponta Grossa Formation (Devonian rocks from Paraná Basin) occurs as isolated outcrops covers (Martinelli, 1998). Cenozoic sediments cover the eastern limit of the Paraguay fold belt with the Brasilia Belt (Goiano Complex) (Pimentel *et al*., 1996; Figure 2).

Local studies carried out by Pinho (1990) defined the Nova Xavantina meta-volcanosedimentary sequence based on petrographic and lithogeochemical analysis. Martinelli (1998) reported detailed petrographic studies and concluded that the protoliths of the metamorphic units are phyllites, graphitic phyllites, cherts and banded iron formations; siliciclastic sedimentary rocks such as quartz-phyllites, quartzites and conglomerates; and volcanic units comprised of ultramafic, mafic and intermediate rocks.

Plagioclase chlorite-schists are observed with local occurrence of quartz, sericite and carbonate. Schists may be coarse-grained with chlorite associated with sericite and pyrite and minor minerals as zircon, apatite and titanite. Amphibolite and meta ultrabasic rocks are subordinated units interleaved within in the mica-schists. They present nematoblastic texture where biotite predominates over plagioclase, with quartz, titanite, biotite and epidote as accessory minerals. Martinelli (1998) reported andesitic rocks with feldspar (30%), quartz (30%), sericite (25%), carbonate (10%) and as minor minerals (5%) zircon, apatite and pyrite. Preserved pyroclastic fabric is represented by lapilli-tuffs with feldspar (sericitized) and quartz associated to fine-grained sericite and quartz probably deposited as ash flow. The predominant rocks are phyllite constituted by sericite, quartz-sericite and eventually iron-rich layers. They may show centimetric crystals of pyrite or magnetite. Carbonaceous layers are common but rarely exceed 10 cm. Some volcanic-derived rocks may show aspects very similar to these phyllitic rocks, and they may be indistinguishable from phyllitic rocks due to deformation and metamorphism. Quartzite beds may occur as thick as 10 m, usually with fine-grained and small layers of phyllite. Banded iron formations present wide distribution and occur as intercalated layers of magnetite and reddish quartz. Quartz bands may locally predominate in relation to magnetite layers. Microscopic studies indicate martite, hematite, pyrite and limonite as major minerals (Martinelli & Batista, 1992).

The primary structures (such as parallel bedding) are mainly observed in the BIF's, quartzites and phyllites and are subparallel to the sedimentary bedding occurs the penetrative foliation. This foliation was interpreted by Martinelli *et al.* (1998) as the result of deformation (Araés shear zone) during the regional metamorphism. Both main the foliation and

