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On the geology, mineralogy and geochemistry of the bauxite-bearing regolith in the lower Amazon basin: Evidence of genetic relationships

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ABSTRACT

The wide distribution of Cenozoic world-class bauxite deposits in the Amazon shows that this region was the scene of intense lateritization. The Juruti bauxites, currently being mined in the lower Amazon, are one of these deposits, where the bauxite-bearing profile is covered by thick yellow clay (Belterra Clay). The laterite profile sequence consists of a mottled horizon at the base, a massive to cavernous bauxite, an aluminous iron crust with ferruginous nodules and bauxitic nodules in contact with yellow clay on the top. Cryptocrystalline to microcrystalline gibbsite is the main mineral of bauxite; hematite, goethite, kaolinite and anatase are accessories. The same minerals constitute the upper horizons, but in distinct concentrations. The relict structures, minerals (zircon) and chemical composition suggest an affiliation to sedimentary rocks of the Paleo-Mesozoic Amazon basin (Alter do Chão formation). The mineralogy, geochemical associations and Ti mass balance show a continuous evolution from the mottled horizon to the aluminous iron crust and even to the ferruginous nodules. Kaolinite, hematite, goethite and anatase are the early minerals and gibbsite is the late mineral. Hematite, zircon and anatase are the potential carriers of trace elements. The dissolution of hematite and goethite and the reprecipitation of iron as Al-free goethite reached the bauxite horizon and strongly fixed the mobile elements (Ba, Ag, As, Bi, Hg, Mo, Se, V, Pb, Sb, Se and Zn). The increasing upward content of zircon, anatase and residual trace elements (HFSE, Sc, Ga, Sn, U, W and Y and REE) throughout the regolith, an inheritance of the bauxite-bearing laterites, enhances the affinities between the two units. The laterite was developed during the Eocene, and its cover may be a product of deep plant root activity (tropical soil forming) on the top of the profile, which formed kaolinite and Al-goethite that was transported by wash flooding during the Miocene. The bauxitic nodules may represent an incomplete second bauxitic event, as erosion had already established the actual plateau landscape during the Pliocene.

1. Introduction

The predominance of the seasonal hot and humid climate of the Amazon region dating from the Mesozoic–Cenozoic transition period is demonstrated by the widespread formation of thick, complex and mineralized lateritic profiles (Costa, 1991; Boulangé and Carvalho, 1997; Costa, 2007), which are consistent with the lateritization and bauxitization events that occurred at 65 Ma, 16 Ma and 12 Ma. The Amazonian bauxitic laterites would have been formed primarily during the fifth and sixth phases.

The principal bauxite deposits in the Amazon basin were derived from the siliciclastic and aluminosilicate rocks of the Itapecuru/Ipixuna (Paragominas deposits) and Alter do Chão formations (Juruti, Trombetas and Almerim deposits) located in the Grajaú and Amazon basins, respectively (Greig, 1977; Kotschoubey and Truckenbrodt, 1981). Smaller deposits were formed from Paleozoic sediments (Peixoto and Horbe, 2008) and Proterozoic granites, rhyolites, basalts, schists and gneisses (Costa, 2007). All of these deposits are included in Bogatyrev and Zhokov's (2009) South American bauxite province.

Dennen and Norton (1977) recognized two bauxitic horizons in the deposits of Almeirim on the lower Amazon River, which were similar to the bauxite deposits in Suriname described by Van Kersen (1956). Grubb (1979) identified a polyphasic process of evolution beginning with the complete bauxitization of the sedimentary rocks, followed

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by ferrification under podzolic conditions and a second phase of bauxitization in the fracture zones of the existing bauxite deposits. This sequence emphasizes the importance of the aluminum and iron's migration and the mechanical reworking in the formation of the lateritic profile. Kotschoubey and Truckenbrodt (1981) emphasize the polyphasic evolution, that is, the formation and partial reworking of the saprolite and iron-aluminous crust and the formation of the bauxitic horizon. Kotschoubey et al. (1997, 2005a, 2005b) subsequently added a new formation of extensive ferruginized glacis and recognized four bauxite facies that formed from the regional zoning.

Kronberg et al. (1979, 1982) identified geochemical affinities between the bauxites and the adjacent and subjacent sedimentary rocks of the Amazon basin. Although derived from igneous rocks, the rhyolites and alkaline granites found in the bauxite deposits from Pìtinga in the Brazilian state of Amazonas are similar to those found in the lower Amazon basin and Paragominas. One other marked characteristic of the Amazonian bauxite deposits is the presence of a thick covering of predominantly yellow clays, which may be reddened locally (at Carajás, derived from mafic rocks; Costa et al., 1997). This covering is known as Belterra Clay (Kotschoubey et al., 1997; Horbe and Costa, 1997, 1999), a term adopted from Sombroek (1966). The Belterra Clay is equivalent to the region's latosols (Beauvais and Tardy, 1993; Horbe and Costa, 2005; Lucas et al., 1993; Tardy, 1993; Truckenbrodt and Kotschoubey, 1981Truckenbrodt et al., 1991) and occurs in both autochthonous and allochthonous sequences deposited by mud flows or sheet floods under arid climatic conditions (Truckenbrodt and Kotschoubey, 1981) or colluvial deposition (Grubb, 1979). However, it may simply be derived from the related adjacent and/or overlying bauxites and ferruginous crusts or even from exposed saprolites (Horbe and Costa, 1997, 1999, 2005) through tropical weathering. Other possibilities include the actions of termites moving the saprolitic material to the surface (Truckenbrodt et al., 1991), the partial desaluminization of the bauxite (Bardossy and Aleva, 1989) or the in situ formation (geochemical differentiation) under the tropical rainforest and the input of biological silica (Lucas et al., 1993).

