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C-, Sr-isotope stratigraphy of carbonate rocks from the Southern Espinhaço Ridge, Minas Gerais, southeastern Brazil

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ABSTRACT

Neoproterozoic carbonate rocks comprise different stratigraphic units in the southern part of the Espinhaço Ridge, Minas Gerais, Brazil. C, O- and Sr-isotope analyses were carried out along four selected stratigraphic sections across these formations. These are: (i) the Rio Pardo Grande Formation in the upper portion of the Espinhaço Supergroup, sampled in section 3; (ii) Macaúbas Group laminated limestones (Tijucuçu Farm) and dolostone layers (Domingas Formation) have been respectively sampled along the so-called sections 1 and 2, and (iii) the lower stratigraphic units of the Bambuí Group, sampled in section 4. Laminated limestone samples from the Macaúbas Group have $\delta^{13}\text{C}$ values as high as 10.9‰ decreasing up section to -1.1‰ and $^{87}\text{Sr}/^{86}\text{Sr}$ values vary from 0.7072 to 0.7076, a range commonly observed in Cryogenian rocks. In section 2, dolomitic samples exhibit $^{87}\text{Sr}/^{86}\text{Sr}$ from 0.7076 to 0.7077 while in section 3, $^{87}\text{Sr}/^{86}\text{Sr}$ from 0.7074 to 0.7079. In section 4, $^{87}\text{Sr}/^{86}\text{Sr}$ values are around 0.7080. The values of $^{87}\text{Sr}/^{86}\text{Sr}$ observed in carbonate samples from the Macaúbas Group are similar to those observed in the Sr-isotope secular curve for the Neoproterozoic. Carbonate samples from the base of the Bambuí Group correlate with Ediacaran fingerprints, after the Marinoan (ca. 635 Ma) glaciation.

Key words: Sr isotopes, C isotopes, carbonates, Macaúbas Group, Bambuí Group, Marinoan glaciation.

INTRODUCTION

The main scope of this study is to investigate the C-, O- and Sr-isotope stratigraphy of carbonate rocks of the Mesoproterozoic Espinhaço Supergroup and the Neoproterozoic Macaúbas and Bambuí groups, exposed in the southeastern portion of the São Francisco Craton and Araçuaí Belt, southeastern Brazil.

This investigation aims at understanding the nature of the depositional environments and climatic

conditions that predominated during the deposition of the above-mentioned units, as well as to examine how C and Sr-isotope data fit the global Meso- to Neoproterozoic secular isotope curves (Veizer et al. 1983, Kaufman et al. 1993, Hoffman et al. 1998, Halverson et al. 2007, 2010).

The Espinhaço Ridge in southeastern Brazil (Minas Gerais) comprises Archean Basement and Rio Paraúna Supergroup, the Paleo-Mesoproterozoic Espinhaço Supergroup (divided into the Diamantina and Conselheiro Mata Groups), the Neoproterozoic

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Macaúbas and Bambuí Groups (Fig. 1). The Macaúbas Group crops out at the western margin of the Araçuai Belt and overlies stratigraphically metasediments of the Espinhaço Supergroup. The contact between these two units has been described either as an angular unconformity or as an erosive disconformity (Pflug 1965, Schöll and Fogaça 1979, Uhlein 1991). The Bambuí Group crop out at the eastern margin of the São Francisco Craton and includes mixed carbonate and siliciclastic strata deposited on tectonically stable craton.

A package of carbonate rocks occurs at the central portion of the Espinhaço Ridge. They include gray dolostones of the Rio Pardo Grande Formation (top of the Conselheiro Mata Group) as well as limestones of the Neoproterozoic Bambuí Group exposed along the western side of this ridge. Dolostone lenses of the Domingas Formation and laminated limestones at the Tijucuçu Farm are equivalent to the basal sequence of Macaúbas Group in the northeastern portion of the Espinhaço Ridge.

Carbonatic and siliciclastic lithofacies from sections at the Tijucuçu Farm, dolostone with stromatolitic lenses exposed along the Jequitinhonha River and in the Boqueirão Farm (Inhaí and Senador Mourão-Diamantina), gray dolostone samples of the Rio Pardo Grande Formation and limestones of the Bambuí Group (Rodeador-Monjolos) are here described and the C, O and Sr isotopic results are discussed (Fig. 1; Area 1 and Area 2).

GEOLOGIC BACKGROUND

The Espinhaço Ridge is essentially composed of crystalline basement rocks (Congonhas Group and Gouveia granites), metavolcanic and schists (Rio Paraúna Supergroup) and metasedimentary rocks of the Espinhaço Supergroup (metaconglomerates, quartzites and phyllites), deposited in a rift basin during the Paleo-Mesoproterozoic (Dussin and Dussin 1995, Martins-Neto 1998). The Neoproterozoic Macaúbas Group crops out at the northeastern margin of the Espinhaço Ridge and

it is composed of metadiamicrite, quartzite and schist. The Neoproterozoic Bambuí Group crops out at the western part of the Espinhaço Ridge, with carbonates and pelitic sediments. Tectonic convergence during the Brasiliano Cycle (580-550 Ma) turned this region into a thrust-fold belt with structures verging westward. Rocks have undergone regional metamorphism up to greenschist facies (Schöll and Fogaça 1979, Uhlein 1991) low grade deformational zones have allowed preservation of much of the original sedimentary structures. Uhlein (1991) has reviewed the regional geology of the central portion of the Espinhaço Ridge, encompassing the southeastern limit of the São Francisco Craton and the external domain in the transition zone to the Araçuai orogenic belt.

In the northeastern part of the Espinhaço Ridge (area 1, Fig. 1), carbonate layers comprise part of the basal sequence of the Macaúbas Group. The Duas Barras Formation (Noce et al. 1997, Fraga et al. 2011, Fraga 2013) is formed by sedimentary rocks deposited in proximal fluvial system (conglomeratic sandstones grading down to fine-to medium-grained sandstones). This formation is overlapped by the Domingas Formation (massive siltstones and laminated mudstones with dolostone lenses) deposited in a coastal environment (Noce et al. 1997, Fraga et al. 2013). Glacial diamictites of the Serra do Catuni Formation overlie these units. A strong erosive unconformity separates the Duas Barras Formation and the Serra do Catuni Formation suggesting installation of a continental glacier. Diamictites of the Serra do Catuni Formation overlie this unconformity, and represent glacio-continental to glacio-marine environments, while the pelitic-sandstone association of the Chapada Acauã Formation comprises a glacio-marine facies. Glacial erosion caused the destruction of a large portion of the carbonate rocks, locally juxtaposing diamictite packages and carbonate layers in one topographical level.