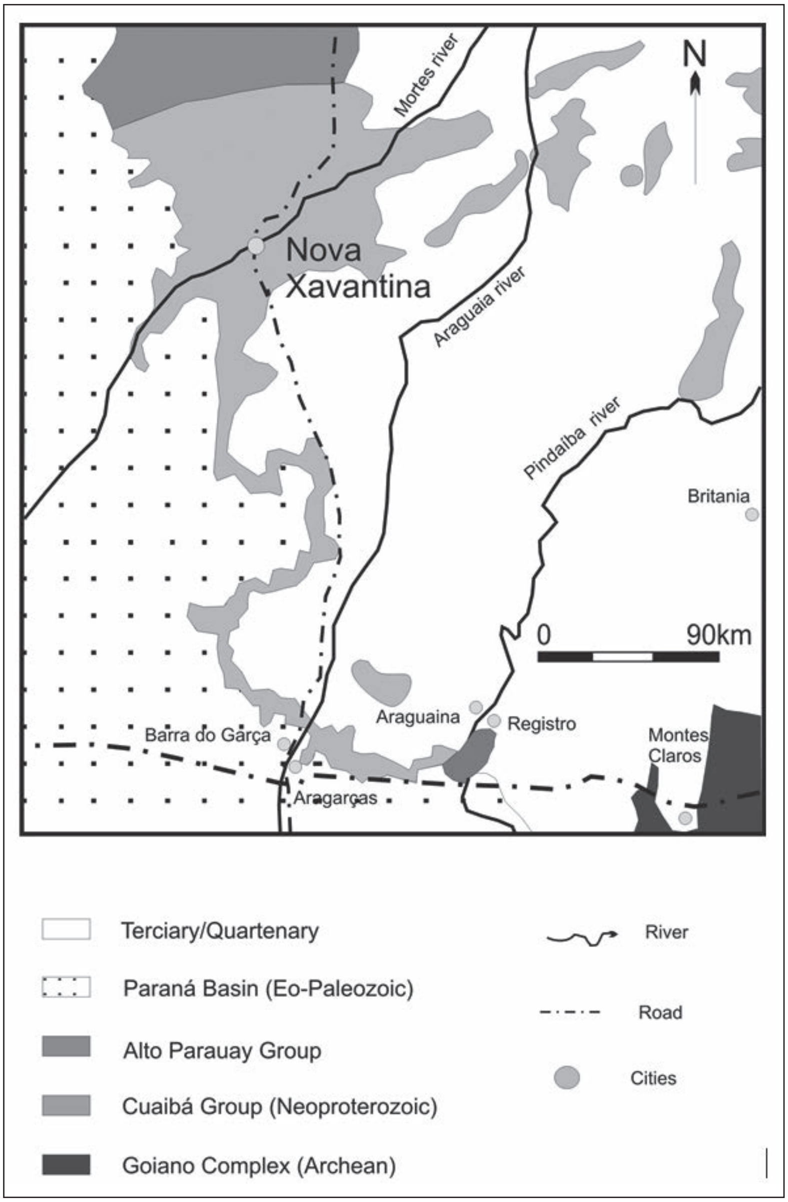

Figure 2 Regional geologic map of Nova Xavantina Region modified from Martinelli (1998). The Paraguay Belt (Cuiaba Group) rocks are partially covered: Cenozoic sediments (East), Paleozoic Paraná Basin rocks (West) and Alto Paraguay undeformed sedimentary rocks (North).

the bedding (both locally with W-E) strike are deformed in open fold axial planes with NW-trending.

## 4 Analytical Methods

The samples from the Paraguay Belt are from the Araés gold deposit area; two open pits and shafts. The metabasites samples were crushed and sieved at 30-60 mesh, and the biotite crystals were separated from quartz and oxides by handpicking under a binocular microscope.

Four grains of biotite from the metabasites the Ar isotope composition of were determined at the CPGeo-USP $^{40}$Ar/$^{39}$Ar laboratory. The grains were irradiated, together with appropriate neutron flux standards, at the IPEN/CNEN IEA-R1 nuclear reactor. The samples and standards were placed inside aluminum containers. The standard used was the biotite GA-1550 (McDougall & Harrison, 1999), and the age adopted of 98.8 ± 0.5 Ma was suggested by Renne *et al.* (1998). The samples and standards were placed in irradiation disks, closed with appropriate lids, and placed into a silica tube maintained under vacuum. The sealed vial is placed inside a 1.5 mm wall Cd-container (ensuring that the samples are not exposed to excessive heating during encapsulation), which was finally placed in a rotable system to ensure that each position in the irradiation disks receives the same neutron dosage. This rod was placed in the irradiation position just outside the reactor core for 30 hours.

The argon extraction line is equipped with a home built fully automated noble gas extraction and purification system. The system is composed of an optical table, where sample visualization and gas extraction by a 6-W continuous Ar-iron laser bean occurs, and a stainless steel ultra-high vacuum gas purification system equipped with a Polycold Cryocooler and two C-50 Fe-Ti-Zr SAES getters. The step-heating procedure was used, in which laser output power is computer-driven to a predetermined value and maintained at that intensity for 30-60 seconds. This procedure is repeated several times for each sample, at progressively higher laser output power. Because of this procedure, several fractions of the Ar gas contained in the sample are extracted at progressively higher temperature. Each Ar gas fraction obtained separately is analysed in the mass spectrometer, yielding separated results, which are plotted in the apparent age *versus* % $^{39}$Ar released diagram. If 50% of the released gas yields the same age (within errors) a plateau age is defined. If less than 50% of the released gas is within errors a forced plateau is defined. The integrated age comprises the average of all gas fractions released during the step-heating technique.

