Sedimentary and tectonic breccias at the base of the Ediacaran Tamengo Formation (Corumbá Group): a comparative study

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Abstract

The Corumbá Group is a Neoproterozoic succession of terrigenous and carbonate sedimentary rocks located at the southern Paraguay Belt, central Brazil. The upper units of the Corumbá Group include the Ediacaran carbonate Bocaina and Tamengo formations, whose limit is characterized by polymictic breccias recognized in several sites from Corumbá to Serra da Bodoquena, Mato Grosso do Sul. Despite the widespread occurrence, the breccias are poorly described and their origin is uncertain. The aim of this study is to present the differences between sedimentary and tectonic breccias of the Corumbá Group and propose a genesis model for each. The sedimentary breccias comprise mainly matrix-supported chaotic facies that formed by submarine mass flows on slope aprons. Sea level fall and/or increased faulting rates exposed the underlying units and triggered the gravity fluxes by creating a steep slope. The base of the sedimentary breccia represents a major unconformity within the carbonate sedimentation of the Corumbá Group, with potential correlation to other Ediacaran units. The subsequent development of the Paraguay fold-thrust belt caused the formation of tectonic breccias in reverse fault zones. Cataclasis and mylonitization deformed the dolomitic host rock by fracturing and produced a fine foliated matrix.

KEYWORDS: Ediacaran; sedimentary breccia; fault breccia; Tamengo Formation; Corumbá Group.

INTRODUCTION

From a descriptive point of view, breccias are rocks composed of coarse angular fragments, fine matrix and/or cement (Laznicka 1988), and can be formed by several processes, in sedimentary, tectonic and igneous contexts or a combination of these (Shukla and Sharma 2018). Sedimentary breccias can be formed by karst collapse (Loucks 1999, He *et al*. 2019), submarine mass flow (McIlreath and James 1978, Krause and Oldershaw 1979, Spence and Tucker 1997), subaerial mass flow (Bertran and Texier 1999), talus sedimentation (Veevers and Roberts 1966, Tanner and Hubert 1991), evaporite dissolution (Blount and Moore Jr. 1969, Kendall and Warren 1987) and in glacial environments (Eyles *et al*. 1983). Carbonate breccias, specifically, may provide key information regarding controlling influences in the sedimentary system and basin evolution (Madden *et al*. 2017), but their origins are not always obvious (Morrow 1982).

Each process prints specific sedimentological and paleontological features that allow each breccia to be distinguished. Nevertheless, in Precambrian successions, the lack of widespread macroscopic fossils complicates the interpretation of sedimentary systems.

Regarding tectonic breccias, cataclasis is the main process during their formation (Engelder 1974), in extensional, strike-slip or compressive fault zones. It operates at relatively shallow levels (ca. 5 km) through macro (e.g. fracturing and rotation) and micro-mechanisms (e.g. chipping and intragranular extensional fracturing) in grains (Billi 2010, Ferraro *et al*. 2018), displacing fragments of a host rock. Typically, fault rocks in the damage zone and in the fault core differ regarding matrix proportion, fragments size and their fractal organization (Blenkinsop 1991, Billi and Storti 2004).

In the Corumbá Group, the limit between the Bocaina and Tamengo formations comprises a thick (tens of meters) polymictic breccia with large clasts found within the exposition along the Corumbá and Serra da Bodoquena regions. Boggiani (1998) first described this breccia as a cuneiform body that crops out along the Bonito–Bodoquena Road, Porto Morrinhos and Corumbá, and interpreted its origin as resedimentation in slope margins of the paleocontinent. In contrast, Oliveira *et al*. (2019) suggested that the breccia was formed in a carbonate inner ramp by wave reworking. Ramos (2019) interpreted the breccia origin as sediment loading on local grabens during an interval of extensional

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tectonics. Therefore, despite its widespread occurrence and key stratigraphic importance, the genesis and significance of this sedimentation interval is uncertain. Moreover, tectonic breccias, which occur closely to the sedimentary breccias at the Bocaina–Tamengo limit, have their origin often misunderstood as sedimentary.