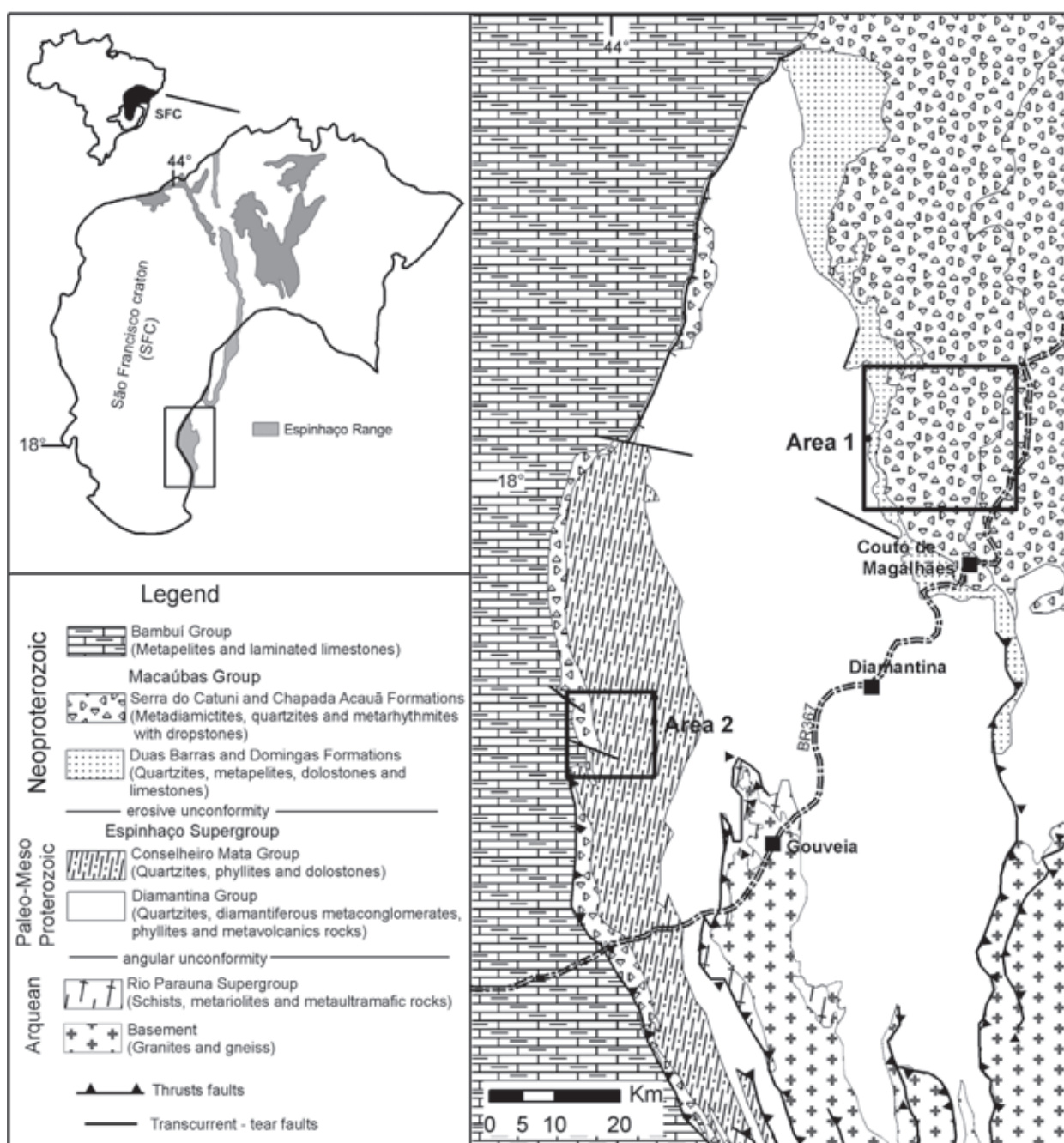


Figure 1 - Location map and simplified geological map of the central region of the Espinhaço Ridge, highlighting the areas studied: Area 1 – Northeast region; Area 2 – western edge (modified from Geological Map of the state of Minas Gerais, 2003 and Almeida 1977).

The Area 1 (Fig. 2) shows the Duas Barras, Domingas and Serra do Catuni Formations, in the Macaúbas Group. In this area, gray dolostone lenses occur laterally, associated with layers of massive siltstones and laminated pelites, on top of the

Domingas Formation. This unit is found in a semi-continuous range along the Jequitinhonha River (section 2), and near the district of Inhaí (Boqueirão Farm; Fig. 2). Thick dolostone lenses occur in the river ledge and, at the Boqueirão Farm, they are

observed as two smaller aligned lenses. In both localities, stromatolites without branches, classified as *Conophyton metula kirichenko* by Schöhl (1976), have been found. In the Tijucuçu Farm (section 1; Fig. 2), one sedimentary association occur at the base, formed by alternating layers of calcarenites

and laminated pelites, followed by a succession of calcarenites and laminated calcilutites layers.

At the western margin of the Espinhaço Ridge, the area 2 (Fig. 3) shows the Rio Pardo Grande Formation (Espinhaço Supergroup), the A Level (Macaúbas Group) and Bambuí Group. Gray

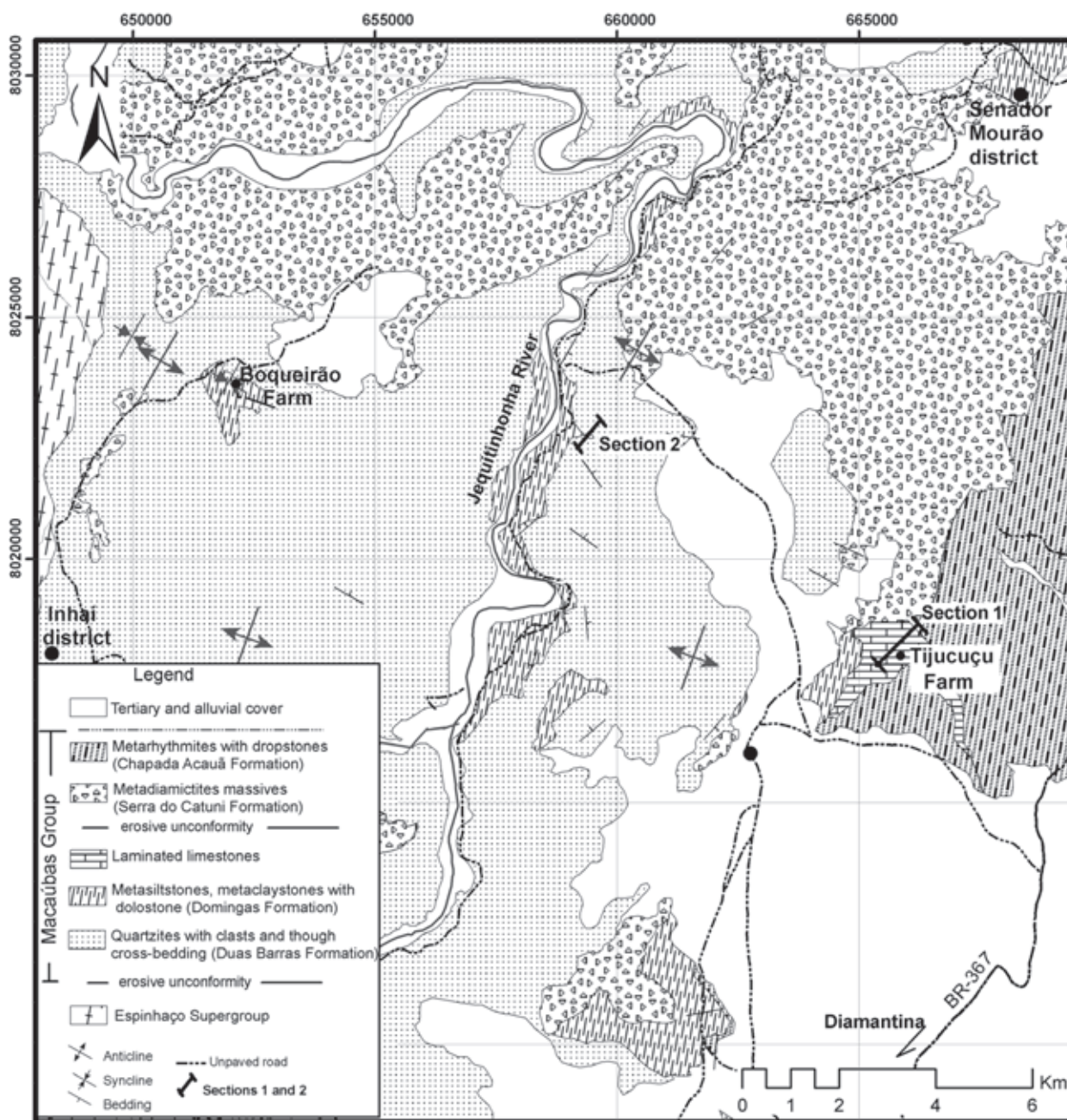


Figure 2 - Geological sketch map of the northeastern part of the Espinhaço Ridge. The location of the investigated sections (sections 1 and 2) are indicated (modified from Fraga 1999).

dolostones with stromatolites (section 3) of the Rio Pardo Grande Formation (Conselheiro Mata Group) are observed above the sandy units of the Córrego Pereira Formation, Espinhaço Supergroup (Pflug 1965, Baptista et al. 1986, Dupont 1995). The rocks of the Conselheiro Mata Group comprise a marine sequence with pelites and fine-grained

sandstones representing deposition during thermal-flexural subsidence in a transgressive environment (Martins-Neto 1998), following the deposition of the basal sequences (Diamantina Group; Espinhaço Supergroup) in the Espinhaço Rift system.