The samples were analyzed at the Mass Analyser Products (UK) MAP-215-50 mass spectrometer with 15 cm radius with extended geometry and 50 mm 90$^{o}$ sector electrostatic analyser equiped with a Nier-type source. The mass spectrometer houses two independent collectors, a Faraday collector positioned on the high-mass side of the optic axis and a Balzers 217 electron multiplier positioned on the low-mass side. A fixed collector slit enables mass resolution of all Argon peaks from their nearest-neighbor hydrocarbon interferences. The laboratory is fully automated through Mass Spec version 5.11, a Macintosh MS Basic software written specifically for $^{40}$Ar/$^{39}$Ar analysis and data reduction (Deino, 1996; unpublished software manual; personal communication in LaGarry, 1998). Blanks were measured between each step of the step-heating procedures. Procedures details may be obtained in Vasconcelos *et al.* (2002).

## 5 Results

The results of the $^{40}$Ar/$^{39}$Ar analysis of two biotite grains from two metabasites samples are reported beyond two data from literature for comparison. The results (Table 1) of each grain is presented individually.

Sample AR-105 is a metabasic rock collected from a 40 m deep shaft. One grain of biotite from this sample was analyzed and yielded a plateau age of 553.8 ± 0.5 Ma interpreted as cooling age of the sample analysed. The step heating spectrum of grain 2 was built with 13 steps and the results are plotted in the cumulative $^{39}$Ar released *versus* apparent age (Ma) yielded an integrated age of 567.2 ± 0.4 Ma (Figure 3). The integrated age of 567.2 ± 0.4 Ma is anomalously high and the spectrum “saddle” form

| Sample | $^{40}$Ar/$^{39}$Ar | $^{38}$Ar/$^{39}$Ar | $^{40*}$Ar/$^{39}$Ar | %rad. | Laser (W) | Age (Ma) | Error (Ma) | $^{40}$Ar (mols) |
|---|---|---|---|---|---|---|---|---|
| AR-107 - biotite grain 2 | 32.36052 | 0.01854 | 20.34017 | 62.9 | 0.30 | 485.03 | 4.87 | 8.40E-15 |
| | 26.80149 | 0.01455 | 23.43229 | 87.4 | 0.50 | 548.55 | 2.37 | 1.67E-14 |
| | 24.07508 | 0.01132 | 23.44815 | 97.4 | 0.80 | 548.87 | 0.99 | 7.65E-14 |
| | 23.29139 | 0.01109 | 23.17813 | 99.5 | 1.20 | 543.41 | 0.93 | 1.33E-13 |
| | 23.02268 | 0.01083 | 22.88403 | 99.4 | 1.80 | 537.45 | 2.33 | 1.56E-13 |
| | 23.87472 | 0.01125 | 23.71427 | 99.3 | 2.40 | 554.23 | 1.21 | 6.89E-14 |
| | 24.28474 | 0.01181 | 24.03521 | 99 | 2.80 | 560.68 | 1.29 | 2.27E-14 |
| | 24.36478 | 0.01149 | 24.29040 | 99.7 | 3.60 | 565.79 | 1.71 | 1.43E-14 |
| | 24.44530 | 0.01193 | 24.24142 | 99.2 | 4.40 | 564.81 | 1.91 | 1.33E-14 |
| | 25.64641 | 0.01145 | 25.54206 | 99.6 | 5.00 | 590.64 | 2.1 | 2.06E-14 |
| | | | | | | | | |
| AR-105 - biotite grain 2 | 30.38431 | 0.01227 | 29.65008 | 97.6 | 0.20 | 669.89 | 1.86 | 2.28E-14 |
| | 56.96682 | 0.07235 | 43.98044 | 77.1 | 0.40 | 921.89 | 58.68 | 5.27E-16 |
| | 161.71860 | 0.51520 | -8.65968 | -5.3 | 0.60 | -253.99 | 2855.77 | 1.43E-16 |
| | 44.52562 | 0.05561 | 9.88043 | 22.1 | 0.80 | 251.89 | 321.77 | 9.46E-17 |
| | 87.80953 | 0.13728 | 176.9202 | 201.5 | 1.00 | 2352.02 | 777.24 | 3.60E-17 |
| | 71.19822 | -7.40545 | 1874.2790 | 2632.5 | 1.20 | 6101.01 | 11869.83 | -1.35E-19 |
| | -18.87752 | 0.00434 | -101.4527 | 488.4 | 1.50 | 0 | 4834.03 | 2.72E-18 |
| | 15.91056 | 0.24903 | 45.70024 | 283.7 | 1.80 | 949.9 | 1809.5 | 7.76E-18 |
| | 3.14652 | 0.16140 | -107.0641 | -3316.2 | 2.10 | 0 | 5098.35 | 3.05E-18 |
| | 21.22498 | 0.80598 | -259.2466 | -1221 | 2.50 | 0 | 1142.57 | 7.02E-18 |
| | 58.56049 | -0.06192 | -54.13731 | -92.4 | 3.00 | -3103.6 | 12029.38 | 2.92E-17 |
| | 25.01712 | 0.06125 | -22.09639 | -87.5 | 4.00 | -736.23 | 429.54 | 6.81E-17 |
| | 234.1684 | -0.06253 | 207.99260 | 88.8 | 5.00 | 2569.23 | 125.13 | 8.11E-16 |