This paper presents new data on the sedimentology of the Bocaina–Tamengo limit based on investigation of outcrops along Corumbá and the east side of Serra da Bodoquena. The sedimentary polymictic breccia located in the Bocaina–Tamengo boundary is described and analyzed together with associated deposits in order to establish details of its depositional setting, provenance, and potential tectonic and paleoenvironmental relevance.

GEOLOGICAL SETTING

The Paraguay Belt is a Neoproterozoic to early Cambrian fold-thrust belt located southeast of the Amazonia Craton and east of the Rio Apa Cratonic Terrane, created during the amalgamation of western Gondwana (Alvarenga et al. 2009, Campanha et al. 2011). It is divided in two parts, with the Cenozoic Pantanal Basin in between (Fig. 1A). The southern and northern parts of the Paraguay Belt hold significant differences regarding lithostratigraphy and age distribution (Boggiani and Alvarenga 2004, Alvarenga et al. 2011, Babinski et al. 2018).

In the southern Paraguay Belt, the orogenic front migration to the west deformed the rocks of the Corumbá Group during the evolution of the fold-thrust belt (D'el-Rey Silva et al. 2016). Moreover, the main thrusts likely reactivated
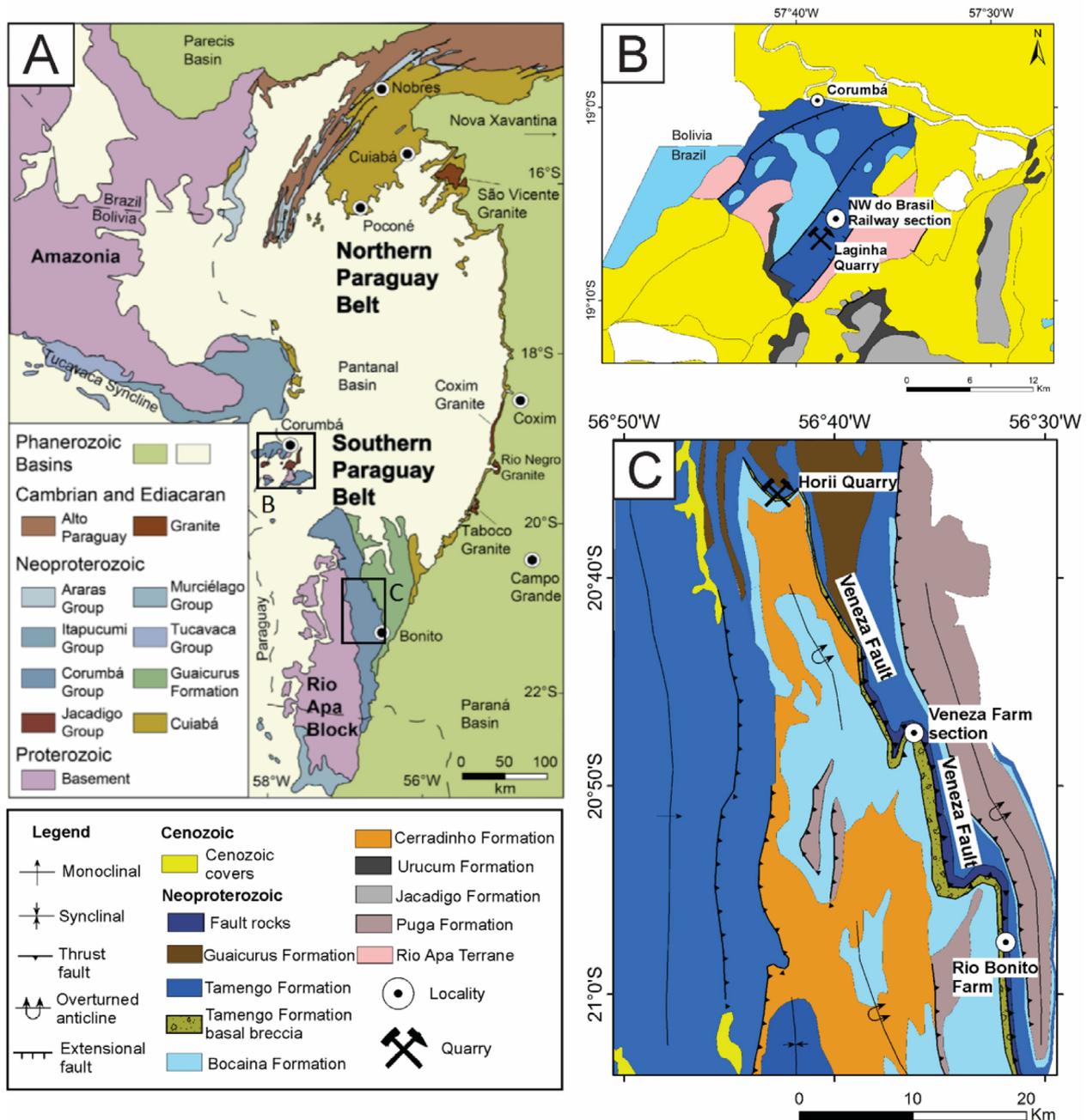
Figure 1. (A) Geological map of the Paraguay Belt. Black rectangles indicate the study areas (modified from Babinski et al. 2018). (B) Geological map of the Corumbá region (based on the CPRM Mato Grosso do Sul 1:1,000,000 map). (C) Geological map of the Serra da Bodoquena region (modified from Campanha et al. 2011).