Fine- to medium-grained feldspar-rich sandstones, with angular dolostone fragments (Level A –

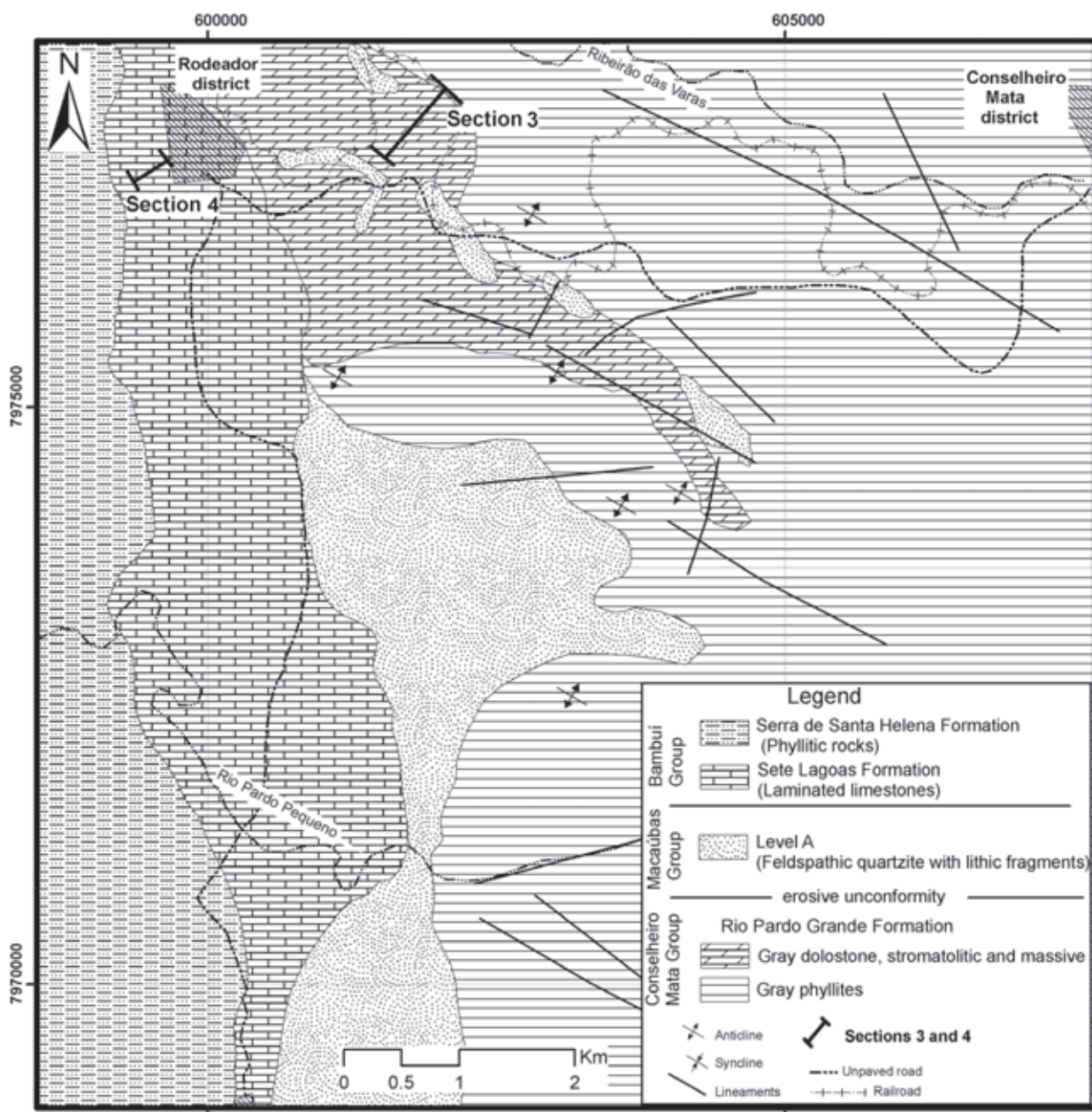


Figure 3 - Simplified geological map of the Conselheiro Mata and Rodeador districts. Lines indicate location of the studied chemostratigraphic sections (modified from Baptista et al. 1986).

Macaúbas Group) overlies a gray dolostone of the Rio Pardo Grande Formation, filling an erosive paleo-surface, in amalgamated parallel layers (Fig. 3). These rocks (Level A) occur at the base of diamictites of the Serra do Catuni Formation (Dossin and Dardenne 1984, Dupont 1996) a glacial sequence in the western margin of the Espinhaço Ridge (Fig. 1).

ANALYTICAL METHODS

Sixty-four limestone and dolostone samples were collected, at 1.5m to 2m interval, along the selected sections. These samples were powdered at the CPMTC of the Federal University of Minas Gerais, using an electric drill or shatter box and then analyzed for C and O isotopes at the Stable Isotope Laboratory (NEG-LABISE), Federal University of Pernambuco, using the methods described by Sial et al. (2000) and Pandit et al. (2002). Powdered samples were reacted with H_3PO_4 at 25°C to release the CO_2 . An extended reaction period was preferred for the dolomite-rich samples instead of increasing the reaction temperature. The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values were measured on cryogenically cleaned CO_2 (Craig 1957) using a triple collector SIRA II or Delta V advantage mass spectrometers. The C and O isotopic data are reported as ‰ deviation with reference to V-PDB and V-SMOW, respectively. Borborema skarn calcite (BSC), calibrated against international standards, was used as the reference gas and reproducibility of the measurements was better than $\pm 0.1\text{‰}$. The values obtained for the standard NBS-20 in a separate run against BSC yielded $\delta^{13}\text{C}_{\text{V-PDB}} = -1.05\text{‰}$, and $\delta^{18}\text{O}_{\text{V-PDB}} = -4.22\text{‰}$. These results are in close agreement with the values reported by the US National Bureau of Standards (-1.06‰ and -4.14‰ , respectively).

For Sr-isotope analysis, 100mg of powdered carbonate samples were separated from 19 fresh samples, from the same sections analyzed for C and O isotopes. Laboratory procedures are found in Sial et al. (2000), Alvarenga et al. (2007) and

Vieira et al. (2007). These samples were analyzed at the laboratory of Isotope Geology of the Federal University of Rio Grande do Sul, Brazil.

Elemental concentrations (Sr, Mn) were determined by inductively coupled plasma optical emission spectroscopy (ICP-OES) in the Lakefield Geosol Laboratories in the city of Belo Horizonte. The Mn/Sr ratio is the most commonly used geochemical criteria for assessing the degree of alteration of Neoproterozoic carbonates.

ISOTOPE DATA EVALUATION

SECTION 1- LAMINATED CALCARENITES AND CALCILUTITES (TIJUCUÇU FARM)

The section at the Tijucuçu Farm (Figs. 4 and 5) comprises a 30m-thick rhythmic carbonate-pelitic succession at the base, followed by a thick layer of laminated calcarenite and calcilutite with intraclastic material resulting from reworking. In this section, 15 samples were collected at 1.5 m interval.

In this section, $\delta^{13}\text{C}$ values vary from 7‰ to 11‰ with sharp decrease to -1.0‰ in laminated calcilutites in the upper part of the section, which displays higher $\delta^{18}\text{O}$ values in relation to the base of the section. $\delta^{18}\text{O}$ values on the base of this section show a sympathetic fluctuation with $\delta^{13}\text{C}$ (from -13 to -12‰). This gradual change suggests a decrease in the sedimentation rate associated to warmer and dryer climatic conditions. The decrease in the contribution of continental sediments allowed for accumulation of carbonate sediments in the coastal region (Nagarajan et al. 2008).

The carbon isotope behavior suggests eustatic sea-level fluctuation, with minor transgressions followed by regressions, which generally precede a significant climate change (Hall and Veizer 1995, Halverson et al. 2007, 2010). These isotopic variations follow the lithological variations in the carbonate sequence (Fig. 5).

Weathering may have partially affected isotopic results for samples from calcarenite layers

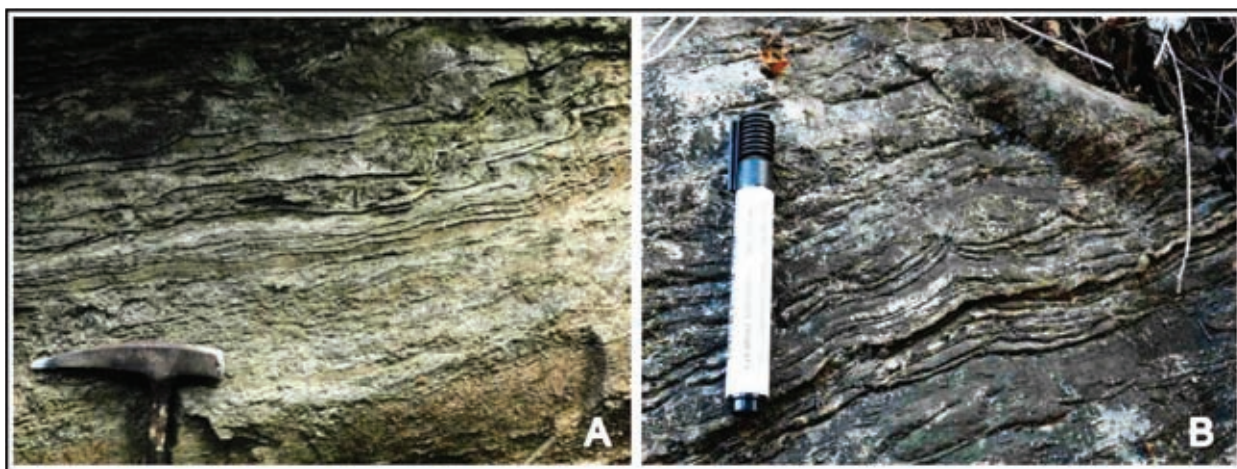


Figure 4 - Exposures of calcilutite and calcarenite at the Tijucuçu Farm showing plane-parallel lamination (A) and tepee structures (B).

in the profile Tijucuçu (samples B and Q; Macaúbas Group), but the corresponding Mn/Sr ratios are within the limits for primary signals ($\text{Mn/Sr} < 2$). Therefore, it is assumed here that the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios reported are probably near-primary values.

