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Boolean and fuzzy methods for identifying lateritic regoliths in the Brazilian Amazon using gamma-ray spectrometric and topographic data

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ABSTRACT

Airborne gamma-ray spectrometry is relatively well understood when associated with rocks, but the response and radioelement distribution in weathered materials is less known. This work used airborne gamma-ray spectrometry and altimetry to identify domains with higher probability of occurrence of lateritic crust and dismantling products in an area located in the west of the Brazilian Amazon. Map algebra was used through the Boolean and fuzzy techniques to create predictability digital models highlighting favorable areas for the occurrence of lateritic crusts. The Index Overlay Method was used in the Boolean technique. The fuzzy technique used the fuzzy algebraic product operator, fuzzy algebraic sum operator, and fuzzy gamma operator. Both models showed good correlation between the favorability predicted and the presence of crusts in the field, however, the fuzzy model showed higher correlation and highlighted areas not identified by the Boolean model. In contrast, the Boolean model allowed the visualization of the areas related to the influence of each variable or its possible combinations individually on the final map. Thus, the identification of lateritic crusts based on mathematic models applied to altimetric and airborne gamma-ray spectrometric data is a new tool that will contribute significantly to geological mapping and to the understanding related to the response and radioelement distribution in weathered materials.

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1. Introduction

Throughout Earth's geological history, weathering has been an important process for the modification of the landscape and formation of soils and mineral deposits and has also had a significant impact on controlling the relief and reflecting paleoclimatic variations. In humid tropical climates, lateritic crusts are the final product of weathering (Bardossy and Aleva, 1989; Tardy and Roquin, 1998). The lateritic crusts in the Amazon and along the intertropical belt are related to the Cenozoic (Lucas et al., 1989; Nahon et al., 1989; Boulangé and Carvalho, 1997; Costa, 1997; Horbe and Da Costa, 1999; Kotschoubey et al., 2005; Horbe and Da Costa, 2005).

Climate, relief, parent rock, time, and tectonics are among the main factors that affect intensity of the weathering and erosion processes; thus, these factors are strongly related to geomorphologic aspects. Thomas (1974) stated that climate is an important factor regulating weathering and therefore it determines the nature and speed of the chemical reactions on the Earth's surface. Pomerol et al. (2013) noted that the main factors related to relief evolution are tectonics and climate, whose actions are measured by long geological intervals.

Aleva (1993) and Anand and Paine (2002) noted that the lateritization process is favored by alternation between dry and wet seasons. Within this context, these authors also noted that the water table fluctuates; such fluctuations promote alternations between more or less oxidizing conditions, favor successive iron remobilization, concentrate the iron, and thus lead to the generation of ferruginous nodules. Iron accumulates during lateritization, residually forming lateritic crusts. In arid conditions, the lateritic crust tends to be preserved, thus maintaining the planation paleosurfaces, making such crusts excellent paleogeomorphologic records. In contrast, the permanent humid regime leads to intense chemical leaching and reduced water table fluctuations, thus interrupting the formation of the mottled zone and accelerating saprolite formation and degradation of the lateritic crust, which leads to the generation of oxisols. Horbe and Da Costa (2005) demonstrated the direct relationship between the lateritic crust and the overlying oxisol through textural, mineralogical, and chemical arguments and noted that the latter could be derived from the chemical alteration and consequent disaggregation of the crusts.

Taylor and Eggleton (2001) discussed climatic and topographic factors in the construction of the landscape and exploration of regoliths, particularly for Al, Fe, Mn, Ni, Cu, Pb, and Au, in addition to aggregates for civil construction. According to McFarlane (1976); Büdel (1982); Butt and Zeegers (1992), and Beauvais (1999), among others, the study of regoliths and mapping of lateritic crusts aids in the understanding of

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geomorphologic and paleoclimatic evolution and the identification of anomalous metallogenic occurrences.

The lateritic crusts in the Amazon have not been mapped at adequate scales or are located in areas with limited access. Moreover, in this region as well as other parts of Brazil, lateritic crusts have been mapped as undifferentiated sedimentary covers, which include products such as the lateritic crust itself, oxisols, nodules and pisoliths and other dismantling products. In some of these areas, there are records of several mineral occurrences, such as Ni–Co and Cu–Ni–EGP, and artisanal gold mining (Rizzotto, 2010, 2012a,b). Therefore, the identification and discrimination of lateritic crusts is essential in mineral exploration and useful for the improvement of geological mapping.

The use of the airborne gamma-ray spectrometry and altimetric data in regolith studies must be investigated, especially when applied with mathematical techniques, raster image algebra, and in the evaluation of multi-source data (e.g., Darnley and Grasty, 1971, Tucker et al., 1984, Duval, 1990, Burrough et al., 1992, Graham and Bonham-Carter, 1993, Wilford et al., 1997, Dickson and Scott, 1997, McKenzie & Ryan 1999, Zhu et al., 2010, Carrino et al., 2011, Wilford, 2012 and Dent et al., 2013).

Airborne gamma-ray spectrometry measures the concentration of potassium (K) and series of uranium (U) and thorium (Th) radioisotopes in rocks and soils at depths of 30–45 cm (Gregory and Horwood, 1961; Dickson and Scott, 1997). The intensity of gamma rays emitted from the surface depends on the mineral composition of the rock or regolith, nature and type of weathering, geological heterogeneity, distribution of allochthonous or autochthonous soils and vegetal cover, and humidity, among other factors (Wilford et al., 1997; Minty, 1997; Dickson and Scott, 1997). In general, eU, eTh, and K are the only elements that occur naturally and produce gamma rays with sufficient energy and intensity to be measured by airborne gamma-ray spectrometry (Minty, 1997).