Table 1 Ar isotopes results from Paraguay Belt rocks.

may indicate Ar excess or partially overprinted biotite (Figure 3; see text for discussion).

The sample AR-107 is also a metabasite sampled from a 60 m deep open-pit. One grain of biotite was analyzed and yielded an apparent age of 648 ± 12 Ma which is equivalent to K-Ar age and it is meaningless for the studied case (see text for discussion). The flat plateau form reflects the fact that practically all Ar was released from only one step heating. The step-heating spectrum of grain 2 was built with two steps and the results when plotted in the cumulative $^{39}$Ar released *versus* apparent age (Ma) yielded an integrated age of 684 ± 12 Ma. Practically all the argon released was obtained from the first step, producing a total-fusion equivalent analysis (Figure 4).

## 6 Discussion

The $^{40}$Ar/$^{39}$Ar step-heating dating here presented indicates that the complex crustal evolution of the Paraguay Belt requires high analytical precision and improved spatial resolution. The apparent age (Ma) *versus* cumulative % $^{39}$Ar released diagrams show complex patterns and their interpretations need accurate analysis.

However, the biotite grain from samples AR-105 analyzed in this work yielded a disturbed argon step-heating spectrum that is quite complex and present a marked “saddle” shape (see Figure 3). Anomalously high ages are obtained at both low and high temperatures of the gas released and that this spectrum pattern occurs because the mineral may trap argon that was not generated by *in situ* decay of $^{40}$K, presenting a $^{40}$Ar/$^{39}$Ar ratio greater than the present-day value of 295.5. The excess argon may occur during crystallization and subsequent cooling of the mineral or during some later thermal/metamorphic event, due the presence of an external high partial-pressure of argon. Since such excess argon