The $^{87}\text{Sr}/^{86}\text{Sr}$ values in the Tijucuçu section range from 0.7072 to 0.7076 (respectively samples C and S; Fig. 5), similar to those observed in the post-Sturtian rocks (Veizer et al. 1983, Hoffman et al. 1998, Halverson et al. 2007, 2010). These Sr-isotope values suggest that carbonate and metapelitic rocks of the Tijucuçu section are Cryogenian in age.

Highly positive $\delta^{13}\text{C}_{\text{carb}}$ excursions as well as several negative anomalies are observed in the Neoproterozoic, caused by glacial events as signatures of extreme points of the exogenous carbon cycle fluctuation (Frimmel 2010, Halverson et al. 2010). According to Halverson et al. (2010), trends of positive values towards negative ones are the first evidence for glaciation in the Neoproterozoic. Therefore, positive $\delta^{13}\text{C}_{\text{carb}}$ excursions in the Neoproterozoic may be explained by three processes recorded during interglacial periods: (1) high rates of C_{org} burial, (2) increased flow of carbon in surface environments, (3) increase of the isotopic fractionation coefficient between C_{carb} and C_{org} .

Thus the variation of positive $\delta^{13}\text{C}$ values from the base to negative values at the top of the section indicates a trend of climatic change in coastal depositional environment, possibly indicating the installation of a glacial period.

SECTION 2 - LENS OF DOLOSTONE WITH STROMATOLITES (DOMINGAS FORMATION)

Section 2 was performed over a dolostone lens with stromatolites exposed along the Jequitinhonha River, at the top of Domingas Formation. This association consists of massive white-gray meta-siltstone, followed by laminate metaclaystone containing isolated dolostone lenses at the top with columnar stromatolitic structures (Fig 6). The stromatolites were classified by macro and mesostructures. This way, two distinct species of stromatolite were recognized where conical shapes, without branches, show high degree of laminar heritage, and thus were classified as *Conophyton*s. The branched shapes, usually with parallel dicotomas and convex growth were classified as *Jacuthophyton*s (Fraga et al. 2013).

In this section, ten samples were collected in two-meter intervals. In lenses from the Boqueirão Farm (Fig. 2) only two Sr isotopic analyses were carried out.

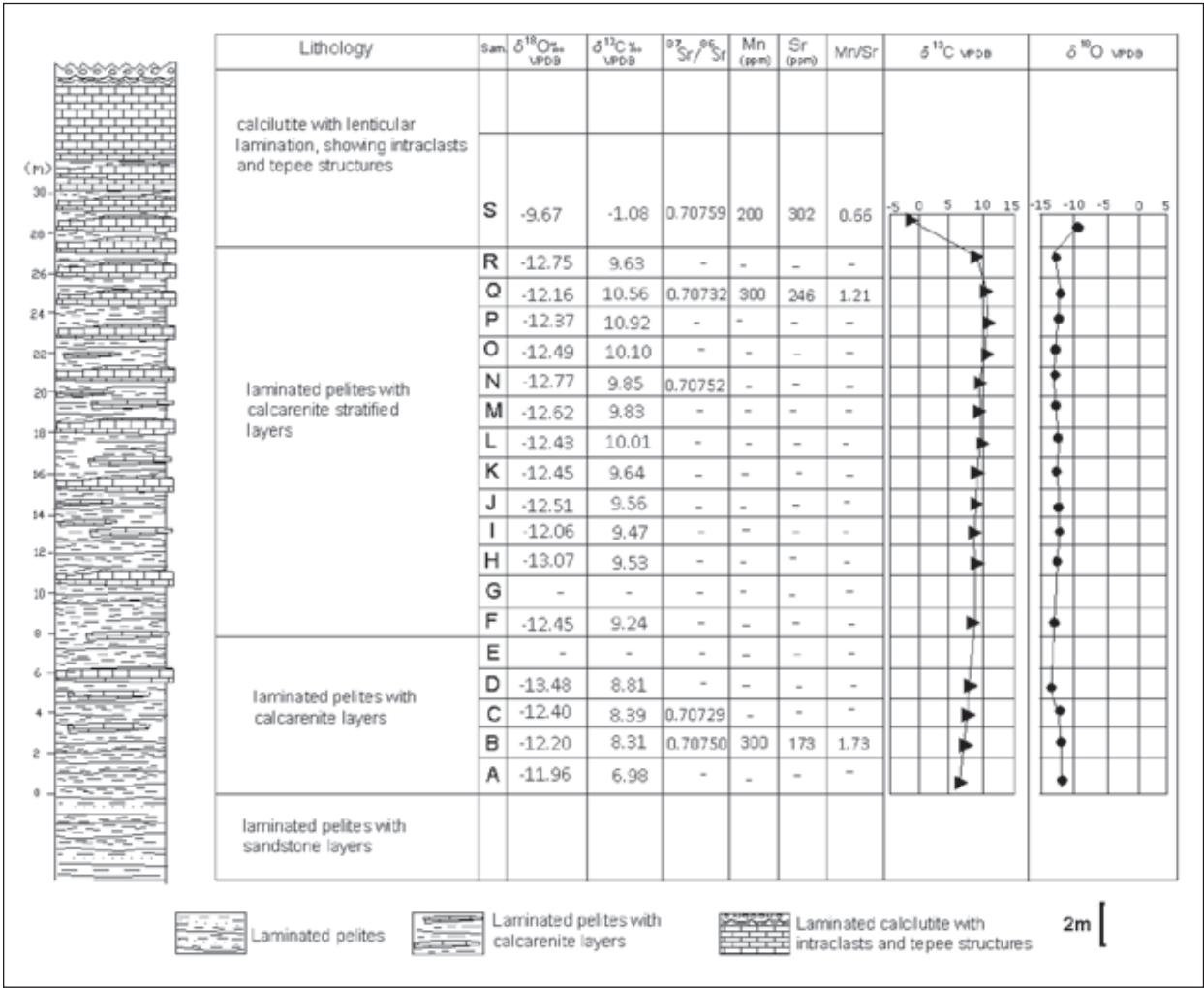


Figure 5 - Lithological variations, elemental and isotopic data of Section 1- Tijucuçu Farm (see Fig. 2 for location).

The geometry of the lenses and their stratigraphic position suggest that these rocks had been chemically precipitated in coastal lagoons (Fraga et al. 2013). There is a clear difference between the $\delta^{13}\text{C}$ isotopic behaviors of these rocks when compared to data from the Tijucuçu Farm (Fig. 6). The dolostone lenses do not show gradual variations in $\delta^{13}\text{C}$ values, with minimum values around 0‰ and maximum values in the 0.6 - 0.8‰ interval. The behavior of $\delta^{18}\text{O}$ in dolostones of the Macaúbas Group suggests warmer climates for the various depositional environments.

However, dolostone lenses in the Jequitinhonha River (samples 1, 3, 5 and 9; Fig. 7) show $^{87}\text{Sr}/^{86}\text{Sr}$

values between 0.7078 and 0.7079, slightly higher than those observed in the adjacent marine environment (section 1). Dolostone lenses in the region of Boqueirão display Sr isotope values similar to those observed at the top of the Tijucuçu Farm section (0.7076 and 0.7077).

Due to the distinct behavior of Mn and Sr during diagenesis (in marine and meteoric environments) of limestone, the Mn/Sr ratios are generally regarded as an important indicator of the degree of preservation of the isotopic signal acquired during deposition (Nagarajan et al. 2008). These authors state that limestones with $\text{Mn}/\text{Sr} < 2$ generally show unchanged isotopic signals, as



Figure 6 - Outcrop of columnar estromatolitic structures containing gray dolostone (A) at the Boqueirão Farm. Stromatolites have elliptical shape in basal section, branched or unbranched, with micrite deposition in the free space (B).

well as Sr amounts between 150 and 2500 ppm. In the samples analyzed in section 2 (Domingas Formation, Macaúbas Group) meteoric alterations could have partially affected the isotopic results in layers of stromatolitic dolomite where Mn/Sr ratios are above 2.

SECTION 3 - GRAY DOLOSTONE OF RIO PARDO GRANDE FORMATION

The lithological composition and the paleontological records of these dolostones are different from those found on the dolostone lenses of the Macaúbas Group. In the Rio Pardo Grande Formation, these rocks are found at the base of this stratigraphic unit, and consist of a thick layer of gray massive dolostone, followed upwards by layers with stratiform stromatolites (Fig. 8). At the top of this sequence, intraclastic conglomeratic lenses are observed, indicating marine reworking processes on a platform environment.