Potassium is the most abundant radioisotope in Earth's crust; it has an average concentration of 2.4% and is generally present with high and low contents in felsic rocks and mafic rocks, respectively (Dickson and Scott, 1997, Minty, 1997). Potassium released during weathering can be partially fixed as illite. In contrast, U and Th are relatively rare compared with K, varying between 3 and 12 ppm on average. Uranium can occur as uraninite and uranothorite, whereas Th can form thorite and may be present in allanite, monazite, xenotime, and zircon at levels higher than 1000 ppm (Dickson and Scott, 1997).

During weathering, radioelements are redistributed due to geochemical reorganization. They can accumulate residually and combine to form stable to weathering minerals, such as monazite, xenotime, zircon, and thorite; alternatively, they can be incorporated into newly formed minerals, such as iron and titanium oxides and hydroxides and clay minerals, or leached. In many cases, this redistribution generates different spectrometric responses for the regolith and underlying bedrock. Dickson and Scott (1997) suggested that areas with lateritic crust tend to have low K contents and relative high Th and U contents. Moreover, Wilford et al. (1997) stated that ferruginous duricrusts, particularly those developed over greenstone, are radiometrically barren (they appear black) in a ternary RBG diagram (KThU).

Wilford et al. (1997) noted that airborne gamma-ray spectrometry is relatively well understood when associated with rocks, but the response and radioelement distribution in weathered materials is less known. Traditional geological and soil mapping can be easily performed when the area is accessible with several outcrops; otherwise, remote tools must be used to reach inaccessible areas, including Indian reservations, deep forests, areas with no roads, and areas where the lateritic crust is covered by soil. Among remote tools, remote sensing and airborne gamma-ray spectrometry can be used to provide important information that may be difficult to collect with other techniques. In accessible areas, these tools can be used as a support in the planning phase of field works, saving field time by increasing the mapping efficiency. Gamma spectrometric data are advantageous in that they provide the radioactive signatures of eTh, eU, and %K, which provide additional information for geologic mapping and can be used as a complementary tool.

The purpose of this work was to use airborne gamma-ray spectrometry and altimetry to identify geophysical and topographic parameters for the delimitation of domains with a higher probability of occurrence of lateritic crust and dismantling products. Boolean and fuzzy techniques are compared using relief and geophysical data (eTh/K, eU/K), with the aim of facilitating field work and improving the final cartographic products.

2. Materials and methods

The altimetric base used in this study was the Shuttle Radar Topography Mission (SRTM) performed in 2000, which had a spatial resolution of 30 m. The airborne gamma-ray spectrometric images were obtained by FUGRO AIRBORNE SURVEYS for the CPRM/Geological Survey of Brazil in the 2005–2006 period (refer to the airborne geophysical survey “Sudeste de Rondônia — RO” CPRM, 2006 for further information). The data were processed by LASA Prospecções S.A. and involved the application of routines in Oasis Montaj software, version 8.2.0.5, with minimum curvature interpolators and grid cells of 125 m. The main products generated from the interpolation were individual images of the eU, eTh, and K channels and the ratios eU/K and eTh/K. These products allowed for the generation of the ternary composition of K, eTh, and eU (RGB) as well as eTh/K, SRTM and eU/K (RGB) images. The software used to integrate the data was ArcGIS 10.2 with the Geosoft extension that allowed the processing of the airborne geophysical images and the integrated handling of all of the products. The statistic data were processed and interpreted using Statistica 12 software.

The method developed in this work used airborne geophysical (gamma-ray spectrometric), and elevation (SRTM) images, which were analyzed using Boolean and fuzzy mathematical modeling techniques to create predictability maps for the occurrence of lateritic crusts and verify which of the techniques is more efficient. The theoretical base was extracted from An et al. (1991); Zimmermann (1985); Bonham-Carter (1994); Moreira et al. (2003); McBratney et al. (2003); Lagacherie (2005); Carranza (2008); Carrino et al. (2011) and da Silva et al. (2015). However, some modifications were performed to improve the results.

The modeling process consisted of a series of procedures to obtain a simplified hypothetical vision of the studied attributes and the Boolean and fuzzy techniques were used. These techniques are closely related to knowledge-driven models, i.e., models based on previous information or even hypotheses obtained by an expert (Bonham-Carter, 1994 and Carranza, 2008). Field work was performed to verify and calibrate the models presented, and the geologic maps from Quadros and Rizzotto (2007) and Rizzotto (2010, 2012a) and the map of soils from the Brazilian Institute of Geography and Statistic (IBGE — Instituto Brasileiro de Geografia e Estatística) were used as support.

The kappa coefficient (κ) was computed to determine the concordance intensity between the models (predictability maps) and field data. The data used consist of information collected during field work for this research, as well as files stored in the GEOBANK (Geological Survey of Brazil database) available online at www.cprm.gov.br. To calculate the coefficient, 875 checkpoints were considered, classified as lateritic crust and non-lateritic materials.

The kappa coefficient is defined as $\kappa = (n \sum_{i=1}^{c} x_{ii} - \sum_{i=1}^{c} x_{i+}x_{+i})/(n^2 - \sum_{i=1}^{c} x_{i+}x_{+i})$,where x_{ii} is the value on line i and column i, x_{i+} is the sum of line i, x_{+i} is the sum of column i of the confusion matrix, n is the total number of samples and c is the number of classes (Cohen, 1960). According to Landis and Koch (1977), kappa is considered to have a nearly perfect agreement when it is above 0.81 and reaches 1. Substantial agreement is obtained when kappa lies within the interval 0.61–0.80. Kappa values below 0.60 are classified as moderate agreement, with values near zero indicating poor agreement.

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