listric faults originated during the rift stage (Campanha *et al.* 2011). In the Serra da Bodoquena region, an important 50km long thrust fault truncates the rocks at the Bocaina–Tamengo limit. This fault (Veneza Fault; Fig. 1) is oriented roughly at N-S/45ºE and bears the cataclastic rocks studied in this work.

The Corumbá Group occurs both in the cratonic area and in the fold-thrust belt domain. It is divided in five units, namely the Cadiueus, Cerradinho, Bocaina, Tamengo and Guaicurus formations, from base to top (Almeida 1965, Boggiani 1998). The two lower units are often associated to the rift stage of the Corumbá Basin evolution, whereas the upper section is traditionally related to the passive margin setting (Boggiani 1998, Boggiani *et al.* 2010). However, recent studies suggested that the sedimentation of the upper units took place in a foreland basin context, after the basin inversion (Campanha *et al.* 2011, McGee *et al.* 2018).

In the Cadiueus and Cerradinho formations, terrigenous facies predominate, specifically conglomerates, arkosic sandstones and shales (Almeida 1965, Boggiani 1998, Boggiani *et al.* 2010). Gaucher *et al.* (2003) described organic-walled microfossils in the Cerradinho Formation, which are consistent with an Ediacaran age. The Bocaina Formation marks the onset of carbonate sedimentation, with stromatolitic dolomudstone facies and phosphorite layers (Boggiani *et al.* 1993, Fontaneta 2012), with a Doushantuo-Pertatataka-like acritarch fossil assemblage (Morais *et al.* 2021). The Tamengo Formation comprises breccias, grainstones and wackestones interbedded with shales, with *Cloudina* and *Corumbella* skeletonized fossils (Hahn *et al.* 1982, Hahn and Pflug 1985, Adorno *et al.* 2017, Becker-Kerber *et al.* 2017, Zaine and Fairchild 1985, 1987), acritarchs (Zaine 1991, Gaucher *et al.* 2003), macroalgae (Diniz *et al.* 2021) and vendotaenids (Becker-Kerber *et al.* 2021). Lastly, the younger unit of the Corumbá Group is the Guaicurus Formation, characterized by a thick succession of organic-rich black shales (Boggiani *et al.* 2010, Fazio *et al.* 2019, Amorim *et al.* 2020), with organic-walled microfossils (Gaucher *et al.* 2003). The Guaicurus Formation marks the final stages of sedimentation of the Corumbá Group, likely during the Late Ediacaran and Early Cambrian (McGee *et al.* 2018).