$\delta^{13}\text{C}$ values vary from 1.5 to 2.2‰ (Fig. 9) and are in close agreement with those found in Santos et al. (2004). According to Nagarajan et al. (2008), similar values are related to marine environments from which a large amount of carbonates are precipitated.

$^{87}\text{Sr}/^{86}\text{Sr}$ ratios for dolostone layers of the Rio Pardo Grande Formation vary from 0.7074 (grayish massive dolostone at the base, 2C) to 0.7079 (grayish dolostone with stratiform stromatolites, 2G). These Sr-isotope ratios are similar to those found in the carbonate rocks in the northeastern region (Tijucuçu Farm – section 1).

In the samples analyzed in profile 3 (the Rio Pardo Grande Formation, Espinhaço Super-group) the meteoric alteration may have partially affected the isotopic results in the layers of gray dolostone with $\text{Mn}/\text{Sr} > 2$ (samples 2D, 2I and 2L). However, samples 2A and 2G show Mn/Sr ratios within the limits of preservation of primary isotopic signals.

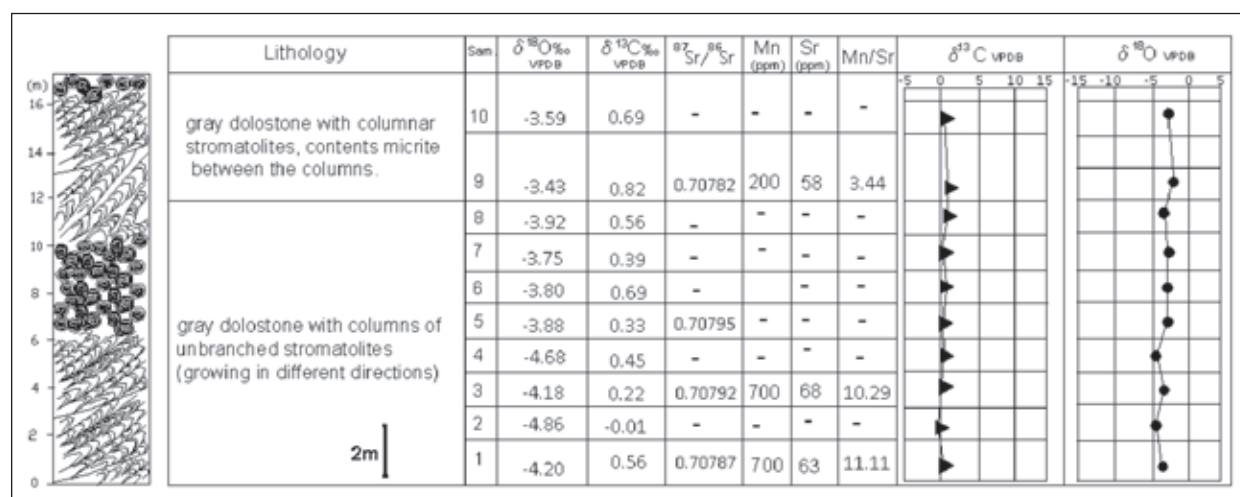


Figure 7 - Lithological variations, elemental and isotopic data in stromatolitic dolostone lenses of the section along the Jequitinhonha River (see Fig. 2 for location).



Figure 8 - Outcrop of gray dolostone along the railway near Conselheiro Mata district (A), with stratiform stromatolite structures (B), and (C) with hemispherical columnar structures.

The isotopic data indicate that the Rio Pardo Grande Formation and the dolostone and carbonate rocks of the northeastern region (Tijucuçu section) were deposited in different marine basins, under different conditions of sedimentation over the basal rocks of the Espinhaço Supergroup during the Neoproterozoic. One belongs to the Macaúbas

Group and the other is considered as upper part of the Espinhaço Supergroup (Conselheiro Mata Group).

The $^{87}\text{Sr}/^{86}\text{Sr}$ values found for these two carbonate sequences (between 0.7072 and 0.7079) correspond to values usually found in the Sr-isotope homogenization process, in post-glacial oceans of the Cryogenian (Veizer et al. 1983, Halverson et al. 2007).

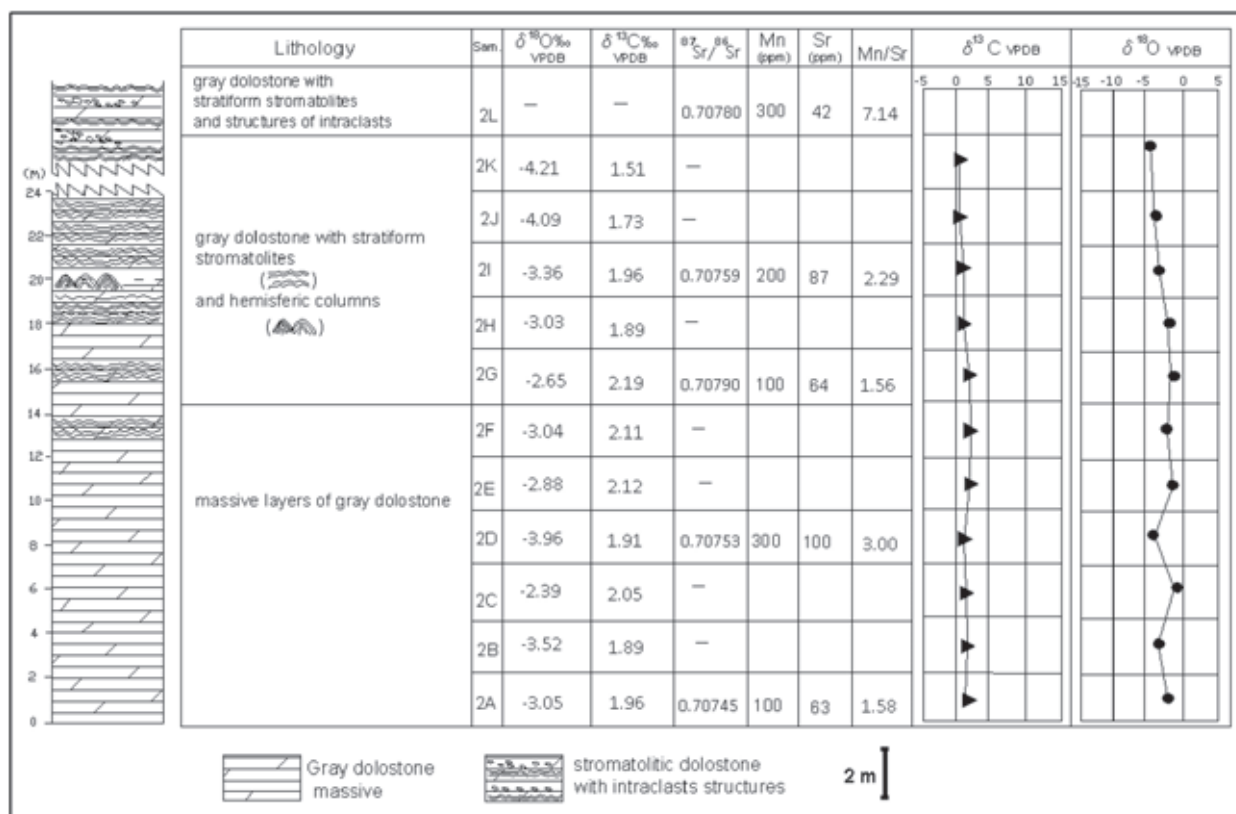


Figure 9 - Lithological variations, elemental and isotopic data of Section 3 – gray dolostone of Rio Pardo Grande Formation (for location, see Fig. 3).

SECTION 4 - LAMINATED CALCAREOUS ROCKS WITH PELITIC LEVELS, BAMBUÍ GROUP

The quarry of Rodeador district (Fig. 3 – section 4) in the western portion of the Espinhaço Ridge consists of perfectly laminated, white to pink limestone, deformed and metamorphosed during the Brasiliano Cycle. These rocks are at angular unconformity with gray dolostones of the Rio Pardo Grande Formation.

Values of $\delta^{13}\text{C}$ between -5 and +5‰ in gray limestones or dolostone of the Sete Lagoas

Formation, Bambuí Group, jump to 10‰ towards the upper part of this stratigraphic unit (Ramos 2000, Santos et al. 2004, Vieira et al. 2007, Martins and Lemos 2007). C-isotope values observed in laminated limestones of the Rodeador quarry suggest that these rocks belong to the middle portion of the Sete Lagoas Formation, prior to the positive isotopic excursion characteristic of the top of this formation (Fig. 10).

