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Application of multi-dimensional discrimination diagrams and probability calculations to Paleoproterozoic acid rocks from Brazilian cratons and provinces to infer tectonic settings

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ABSTRACT

In present work, we applied two sets of new multi-dimensional geochemical diagrams (Verma et al., 2013) obtained from linear discriminant analysis (LDA) of natural logarithm-transformed ratios of major elements and immobile major and trace elements in acid magmas to decipher plate tectonic settings and corresponding probability estimates for Paleoproterozoic rocks from Amazonian craton, São Francisco craton, São Luís craton, and Borborema province of Brazil. The robustness of LDA minimizes the effects of petrogenetic processes and maximizes the separation among the different tectonic groups. The probability based boundaries further provide a better objective statistical method in comparison to the commonly used subjective method of determining the boundaries by eye judgment. The use of readjusted major element data to 100% on an anhydrous basis from SINCLAS computer program, also helps to minimize the effects of post-emplacement compositional changes and analytical errors on these tectonic discrimination diagrams. Fifteen case studies of acid suites highlighted the application of these diagrams and probability calculations. The first case study on Jamon and Musa granites, Carajás area (Central Amazonian Province, Amazonian craton) shows a collision setting (previously thought anorogenic). A collision setting was clearly inferred for Bom Jardim granite, Xingú area (Central Amazonian Province, Amazonian craton) The third case study on Older São Jorge, Younger São Jorge and Maloquinha granites Tapajós area (Ventuari-Tapajós Province, Amazonian craton) indicated a within-plate setting (previously transitional between volcanic arc and within-plate). We also recognized a within-plate setting for the next three case studies on Aripuanã and Teles Pires granites (SW Amazonian craton), and Pitinga area granites (Mapuera Suite, NW Amazonian craton), which were all previously suggested to have been emplaced in post-collision to within-plate settings. The seventh case studies on Cassiterita-Tabuões, Ritápolis, São Tiago-Rezende Costa (south of São Francisco craton, Minas Gerais) showed a collision setting, which agrees fairly reasonably with a syn-collision tectonic setting indicated in the literature. A within-plate setting is suggested for the Serrinha magmatic suite, Mineiro belt (south of São Francisco craton, Minas Gerais), contrasting markedly with the arc setting suggested in the literature. The ninth case study on Rio Itapicuru granites and Rio Capim dacites (north of São Francisco craton, Serrinha block, Bahia) showed a continental arc setting. The tenth case study indicated within-plate setting for Rio dos Remédios volcanic rocks (São Francisco craton, Bahia), which is compatible with these rocks being the initial, rift-related igneous activity associated with the Chapada Diamantina cratonic cover. The eleventh, twelfth and thirteenth case studies on Bom Jesus-Areal granites, Rio Diamante-Rosilha dacite–rhyolite and Timbozal-Cantão granites (São Luís craton) showed continental arc, within-plate and collision settings, respectively. Finally, the last two case studies, fourteenth and fifteenth showed a collision setting for Caicó Complex and continental arc setting for Algodões (Borborema province).

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1. Introduction

With the renewed interest in how far back in time we can track modern-style plate tectonics, we might ask where we should go from here. Such a challenge bringing about renewed efforts to understand if and how the Archean and Proterozoic differ from later time in the Earth's history. A wealth of geological, geochemical, structural, volcanologic, and geodynamic evidence seems to demand the operation of plate tectonics in the late Archean (e.g., Condie and Pease, 2008; Ernst, 2009; Van Kranendonk, 2010). There are some similarities of the Archean and Proterozoic with modern-style plate tectonics. Although some authors (e.g., Stern, 2008; Hamilton, 2011) agree that this may certainly be true for the Proterozoic, its validity during the Archean, albeit controversial, has been proposed by numerous workers (e.g., Kerrich and Polat, 2006; Condie and Kröner, 2008; Foley, 2008; Pease et al., 2008; Polat et al., 2008; Shirey et al., 2008; Furnes et al., 2009; Manikyamba and Kerrich, 2012). New evidence could, therefore, better constrain the answers to this vital question of plate tectonic theory.

Therefore, tectonomagmatic discrimination diagrams could be also useful geochemical tool for deciphering the tectonic environment of old terrains as well as of tectonically complex areas (Pearce and Cann, 1971, 1973; Wood, 1980; Shervais, 1982; Pearce et al., 1984; Cabanis and Lecolle, 1989; Rollinson, 1993; Collins et al., 2008; Verma, 2002, 2010). Recently, Verma et al. (2010) extensively evaluated a large number of available diagrams and inferred that those proposed recently (Agrawal et al., 2004, 2008; Verma et al., 2006; Verma and Agrawal, 2011) showed the better functioning of diagrams. Satisfactory functioning of these multi-dimensional diagrams was also confirmed independently by Sheth (2008), Verma et al. (2011), and Pandarinath and Verma (in press).