The base of the Tamengo Formation is marked by the polymictic sedimentary breccia studied in detail in this paper. U-Pb ages for ash beds at the top of the Bocaina Formation of 555.18 ± 0.30 Ma and at the upper Tamengo Formation of 541.85 ± 0.75 Ma (Parry *et al.* 2017) allows for the erosional and depositional processes responsible for the breccia formation to be placed within this interval, once the breccia bed is stratigraphically located between these two units. Importantly, this sedimentary breccia crops out both in the Serra da Bodoquena and Corumbá regions, over 250 km apart (Boggiani 1998). Where the Tamengo Formation overlies other units than the Bocaina Formation, the breccia is absent (Almeida 1965), implying a stratigraphic and paleogeographic control of its occurrence.

METHODS

The breccias facies were analyzed in outcrops in the Serra da Bodoquena and Corumbá regions (Figs. 1B and 1C), where one columnar section in each location was surveyed, focusing on clasts lithologies and sedimentary structures. During the field work, in the Laginha Quarry, all the clasts with a diameter greater than 0.5 cm in 1 m x 1 m *in situ* squares located in four different stratigraphic positions along the Tamengo Formation basal breccia body (lower, lower middle, upper middle and upper; Fig. 2A) were counted. In total, 537 clasts were considered for a more statistically accurate distribution. Additionally, petrographic analysis of 22 thin sections of the breccia facies and associated rocks were carried out.

Tectonic breccias were classified according to the descriptive nomenclature of fault rocks proposed by Woodcock and Mort (2008), which considers the proportion of large clasts (> 2 mm), small clasts (0.1 to 2 mm) and matrix (< 0.1 mm). This is a useful method of field and petrographic classification, and contrasts with most of the genetic classifications available for fault rocks. The carbonate sedimentary facies description followed the traditional classification of Dunham (1962).

RESULTS

Serra da Bodoquena region

In the Serra da Bodoquena region, the breccias crop out continuously along the Bonito–Bodoquena road up to the Horii Quarry Hill, for nearly 60km in extension (Fig. 1). There are two thick (ca. 30 m) sedimentary breccia beds, B1 and B2 (Fig. 3), separated by layers of dolomudstone and dolomitic ooid wackestone. At the top of B2, there is a tectonic contact with rocks from the Veneza Fault (B3). The layers are oriented roughly at N-S/40ºE, following the regional structure of the Paraguay Belt.

Both B1 and B2 are dolomitic matrix-supported to clast-supported carbonate breccia facies (Fig. 4) and do not present paleocurrent structures. B1 contains poorly sorted subrounded to angular clasts of dolomudstone (62%) (Fig. 5), phosphorite (14%), silexite (9%), limestone (6%), sandstone (5%), and ooid grainstone (4%) (Fig. 4D), whereas B2 mainly contains clasts of dolomudstone (> 99%) and sandstone (< 1%) (Fig. 4A). Some of the ooid grainstone clasts present giant ooids (diameter > 2 mm; Sumner and Grotzinger 1993), as shown in Figure 5C, which are usually reported in sedimentary facies of the Bocaina Formation (Boggiani 1998). The clast sizes, in both beds, range from 0.2 cm to nearly 70 cm in diameter, with a rough fining-upwards tendency. The overall matrix proportion ranges from 15 to 55% (Figs. 4A to 4C). The matrix of B1 and B2 shows different degrees of recrystallization, even within the same breccia layer, from widely to locally recrystallized (Figs. 5A, 5B and 5E). Moreover, the amount of quartz in the matrix is minimal, with only few sparse angular crystals (Fig. 5A). Diagenetic features of B1 and B2 include bladed calcite crystals as cement (Fig. 5D), recrystallization and dolomitization.