In section 4 (Rodeador district), carbonate layers from the base of the Bambuí Group (Sete

Lagoas Formation) display $^{87}\text{Sr}/^{86}\text{Sr}$ values around 0.7083. In the samples analyzed in this section, meteoric alteration has not affected the

isotopic results. The Mn/Sr ratios ($\text{Mn}/\text{Sr} < 2$) are within the limits for little affected or primary isotopic signals.

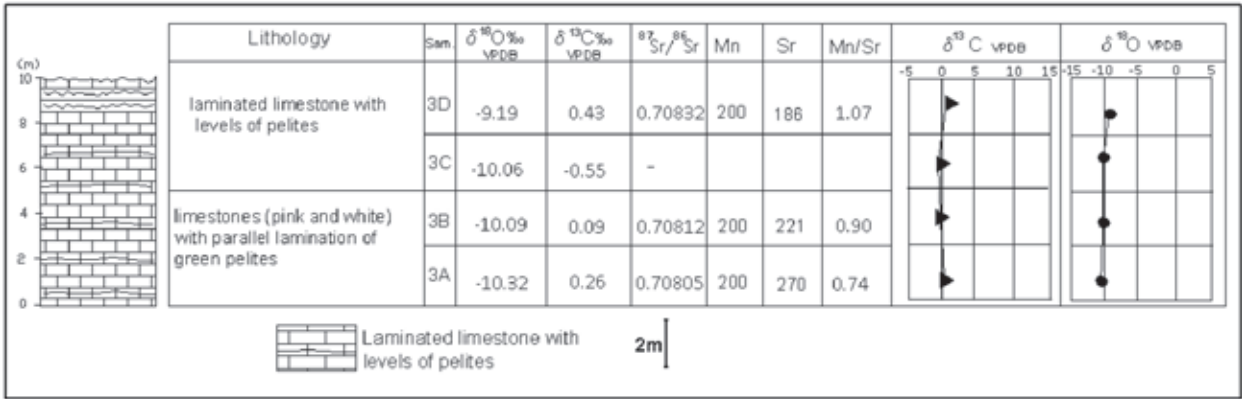


Figure 10 - Lithological variations, elemental and isotopic data of Section 4– laminated limestones at the quarry of the Rodeador district, Bambuí Group (for location, see Fig. 3).

EVALUATION AND INTERPRETATION OF THE RESULTS

A $\delta^{18}\text{O}$ - $\delta^{13}\text{C}$ plot for the four studied sections discriminate three distinct associations (Fig. 11). In group 1, limestones from the Tijucuçu Farm plot, found in a position higher than those of

others groups of carbonate rocks in this study. Their isotopic characteristics are typical of marine environments, related to enrichment in ^{13}C during diagenetic cementation (Milliman 1966, Nagarajan et al. 2008).

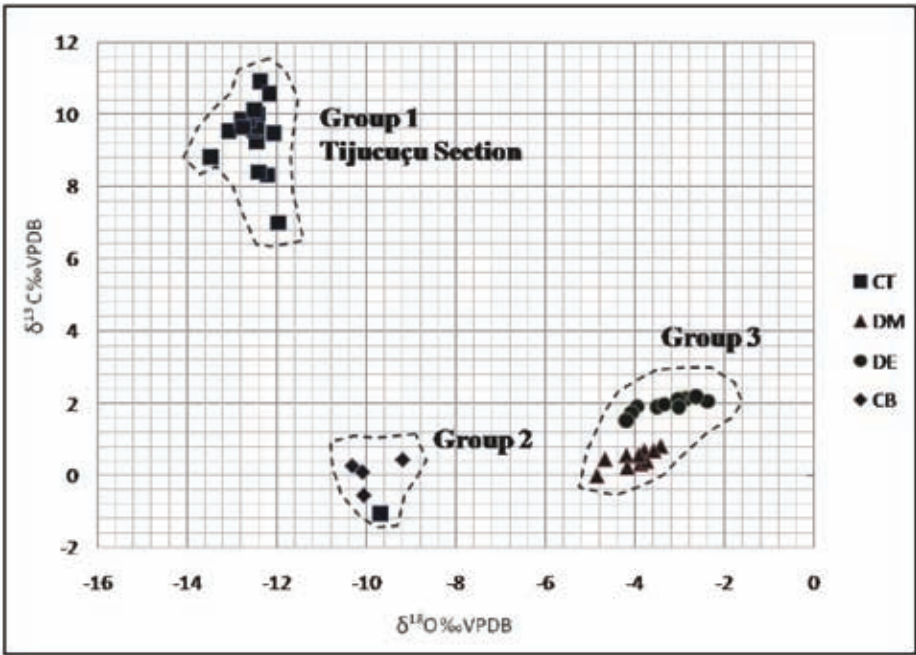


Figure 11 - $\delta^{13}\text{C}_{\text{‰}}$ - $\delta^{18}\text{O}_{\text{‰}}$ plot for samples from the Tijucuçu section (CT), dolostone lenses with stromatolites (DM), dolostone of Rio Pardo Grande Formation (DE), calcareous of the Bambuí Group (CB).

Group 2 is formed by limestone samples of the Bambuí Group. They present $\delta^{18}\text{O}$ values from -8 to -10‰ and $\delta^{13}\text{C}$ values from +1 to -1‰, which are very similar to those observed in the rocks of the faciologic association 2 (FA2) of the Sete Lagoas Formation (Vieira et al. 2007). These limestones are interpreted as an external ramp deposit associated to CaCO_3 -oversaturated seawater in a quiet environment (Vieira et al. 2007).

Group 3 comprises dolostone samples from the Rio Pardo Grande Formation (section 3) and dolostones of the Domingas Formation (section 2). Both groups of samples are predominantly of dolomitic composition with stromatolites, differing from each other only by the $\delta^{13}\text{C}$ composition.

$^{87}\text{Sr}/^{86}\text{Sr}$ values plotted against age for the Neoproterozoic-Cambrian interval (Halverson et al. 2007) allow for the estimation of the age of the studied sedimentary units (Fig. 12).

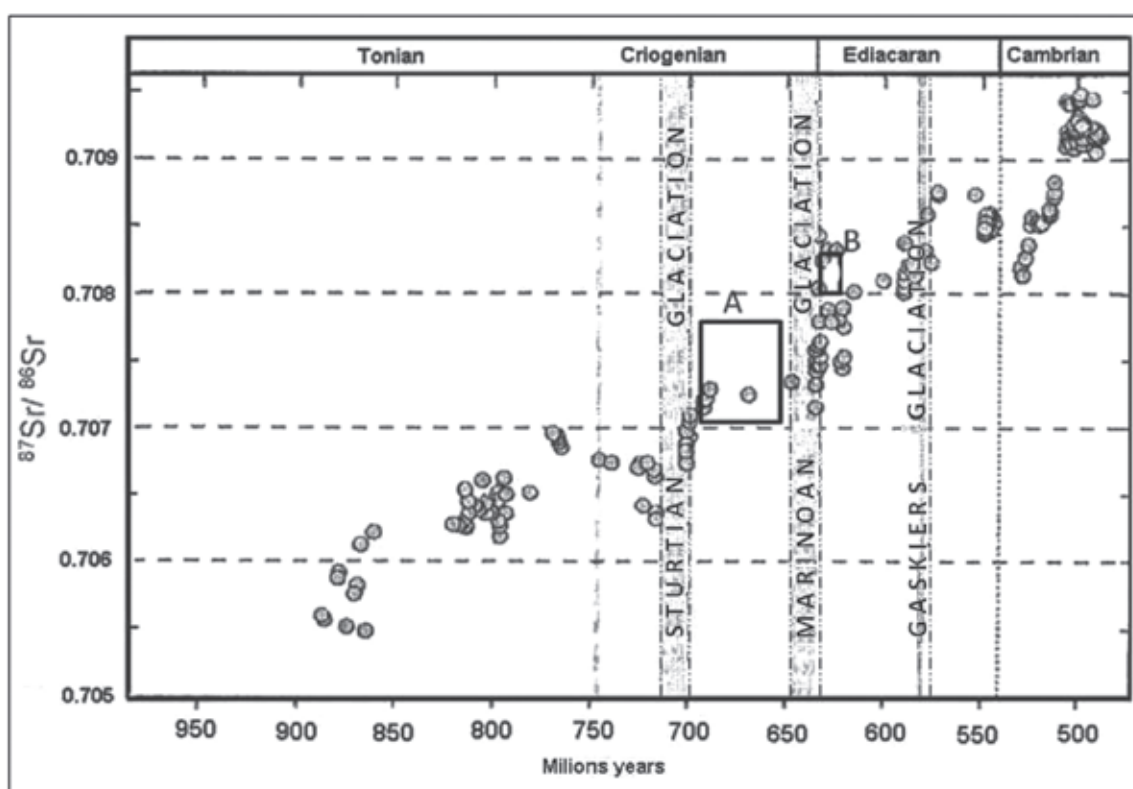


Figure 12 - Distribution of $^{87}\text{Sr}/^{86}\text{Sr}$ from carbonate rocks along the Neoproterozoic (Halverson et al. 2007). The $^{87}\text{Sr}/^{86}\text{Sr}$ data for the sections 1 and 2 (Macaúbas Group) and 3 (Rio Pardo Grande Formation) concentrate in A; while values for samples from the Bambuí Group (section 4) plot in B.

