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Review of the geological and geochronological framework of the Vazante sequence, Minas Gerais, Brazil: Implications to metallogenic and phosphogenic models

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ABSTRACT

The Vazante Group, as originally described, is a thick marine carbonate-dominated succession adjacent to the Brasilia Fold Belt, on the western border of the São Francisco Craton, in south-central Brazil. The sedimentary dolomites of this group contain economically important Zn–Pb and phosphate deposits, but age constraints for the host rocks and mineralization have been controversial. New geochronological data and geological observations have indicated that the upper and middle sections of the Vazante succession belong to a Mesoproterozoic sequence that was thrust over a Neoproterozoic succession correlative with the Bambuí Group. This new stratigraphic framework has significant implications for metallogenic exploration models in both intra-cratonic and passive-margin basins of the São Francisco Craton. Although hosted in Mesoproterozoic units, most of the Zn–Pb mineralization occurred in the Neoproterozoic by circulating hydrothermal fluids during the prolonged breakup of the Rodinia supercontinent. The possibility that an initial stage of mineralization occurred earlier is considered. Phosphorite generation in the Neoproterozoic units is conceivably related to glacial events. The refined stratigraphy combined with a new mineralization model will significantly contribute to the exploration strategy for phosphate and sulfide deposits in the Mesoproterozoic and Neoproterozoic successions of the São Francisco Craton and beyond.

1. Introduction

The Vazante Group, as defined by Dardenne et al. (1998), is a thick marine carbonate-dominated succession adjacent to the Brasilia Fold Belt, on the western border of the São Francisco Craton in south-central Brazil. The sedimentary dolomites of this group contain economically important Zn–Pb and phosphate deposits, but age constraints for the succession have been controversial.

Vazante and Morro Agudo Zn–Pb mines, in the upper section of the Vazante Group, are the largest Zn deposits in South America, with reserves of more than 3 million tons of zinc. Vazante is the largest mine, producing around 170,000 tons of Zn concentrate per year (IBRAM, 2013). The phosphate deposits of Rocinha, Lagamar, in the lower section, are the most important phosphorite mines in South America, ranking among the 200 largest mines of Brazil in 2008. In recent years mine production were, respectively, 261,321 and 250,000 tons/year ROM, with grades ranging from 10 to 15% P_2O_5 (Kulaif, 2009).

Earlier lithostratigraphic comparisons and paleontological observations of *Conophyton* stromatolites suggested that Vazante carbonates belonged to the late Mesoproterozoic or early Neoproterozoic eras, with possible ages ranging between 1.35 and 0.95 Ga (Cloud and Dardenne, 1973; Moeri, 1972). Others researchers, however, suggested a possible correlation of Vazante strata with the Neoproterozoic carbonate platform of the Bambuí Group (ca. 0.9–0.6 Ga), which covers large areas of the São Francisco Craton to the east (Dardenne, 1979; Dardenne, 2000, 2001; Azmy et al., 2001; Misi, 2001). These correlations were based primarily on the similarity of diamictites at the base of both groups (Dardenne, 2000), possibly related to a Sturtian ice age (Azmy et al., 2001; Babinski and Kaufman, 2003; Babinski et al., 2007). In addition, $^{87}Sr/^{86}Sr$ compositions (0.70752 to 0.70794) of high Sr carbonate fluorapatite samples from phosphate deposits of the Rocinha

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Formation (lower Vazante) are identical to those of micrites in Irecê (Una Group likely equivalent to the Bambuí Group on the São Francisco Craton; Misi et al., 2007). These observations were consistent with a Neoproterozoic age assignment (Halverson et al., 2010; Misi, 2001; Misi et al., 1997, 2007; Sanches et al., 2007).

However, since the biostratigraphic utility of *Conophyton* as a time-marker is equivocal and Sr isotope compositions are easily reset, radiometric constraints for both the Vazante and Bambuí successions were needed to provide an absolute age for the glacial deposits a-priori assumed to be from the Neoproterozoic Cryogenian Period. Contrary to this expectation, recent geochronological studies of Vazante rocks utilizing Re/Os measurements from organic-rich shales in the upper part of the succession (Azmy et al., 2008; Geboy et al, 2013) coupled with U/Pb detrital zircon analyses (Azmy et al., 2008; Rodrigues et al., 2012) suggest that upper Vazante strata, including two potential glacial diamictites, may belong to the late Mesoproterozoic Era (Geboy et al., 2013). However, data for the lower part of the succession, including the basal glacial diamictite, indicate Neoproterozoic age.

In this paper we propose a new stratigraphic framework for the Vazante sequence (previously called the Vazante Group). The stratigraphic inversion observed results from a thrust fault near the top of the Rocinha Formation that places older rocks atop younger. This redefinition has significant implications for reviewing the metallogenic and phosphogenic models previously proposed, with important consequences for mineral exploration in both intra-cratonic and passive-margin Meso- and Neoproterozoic basins of the São Francisco Craton and other similar geotectonic settings.