Similarly Polat et al. (2011a) have shown similarities a differences of elemental ratios between the Archean and Cenozoic ultrabasic and basic rocks among other researchers. Nevertheless, evaluation of the geochemical characteristics in multi-dimensional diagrams has been seldom reported for Archean or Proterozoic rocks. Bailie et al. (2010) also confirmed an arc setting by using one of the five multi-dimensional diagrams of Agrawal et al. (2008) for Archean basic rocks from South Africa. As well, Polat et al. (2009a, b, 2011a) used only two of the five diagrams of Agrawal et al. (2008) to infer an arc or an MORB to arc transitional setting for Archean rocks from Greenland. Further, Polat et al. (2011b) also showed a transitional mid-ocean ridge to arc tectonic setting for Eoarchean to Mesoarchean rocks from Greenland by using all five diagrams of Agrawal et al. (2008).

All these recently proposed diagrams were based on linear discriminant analysis (LDA) of natural logarithm of element ratios; and correct statistical treatment of compositional data (e.g., Aitchison, 1986; Aitchison et al., 2000; Thomas and Aitchison, 2005; Agrawal and Verma, 2007; Verma, 2010; Verma et al., 2010). All these multi-dimensional diagrams were proposed for the discrimination of basic and ultrabasic rocks. A computer program TecD (Verma and Rivera-Gómez, in press-a) facilitates their efficient application.

For acid rocks, only bivariate-type diagrams (Pearce et al., 1984) were available until the proposal of new multi-dimensional diagrams (Verma et al., 2012). These new multi-dimensional diagrams based on LDA of $\log_e$-transformed ratios were shown by Verma et al. (2012) to work better than the older concentration-based diagrams of Pearce et al. (1984). Although this set of five diagrams based exclusively on major elements was shown to be useful in several case studies (see Verma and Verma, 2013; Verma, 2012), their generalized use may be questioned by some people because of the relatively mobile nature of most of these elements.

Therefore, in the present work we have used only two sets of the newest multi-dimensional diagrams based on major elements (see below) and immobile major and trace elements (MgO, P_2O_5, Nb, Y and Zr) (Verma et al., 2013) to illustrate their use for the recognition of the most probable tectonic settings for acid rocks of Paleoproterozoic localities of Brazil. We avoid use of trace element based diagrams proposed by Verma et al. (2013) because most researchers did not publish a full suite of trace elements, very few are available. In future we will use trace element based diagrams for these localities as well. This set of fifteen new discriminant-function diagrams based on natural logarithm-transformed ratios of major elements, immobile major and trace elements (each set has five diagrams) has been proposed for the discrimination of island arc (IA, group no. 1), continental arc (CA, group no. 2), continental rift (CR, group no. 3), ocean-island (OI, group no. 4) and collision (Col, group no. 5) tectonic settings. It is important to note that this is the first set of multi-dimensional diagrams proposed to discriminate the two very similar tectonic settings of island and continental arcs in the presence of two other tectonic settings.

2. Database for study area

Fifteen localities of Paleoproterozoic age in Brazil were selected (Fig. 1). The reasons why we have chosen Paleoproterozoic rocks are as follows: Brazil is a key area to study Archean to Proterozoic terrains in South America; the Paleoproterozoic "Transamazonian" (a cycle of orogenies) was first characterized in Brazil; plate tectonics and the associated tectonic settings are generally accepted to have been in operation since the end of the Archean. A synthesis of the relevant information (locality, approximate coordinates, number of compiled samples, age, and literature references) is provided in Table 1. A schematic map showing the location of the studied terranes (cratons and belts) is provided in Fig. 1. Detailed geology and locations of samples can be consulted in the papers from which the data were compiled. In summary, data for six case studies from the Amazonian craton, five from the São Francisco craton, three from the São Luís craton-Gurupi belt, and two from the Borborema Province were compiled in Statistica software. For the ages of rocks, we followed the scheme proposed by the International Commission on Stratigraphy (Gradstein et al., 2004).

All major element chemical compositions were processed in SINCLAS (Verma et al., 2002, 2003) to ascertain that the magma type was acid and to obtain adjusted values of eleven oxides under the Middlemost (1989) option for Fe-oxidation adjustment.

3. Multi-dimensional diagrams

The discriminant functions for five diagrams were calculated from Eqs. (1)–(10) summarized in this section. Five diagrams are required to discriminate five tectonic settings of IA, CA, CR, OI and Col (Verma et al., 2013). For each diagram, two functions must be calculated for each compiled sample.

The first diagram discriminates the tectonic setting of IA and CA together as arc (IA + CA), CR + OI, and Col, for which the *x* and *y* coordinates were calculated, respectively, as $DF1_{(IA+CA-CR+OI-Col)_{macid}}$ and $DF2_{(IA+CA-CR+OI-Col)_{macid}}$ functions from Eqs. (1) and (2). In the subscript macid, m stands for major element (m) based diagram for acid (acid) magmas and refers to a newest set of multi-dimensional diagrams for acid rocks (Verma et al., 2013), this one is fifth set of diagrams. The first four sets of diagrams (Agrawal et al., 2004; Verma et al., 2006, 2012; Verma and Verma, in press) were proposed for the discrimination of basic and ultrabasic magmas, acid magma and intermediate magma.