According to the curve of Halverson et al. (2007), the $^{87}\text{Sr}/^{86}\text{Sr}$ values between 0.7072 and 0.7079 found in the studied carbonate sequences correspond to the time interval for the isotopic homogenization process of oceans between the end-Cryogenian (Marinoan) and Sturtian glaciations (~ 700-650Ma). Therefore, the glacial event in

the Espinhaço Ridge corresponds to the Marinoan event (Caxito et al. 2012).

Hoffman et al. (1998) and Halverson et al. (2007) studying limestones of the Maieberg Formation, Namibia, observed a sudden increase in $^{87}\text{Sr}/^{86}\text{Sr}$ values from 0.7080 where were correlated to the radiogenic-strontium influx from post-Marinoan

oceans. Similar isotopic values are also observed in carbonate rocks of the Bambuí Group (0.7081 to 0.7083; see Fig. 10, sample 3A, B, and D).

Massive diamictite layers deposited during the Marinoan glaciation are housed in the northeastern

region (Serra do Catuni Formation) over carbonate layers of the Macaúbas Group. In the western portion of the Espinhaço Ridge (Fig. 13), these glacial diamictites occur at the base of carbonate rocks of the Bambuí Group.

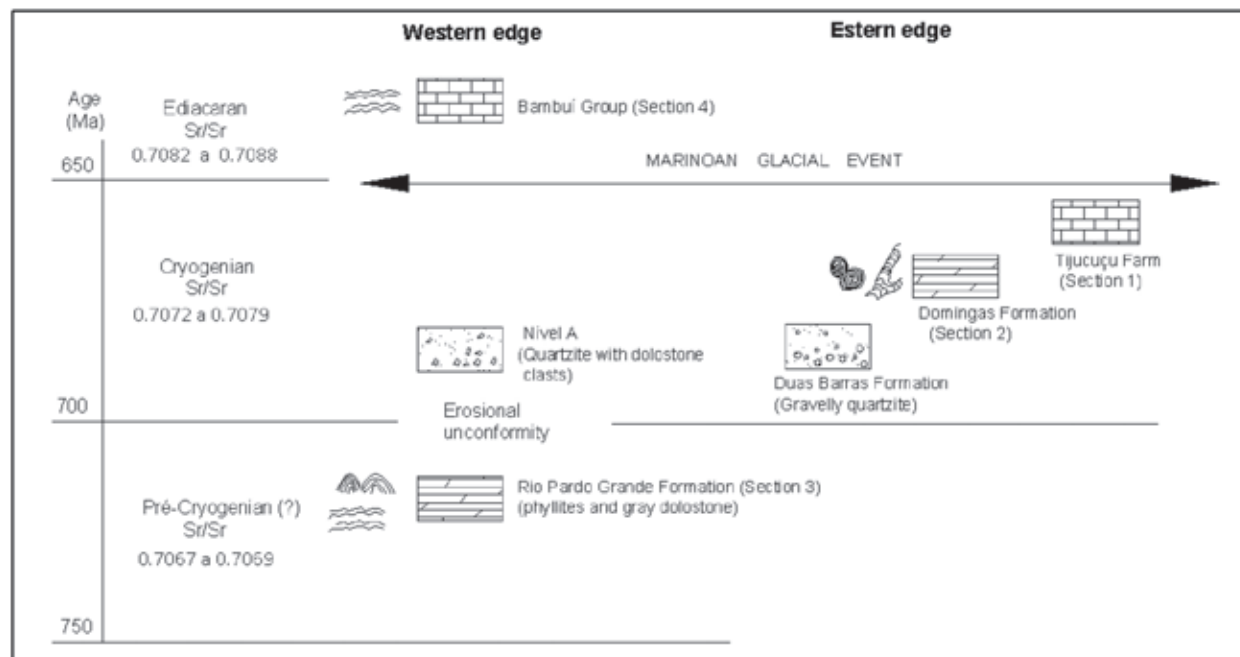


Figure 13 - Correlation between the different lithological units chemostratigraphic data observed in the Espinhaço Ridge sections in this study. Relationship between ages and $^{87}\text{Sr}/^{86}\text{Sr}$ composition were obtained in Halverson et al. (2007).

The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotopic results for rocks of the northeastern and western edge of the Espinhaço Ridge suggest that there was an onset of hot and dry climate, with small amounts of detrital sediments, on a shallow-marine environment. This was possibly related to variation in isostatic tract, allowing the formation of carbonate platforms.

$^{87}\text{Sr}/^{86}\text{Sr}$ values found in the lenses of dolostone with stromatolites in the northeastern region (Domingas Formation, section 2), similar to those found in the section of the Tijucuçu Farm (section 1), indicate Sr isotopic homogenization between coastal lagoons, possibly due to the influence of the mixture of continental waters in the coastal environment.

The $^{87}\text{Sr}/^{86}\text{Sr}$ values for carbonate rocks of the Tijucuçu and Domingas sections (Macaúbas Group) and the Rio Pardo Grande section (Espinhaço Supergroup) show $^{87}\text{Sr}/^{86}\text{Sr}$ values similar to those observed in Neoproterozoic secular isotopic curves (Kaufman et al. 1993, Hoffman et al. 1998, Halverson et al. 2007, 2010) and related to pre-Marinoan glaciation sediments. However, the $^{87}\text{Sr}/^{86}\text{Sr}$ values in the section 3 (dolostone of Rio Pardo Grande Formation) should be looked upon caution, seeing that high corresponding Mn/Sr ratios suggest that these rocks could have undergone substantial secondary alteration.

In section 4 (Rodeador district), carbonate layers from the base of the Bambuí Group (Sete

Lagoas Formation) display $^{87}\text{Sr}/^{86}\text{Sr}$ values around 0.7083, which suggests an Ediacaran age (635-542 Ma) when Sr-isotopic homogenization of oceans took place, after the Marinoan glaciation (Halverson et al. 2010).

From this study, we consider that the regional Neoproterozoic glaciation registered by sedimentary rocks of the Espinhaço Ridge corresponds to the continental-marine end-Cryogenian (Marinoan) glacial event, installed around 635 Ma. Therefore, this study sheds some light on the age of the so-called "Macaúbas glaciation", which was responsible for the deposition of the glaciogenic sediments in the Macaúbas Basin.

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RESUMO

Rochas carbonáticas do Neoproterozóico ocorrem em diferentes unidades estratigráficas na parte meridional da Serra do Espinhaço, Minas Gerais, Brasil. Análises isotópicas de C, O e Sr foram realizadas ao longo de quatro seções estratigráficas selecionadas. São elas: (i) Formação Rio Pardo Grande, na porção superior do Supergrupo Espinhaço, amostrada na seção 3, (ii) calcários laminados (Fazenda Tijucuçu) e camadas de dolomitos estromatolíticos (Formação Domingas) do Grupo Macaúbas, amostrados respectivamente ao longo das seções 1 e 2, e (iii) calcários laminados das unidades estratigráficas inferiores do Grupo Bambuí, amostrados na seção 4. Amostras de calcário laminado do Grupo Macaúbas têm valores $\delta^{13}\text{C}$ tão elevados quanto 10,9‰, diminuindo no final da seção para -1,1‰ e os valores de $^{87}\text{Sr}/^{86}\text{Sr}$ variam entre 0,7072-0,7076, faixa comumente observada em rochas do Criogeniano. Na seção 2, as amostras de dolomito apresentam $^{87}\text{Sr}/^{86}\text{Sr}$ entre 0,7076-0,7077 enquanto na seção 3 $^{87}\text{Sr}/^{86}\text{Sr}$ ocorrem valores entre

0,7074-0,7079. Na seção 4, os valores de $^{87}\text{Sr}/^{86}\text{Sr}$ estão em torno de 0,7080. Os valores de $^{87}\text{Sr}/^{86}\text{Sr}$ observados em amostras de carbonato do Grupo Macaúbas são similares aos observados na curva secular dos isótopos de Sr para o Neoproterozoico. As amostras de carbonato da base do Grupo Bambuí correlacionam-se com a assinatura isotópica do Ediacarano, após a glaciação Marinoana (ca. 635 Ma).

Palavras-chaves: isótopos de estrôncio, isótopos de carbono, carbonatos, grupo Macaúbas, grupo Bambuí, glaciação Marinoana.