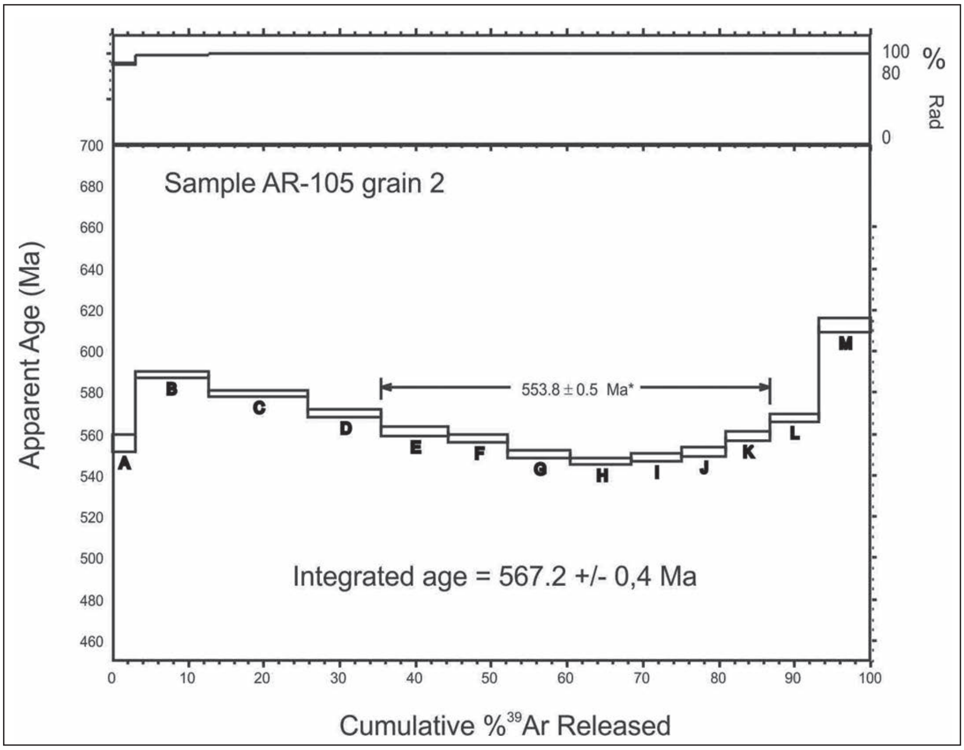

Figure 3 Sample AR-105 Grain 2. Apparent age *versus* cumulative %$^{39}$Ar released diagram. Integrated age is showed in the diagram.

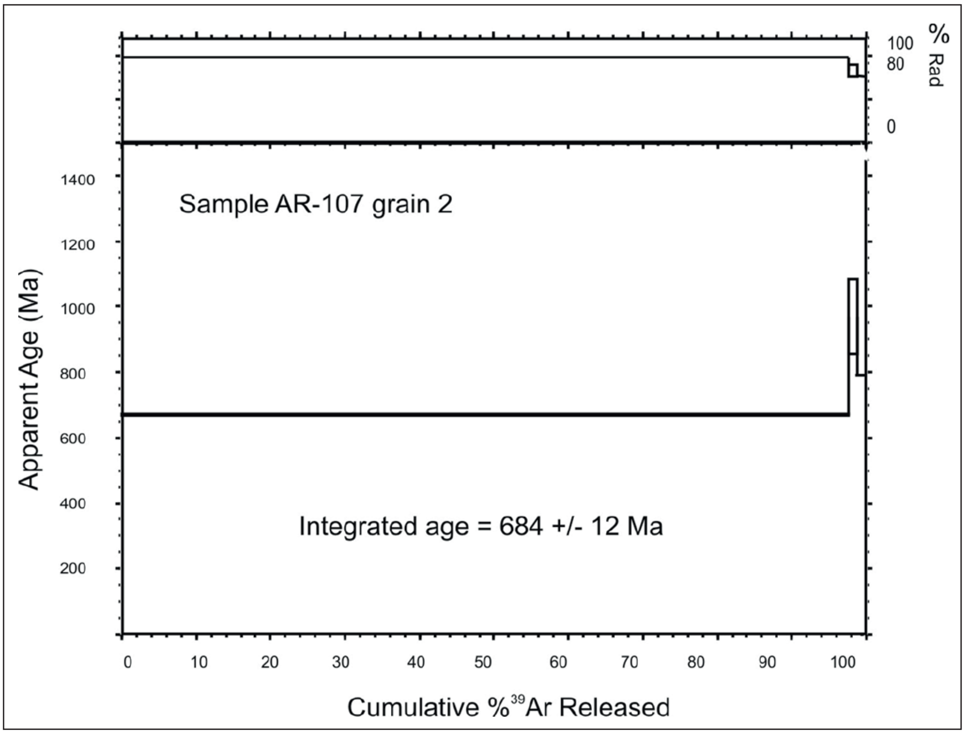

Figure 4 Sample AR-107 Grain 2. Apparent age *versus* cumulative %$^{39}$Ar released diagram. Integrated age is showed in the diagram.

was not observed in the isotopic ratios obtained during the present experiment (no $^{39}$Ar/$^{40}$Ar > 295.5), probably each step-heating gas fraction is likely to have sampled a distinct Ar reservoir in the biotite grain due partial reset. Consequently, for the sample AR-105 (second grain), the calculated integrated age is anomalously high and geologically meaningless. Geraldes *et al*. (2008) yielded a $^{40}$Ar/$^{39}$Ar plateau age of 531 ± 0.6 Ma and an integrated age of 539.3 ± 0.5 Ma for a second biotite grain of the same sample, presenting a geological meaning that is interpreted as the cooling age related to the regional metamorphic event.