2. The geotectonic context of the Brasilia Fold Belt and the Vazante sequences

The Brasília Fold Belt (BFB) lies on the western border of the São Francisco Craton and extends for more than 1000 km along an N–S trend with a width of ~300 km (Fig. 1). The belt is composed of sedimentary and meta-sedimentary rocks, including the following mega-units, according to Dardenne (2000): a) the Paleoproterozoic to Mesoproterozoic Araí and Serra da Mesa groups. The Araí Group is composed of: (i) continental pre-rift (eolian and fluvial) sediments, (ii) rift sequence, including conglomerate, breccias and intercalated volcanic rocks, and (iii) post-rift marine transgressive sediments (carbonates, quartzite). The Serra da Mesa Group consists of a thick sequence of quartzite and micaschist (~1800 m) that, although partially correlated to post-rift sedimentation of the Araí Group, are dominantly Mesoproterozoic in age; b) the Mesoproterozoic Paranoá and Canastra groups (northern and southern segments of the BFB, respectively) consisting of quartzite, pelitic and carbonate rocks metamorphosed in the greenschist facies; c) the Mesoproterozoic to Neoproterozoic Araxá, Ibiá and Vazante groups, in the southern segment of the BFB. The Araxá Group is probably correlated with the Serra da Mesa Group in the northern segment and is composed of micaceous quartzite and micaschists, with volcanic rocks associated. The Ibiá Group is composed essentially of diamictites (basal section), interpreted as glaciogenic, and of calcshists + calciferous phyllite units in the upper section. Diamictite beds have been correlated with the Jequitai Formation of the Neoproterozoic Bambuí Group, and d) the Neoproterozoic Bambuí Group, composed of glaciogenic diamictites + marine carbonates and phyllites. In addition, the BFB contains igneous intrusions and volcano-clastic sedimentary rocks of e) the Paleoproterozoic to Mesoproterozoic Niquelândia, Barro Alto and Canabrava mafic to ultramafic complexes; f) the Mesoproterozoic Juscelândia, Palmeirópolis and Indianópolis volcano-sedimentary sequences, and g) Neoproterozoic synorogenic, late orogenic, and postorogenic granitic and mafic–ultramafic bodies, including the Goiás magmatic arc.

Based on the degree of deformation and metamorphism, Dardenne (1978) and Fuck (1994) have described three geotectonic zones within the BFB from west to east. These zones consist of a western *Internal zone*, which is intensely deformed and metamorphosed to amphibolite facies, a central *External zone*, which is slightly to moderately deformed and metamorphosed, including the Vazante strata, and an eastern *Cratonic zone*, which is only slightly deformed with greenschist to sub-greenschist facies metamorphism, including the Bambuí Group. On the other hand, Marini et al. (1984) described a remarkable E–W lineament (Pirineus lineament) dividing the BFB into two segments, including a *Northern segment* in which the sedimentary rocks are well-preserved and less deformed with very low degrees of metamorphism, and a *Southern segment*, with more intense deformation and metamorphism, including the rock units of the Vazante strata. In the southern segment, the Araxá, Canastra, Ibiá, and Vazante groups were included in a complex imbricated system of nappes and thrusts, which obstructed the recognition of stratigraphic relationships between these rock units and, in some cases, even their internal stratigraphic organization (Dardenne, 1978; Marini et al., 1984).

The seven meta-sedimentary formations of the Vazante Group, as defined by Dardenne et al. (1998) and Dardenne (2000, 2001) are briefly described in structural order below. Sedimentary structures like teepee, columnar stromatolites and ripple marks suggest a normal stratigraphic succession of these rock units. Dardenne (2001) suggested that the total thickness of the Vazante Group was ~5000 m, but thrust faults from the west certainly resulted in stratigraphic repetition. Therefore, the true thickness of these units is only poorly constrained by the available outcrops and cores and will not be considered here (Fig. 2).

2.1. Santo Antonio do Bonito Formation

This unit contains graded quartzite, conglomerates, and intercalated slate beds. Diamictites are characterized by faceted and striated clasts of quartzite, as well as clasts of limestone, dolomite, meta-siltstone and granitoid, all of variable dimensions and floating in a pelitic matrix, which is locally rich in phosphate (Coromandel deposit).

2.2. Rocinha Formation

The unit contains rhythmites with white basal carbonate followed by yellow to reddish slate and meta-siltstone that pass into dark gray, carbonaceous and pyrite-rich slate with fine-grained phosphate laminations and phosphate-rich arenaceous intraclasts. There are two important phosphorite deposits in the Rocinha Formation including the stratigraphically lower Rocinha mine and the overlying Lagamar mine. Other minor phosphate deposits are also present in the formation.

2.3. Lagamar Formation

Basal beds in this interval consist of alternations of conglomerate, quartzite and meta-siltstone with dark-gray limestone clasts, known as the Arrependido conglomerate or Arrependido Member. They are overlain by laminated, brecciated, oncolitic or stromatolitic limestone and dolomite at the top. Stromatolites occur as small mounded bioherms composed of beige to pale pink dolomite, likely constructed from cyanobacterial mats, and as large columns with convex and conical laminations, classified as *Conophyton metula* and *Jacutophyton*. The latter forms were previously used to suggest an age of 1.35 to 0.95 Ga for this formation (Cloud and Dardenne, 1973; Moeri, 1972).

2.4. Serra do Garrote Formation

This unit contains dark-gray to greenish-gray slate and rhythmite with carbonaceous, pyrite-rich slate intercalated with fine-grained quartzite.