REFERENCES

- ALVARENGA CJS, GIUSTINA MESD, SILVA NGC, SANTOS RV, GIOIA SMCL, GUIMARÃES EM, DARDENNE MA, SIAL AN AND FERREIRA VP, 2007. Variações dos isótopos de C e Sr em carbonatos pré e pós-glaciação Jequitai (Esturtiano) na região de Bezerra-Formosa, Goiás – O Cráton São Francisco. *Rev Bras Geocienc* 37 (4-Suplemento): 147-155.
- BAPTISTA AJ, CASTRO WB DE M AND GRECO FM, 1986. Geologia da Serra do Espinhaço entre Conselheiro Mata e Rodeador, Minas Gerais. XXXIV Congresso Bras. Geologia, Goiânia, Anais 2: 949-959.
- CAXITO FA, HALVERSON GP, UHLEIN A, STEVENSON R, DIAS TG AND UHLEIN GJ. 2012. Marinoan glaciations in east central Brazil. *Precambrian Res* 200-203: 38-58.
- CRAIG H. 1957. Isotopic standards of carbon and oxygen and correction factors for mass-spectrometric analysis of carbon dioxide. *Geochim Cosmochim Acta* 12: 133-149.
- DOSSIN IA AND DARDENNE MA. 1984. Geologia da borda ocidental da Serra do Cipó, Minas Gerais (Área do Inhame). XXXIII Congresso Bras. Geologia, Rio de Janeiro, Anais 3: 3104-3117.
- DUPONT H. 1995. O Grupo Conselheiro Mata no seu quadro paleogeográfico e estratigráfico. *Boletim Sociedade Bras Geologia-SBG/MG* 13: 9-10.
- DUPONT H. 1996. O Supergrupo São Francisco entre a Serra do Cabral e as serras do Espinhaço e de Minas: estudo estratigráfico e estrutural e relações de contato com o Supergrupo Espinhaço. XXXIX Congresso Bras. Geologia, Salvador, Anais 5: 489-493.
- DUSSIN IA AND DUSSIN TM. 1995. Supergrupo Espinhaço: Modelo de evolução geodinâmica. *Geonomos* 3(1): 19-26.
- FRAGA LMS, NEVES SC, PIRES GLP, TIBÃES AL AND UHLEIN A. 2013. Estromatólitos colunares na base do Grupo Macaúbas, nordeste da Serra do Espinhaço (MG): paleontologia e ambiente de sedimentação. *Geonomos* 21(1): 34-41.
- FRAGA LMS, NEVES SC, UHLEIN A, SIAL AN AND SOUZA FP. 2011. Dados preliminares sobre a quimioestratigrafia de rochas carbonáticas do Grupo Macaúbas, região nordeste da Serra do Espinhaço Meridional (MG). XIII Congresso Bras. Geoquímica, Gramado, Anais 1: 1223-1226.

- FRAGA LMS. 2013. Análise estratigráfica da sequência basal do Grupo Macaúbas na região nordeste da Serra do Espinhaço Meridional. Tese de doutoramento, IGC/UFMG.
- FRIMMEL HE. 2010. On the reliability of stable carbon isotopes for Neoproterozoic chemostratigraphic correlation. *Precambrian Res* 182: 239-253.
- GEOLOGICAL MAP OF THE STATE OF MINAS GERAIS. 2003. 1: 1 000 000 scale. COMIG – CPRM. Belo Horizonte, CD-ROM.
- HALL SM AND VEIZER J. 1995. Geochemistry of Precambrian carbonates: VII. Belt supergroup, Montana and Idaho, USA. *Geochim Cosmochim Acta* 60: 667-677.
- HALVERSON GP, DUDÁS FO, MALOOF AC AND BOWRING SA. 2007. Evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ composition of Neoproterozoic seawater. *Palaeogeogr, Palaeoclimatol, Palaeoecol* 256: 103-129.
- HALVERSON GP, WADE BP, HURTGEN MT AND BAROVICH KM. 2010. Neoproterozoic chemostratigraphy. *Precambrian Res* 182: 337-350.
- HETTICH M. 1977. A glaciação proterozóica no centro-norte de Minas Gerais. *Rev Bras Geocienc* 7: 87-101.
- HOFFMAN PF, KAUFMAN AJ AND HALVERSON GP. 1998. Coming and going of global glaciations on a Neoproterozoic tropical platform in Mambíbia. *GSA today* 8: 1-9.
- KAUFMAN AJ, JACOBSEN SB AND KNOLL AH. 1993. The Vendian record of Sr and C isotopic variations in seawater: Implications for tectonics and paleoclimate. *Earth Planet Sc Lett* 120(3-4): 409-430.
- MARTINS M AND LEMOS VB. 2007. Análise estratigráfica das sequências neoproterozóicas da Bacia do São Francisco. *Rev Bras Geocienc* 37(4 Suplemento): 156-167.
- MARTINS-NETO MA. 1998. O Supergrupo Espinhaço em Minas Gerais: Registro de uma Bacia Rife-Sag do Paleó/Mesoproterozóico. *Rev Bras Geocienc* 28: 151-168.
- MILLIMAN JD. 1966. Submarine lithification of deep-water carbonate sediments. *Science*: 153: 994.
- NAGARAJAN R, SIAL AN, ARMSTRONG-ALTRIN JS, MADHAVARAJU J AND NAGENDRA R. 2008. Carbon and Oxygen isotope geochemistry of Neoproterozoic limestones of the Shahabad Formation, Bhimabasin, Karnataka, Southern India. *Rev Mex Cienc Geol* 25(2): 225-235.
- NOCE CM, PEDROSA-SOARES AC, GROSSI-SAD JH, BAARS JR, GUIMARÃES MLV, MOURÃO MAA, OLIVEIRA MJR AND ROQUE NC. 1997. Nova divisão estratigráfica regional do Grupo Macaúbas na Faixa Araçuaí: registro de uma bacia neoproterozóica. IX Simpósio Geol. Minas Gerais. *Boletim* 14: 29-31.
- PANDIT MK, SIAL AN, SUKUMARAN GB, PIMENTEL MM, RAMASAMY AK AND FERREIRA VP. 2002. Contrasting mantle sources (depleted and enriched) or temporally widespread carbonatites of southern India: Sr, Nd, C-O isotopic and geochemical constraints. *Cheml Geol* 189(1/2): 69-89.
- PFLUG R. 1965. A geologia da parte meridional da Serra do Espinhaço e zonas adjacentes, Minas Gerais. Rio de Janeiro. DNPM/DGM. *Boletim* 226, 55 p.
- RAMOS MLS. 2000. Geoquímica isotópica de sequências carbonáticas do proterozóico médio/superior no Brasil: um estudo da transição Espinhaço/Macaúbas (Faixa Araçuaí) e Arai/Paranoá (Faixa Brasília). Dissertação de Mestrado. DEGEO/UFOP. (Unpublished).
- SANTOS RV, ALVARENGA CJS, BABINSKY M, RAMOS MLS, CUKROV N, FONSECA MA, SIAL AN, DARDENNE MA AND NOCE CM. 2004. Carbon isotopes of Mesoproterozoic-Neoproterozoic sequences from Southern São Francisco Craton and Araçuaí Belt, Brazil: Paleogeographic implications. *J S Am Earth Sci* 18: 27-39.
- SCHÖLL WU. 1976. Estromatólitos (Conophyton) em dolomitós no Grupo Macaúbas. XXIX Congresso Bras. Geologia, Ouro Preto. *Anais* 2: 67-73.
- SCHÖLL WU AND FOGAÇA ACC. 1979. Estratigrafia da Serra do Espinhaço na região de Diamantina. – I Simpósio Geol. Minas Gerais, Diamantina. *Atas* 1: 55-73.
- SIAL AN, FERREIRA VP, BEZERRA VS, SANTANA GM AND SOARES DR. 2000. Current methodologies at the stable isotope laboratory of the Federal University of Pernambuco, Brazil. Site: <http://www.ufpe.br/neglalabise/staff.php>, p. 110-112.
- UHLEIN A. 1991. Transição cráton-faixa dobrada: exemplo do Cráton do São Francisco e da Faixa Araçuaí (Ciclo Brasileiro) no estado de Minas Gerais. Aspectos estratigráficos e estruturais. Tese de doutoramento, USP, 245 p.
- VEIZER J, COMPSTON W, CLAUSER N AND SCHIDLOWSKI W. 1983. $^{87}\text{Sr}/^{86}\text{Sr}$ Late Proterozoic carbonates: evidence for a "mantle" event at ~900 Ma ago. *Geochim Cosmochim Acta* 47: 295-302.
- VIEIRA LC, TRINDADE RIF, NOGUEIRA ACR AND ADER M. 2007. Identification of a Sturtian cap carbonate in the Neoproterozoic Sete Lagoas carbonate platform, Bambuí Group, Brazil. *CR Geosciences* 339: 240-258.