From the second sample (AR-107), one grain was analyzed by $^{40}$Ar/$^{39}$Ar step-heating technique and another result from literature and both present two different spectra. The grain analyzed in this work had only two steps analyzed, yielding an integrated $^{40}$Ar/$^{39}$Ar age of 684 ± 12 Ma (Figure 4). The spectrum obtained is equivalent to $^{40}$Ar/$^{39}$Ar total-fusion or K-Ar dating technique (Harrison & McDougall, 1982; Krigfield *et al.,* 1986; Kirschner *et al*., 1996).

Geraldes e*t al.* (2008) obtained a forced plateau age of 541 ± 0.7 Ma and an integrated age of 553.7 ± 0.6 Ma. The spectrum shows higher ages in the first five steps where ages reach 700 Ma, indicating argon excess in the biotite grain. These ages probably represent two $^{40}$Ar reservoirs: one has $^{40}$Ar/$^{39}$Ar age of ca. 541 Ma and the second has age ca. 700 Ma or older. Consequently, $^{40}$Ar/$^{39}$Ar total-fusion age is meaningless in the studied case, since it is the mixture of two Ar reservoirs. The obtained spectrum may be interpreted as mixing of two Ar reservoirs: one older, whose isotope composition indicates the pre-metamorphic age of the biotite grain; and the second probably presents the Ar isotopic reset during the last thermal event. Consequently, the step-heating fraction with young ages (as the age obtained by the forced plateau ca. 541 Ma; Geraldes *et al*., 2008) may be interpreted as the cooling age of the regional metamorphic event.

It was recognized by Merrihue & Turner (1965) that $^{40}$Ar/$^{39}$Ar analysis of a single grain can provide information on its thermal history if the sample is analysed by the step heating method. In addition, the plateau spectrum is interesting, but not sufficient to fulfill all necessary information about the thermal history of a polycyclic terrane. However, if the sample have experienced a later thermal disturbance that has caused $^{40}$Ar resetting, the step-heating experiment may sample the Argon reservoirs, producing diffusion-loss profiles and allowing the interpretation that the distinct Ar isotopic composition corresponds to different thermal events (as cooling and reheating) and consequently yielding their respective ages.

The disturbed spectrum showed in sample AR-107 grain 2 and sample AR-105 grain 2 provide useful geochronological data from diffusive-loss profiles and suggest a coherent thermal history of both metabasic samples. Altogether, the compiled data from Geraldes *et al*. (2008) and the new two $^{39}$Ar/$^{40}$Ar steps-heating here presented, suggest metamorphic ages in the range from 541 ± 0.7 Ma to 531 ± 0.5 Ma, that reflect the cooling time, probably linked to the regional thermal event related to Amazonian craton and Paranapanema block collision.

The Paraguay Belt rock association reported in Nova Xavantina region (Martinelli & Batista, 1990; Martinelli, 1998; Geraldes *et al.,* 2001) comprises metamorphosed sedimentary (chemical and siliciclastic) and volcanic (basic and intermediary) rocks related to an ocean floor geological setting. These metabasic rocks present isotopic reservoir of about 648-700 Ma or older and we may admit these rock associations indicate the basement rocks of the Cuiaba Group as postulated by Almeida (1984) and Ruiz & Santos (1999). This hypothesis is corroborated by the extensive continental margin sedimentary sequences represented by the Cuiabá, Corumbá, Boquira and Alto Paraguay groups and it agrees with the Rb-Sr isochronic age of 568 ± 20 Ma reported by Bonhomme *et al.* (1982) interpreted as diagenetic age of the Alto Paraguay group shales.

## 7 Tectonic Implications

As discussed above, the $^{40}$Ar/$^{39}$Ar dating here presented for the Paraguay Belt rocks in the Nova Xavantina region indicates cooling ages in the range from 541.1 ± 0.7 Ma to 531.3 ± 0.5 Ma. The regional metamorphism event is related to the final stage of the western Gondwana collage. This collage was the result of the assembly of cratonic fragments, with special regard to Precambrian of the South America Platform, related to the continental lithosphere plates (Brito Neves & Cordani, 1991; Brito Neves *et al.,* 1999) that were rifted apart during the Rodinia break-up at the beginning of the Neoproterozoic

(Dalziel, 1997; Weil *et al.,* 1998). Successive collision and plate indentation processes during the Brasiliano-Pan African Orogeny formed the Gondwana Supercontinent (Almeida *et al.,* 2000; Campos Neto, 2000; Alkmin *et al.,* 2001).