The Juruti bauxites of the lower Amazon basin were identified in the 1960s and represent a major reserve, the mining of which only began in 2010 when ALCOA opened a third bauxite mine in the Brazilian Amazonia. Despite their considerable economic value, these bauxites are poorly documented and their relationship with the regoliths is still greatly disputed. Boulangé and Carvalho (1997) have suggested an in situ formation process with no lateral input of Al or Fe, along with a progressive transformation of the crust and an individualization of the bauxite horizons. Lucas (1997) proposed an evolutionary succession characterized by the ferruginization of the sedimentary rocks of the Alter do Chão formation, the partial or total bauxitization of the crust and the development of a new lateritic profile based on the previous profile, which is more or less comparable with the Paragominas deposits. Considering these controversial aspects, the excellent profile expositions, the economic importance of the deposits and the value of understanding the processes of lateritic–bauxitic regoliths and their evolution in the Amazon, we carried out a mineralogical and geochemical study on the Juruti bauxite deposit to determine its origin and its relationship to the clay cover.

1.1. Physiographic aspects

1.1.1. The Amazon basin

The Amazon region in Brazil comprises approximately 4,500,000 km^2 of tropical forests in a hot and humid climate, though it has many climatic variations that create several sub-regions. The area of this forest merges with the drainage basin of the Amazonas–Solimões River's fluvial–lacustrine system. Inside and along the axis of the Amazonas–Solimões River, the Amazon Plain, which normally exhibits a low and flat landscape that extends for hundreds of miles, is torn locally by hills and plateaus of varying size. In its northern and southern edges stand plateaus, hills and mountains that reach up to 3,000 m altitude. This complex relief is set on a large variety of geological environments ranging from Archaean to Holocene. The Archaean is represented by the Amazonian Craton, which occupies two main regions to the north and south. This craton is subdivided into the Central Amazonian Province (Archaean basement and Proterozoic volcano-sedimentary sequences; >2.3 Ga), the Maroni-Itacaiúnas Province (2.2 to 1.95 Ga), the Ventuari-Tapajós Province (1.95 to 1.8 Ga), the Rio Preto-Juruena Province (1.8 to 1.55 Ga) and the Rondonian-San Ignacio Province (1.5 to 1.3 Ga), with decreasing ages from NE to SW (Tassinari et al., 2003). In the extensive inland depression between the two cratonic domains is the Amazon's Paleozoic sedimentary basin, which is elongated from east to west and dominated by fluvial–marine sediments. This basin was compartmentalized during the Mesozoic into sub-basins and stemmed bowls with dominantly continental fluvial–lacustrine deposits (mudstones, siltstones and sandstones) (Cunha et al., 1994). The most diverse lithologies representative of the geological environments that were exposed to the surface were transformed during the Paleogene into complex lateritic formations, where bauxite; kaolin; aluminum phosphates; and iron, nickel and manganese ores, among others, are the most significant (Costa, 1991, 1997). Cenozoic sedimentation, focused during the Miocene, was restricted to the regions near the coast, the river valleys and the southwest (Rossett and Valeriano, 2007). A laterite clay cover, known as Belterra Clay, accumulated at this time. A new phase began in the Pleistocene marking the formation of immature laterites that lacked bauxites. From the Pleistocene to the Holocene, sediments settled on the broad plains of the Amazonas–Solimões River (Costa et al., 1995; Latrubesse and Franzinelli, 2002) and formed a coastal plain represented by peat lands, mangroves and sandy bars (Behling, 2001).

The Juruti bauxite deposits are located in the municipality of Juruti in western Pará, Brazil (Fig. 1), near the right bank of the Amazon River in the lower Amazon basin. The terrain of the Juruti region encompasses dissected table uplands and related areas of pediplain. The table uplands are represented by plateaus topped with lateritic crusts, which are generally bauxitic and/or yellow-ochre clays (Belterra Clay) corresponding to the South American Geomorphological Planation Surface (Bardossy and Aleva, 1990). The pediplains are known as the lowered tablelands,

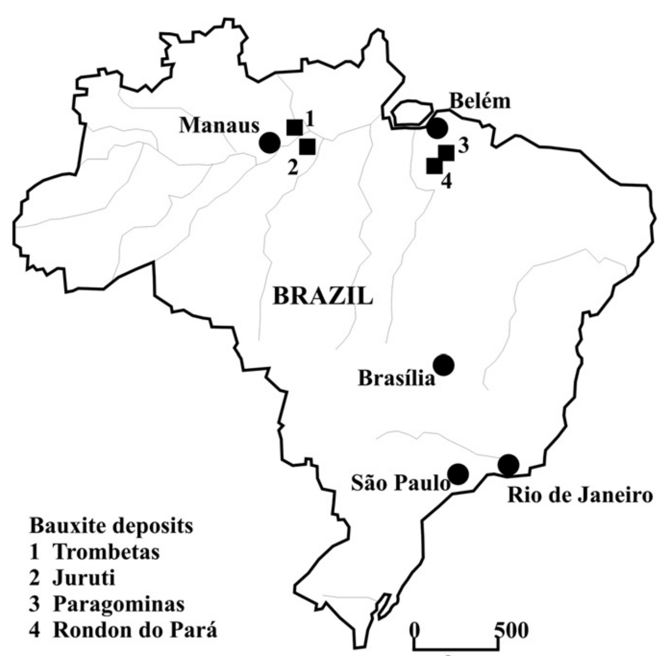

Fig. 1. Location of the bauxite deposits in the Amazonas Region, including the one at Juruti, analyzed in the present study. 1. Juruti, 2. Trombetas, 3. Paragominas 4. Rondon do Pará.