The oldest pre-collisional activity in South America platform is recorded in the Brasilia Belt, with the development of the Mara Rosa magmatic arc at ca. 930-820 Ma (Pimentel & Fuck, 1992) and the closure of the Goianides Ocean. Continental collision in this belt started at ca. 760 Ma with the dockage of Archean and Mesoproterozoic terranes (Figure 5A). The Brasilia Belt (including older terranes) was the result of the ca. 630 Ma collision of the São Francisco Craton and the Rio de la Plata Craton (and its probable extension represented by the Rio Apa Block, a cratonic fragment underlying the sedimentary rocks of the Paraná Basin). In southern Brazil occurred the São Gabriel magmatic arc at ca. 750-700 Ma (Babinski *et al.,* 1996), indicating an ocean closure, probably an extension of the Goianides Ocean, and starting the assembly of Rio de la Plata and Luis Alves cratonic fragments.

According to Valeriano *et al.* (2002) and Tupinambá *et al.* (1998), in the southeastern region of Brazil, the Ribeira-Araçuaí Belt shows pre-collisional lithospheric convergence with the development of the Rio Negro magmatic arc (640-595 Ma). As oceanic lithosphere was consumed, collision and thrusting of the Rio Negro magmatic arc and its basement onto the eastern-southeastern margin of the São Francisco craton took place at 595-530 Ma (Figure 5B). The youngest accretionary event (Buzios Orogeny) recorded in SE Brazil was the docking of the Cabo Frio terrane (530-480 Ma) onto the previously accreted domains (Schmitt *et al.,* 2004).

Following the crustal history cited above, the collision of the southern region of the Amazonian craton occurred not only with the Paranapanema cratonic fragment. At that moment (541-531 Ma) important terranes and microplates had already assembled. Probably the São Francisco craton was joined to Rio de La Plata cratonic fragments (Figure 5C). In this way the Amazonian craton collided at 541-531 Ma with this continuous continental mass (São Francisco-Rio de la Plata-Luis Alves). In addition, the Rio Apa Block collided to the Rio de La Plata Craton and originated the southernmost branch of the Paraguay Belt (Trompete *et al*., 1999) (Figure 5C); and the collision between the Rio Apa Block and Amazonian Craton originated the western branch of the Paraguay Belt denominated as Tucavaca (Litherland *et al.,* 1986) (Figure 5C). Practically, simultaneously to these collisions, there occurred the collision of the last accretion of Ribeira Belt in SE Brazil (Buzios Orogeny), corresponding to the collision of the Congo Craton and the São Francisco Craton (Figure 5C). Probably, at the end of these two last orogenies (Figures 5E and 5F), the Gondwana Supercontinent was formed.

## 8 Conclusions

The $^{40}$Ar/$^{39}$Ar data here reported may suggest important constraints in the geological evolution of the Paraguay Belt as well as tectonic implications. Based upon these $^{40}$Ar/$^{39}$Ar results and the discussion above we may suggest the following conclusions:

1) The cooling age of the metamorphic event of the Paraguay Belt may be constrained between 541 Ma and 531 Ma.

2) This metamorphic event probably is result of the collisional processes between the Amazonian craton and the Paranapanema cratonic block (or an extension of the Rio de la Plata Craton), and comprises late collision of the western Gondwana collage.

3) The $^{40}$Ar/$^{39}$Ar isotopic data and geological evidence suggest a 700-531 Ma basement record (Xavantina oceanic floor) in the easternmost sector of the Paraguay Belt.

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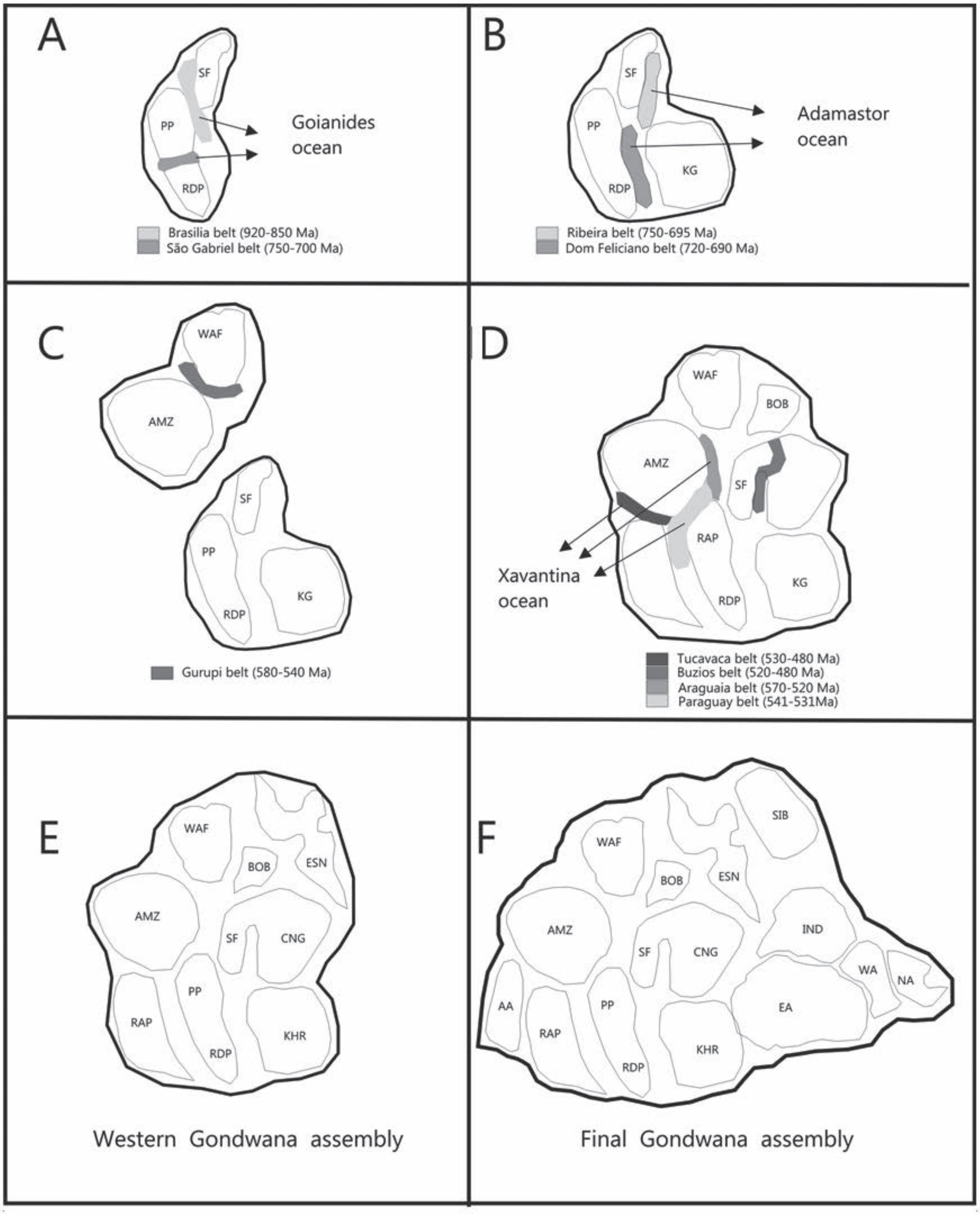

Figure 5 Gondwana assembly speculation. Figures 7A, 7B, 7C, 7D, 7E and 7F represent steps (i.e. collision) during the Gondwana amalgamation. Cratonic areas are: AMZ-Amazonia; WAF-West Africa; RAP- Rio Apa; RDP- Rio de La Plata; SF-São Francisco; CNG-Congo; KHR-Kalahari; BOB-Borborema; ESN-East-Sahara-Nile; SE-Siberia; IND-India; EA-East Antarctica; WA-West Australia; NA-North Australia. Modified form Dalziel (1997) and Trompete (1994).

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