The B3 rocks vary greatly in the different zones of the Veneza Fault regarding textural parameters. Nevertheless, the limits of these zones are not well defined and local variations are frequent, suggesting a highly heterogeneous shear. In the
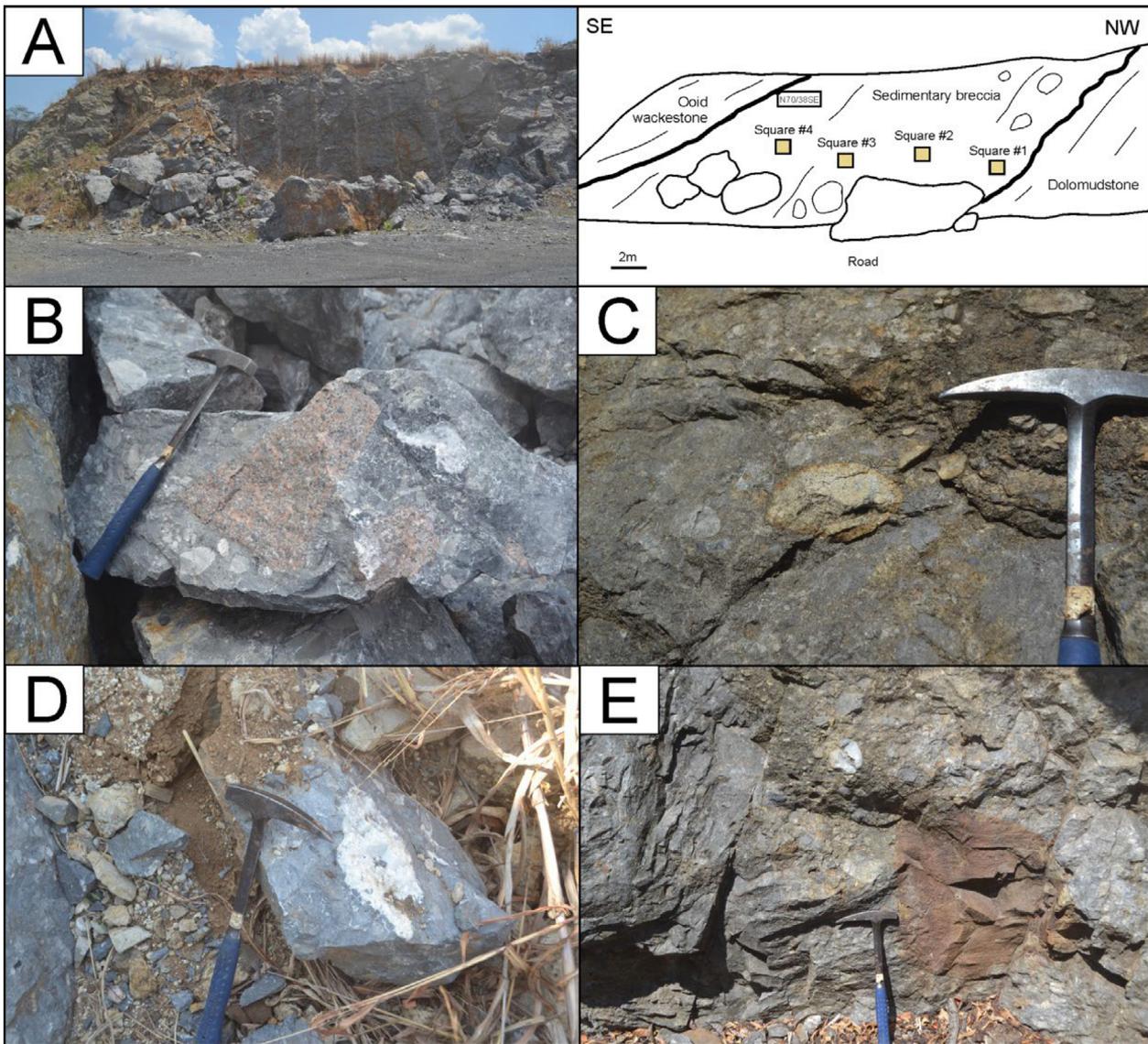
Figure 2. Photographs of the Tamengo Formation sedimentary breccia in Corumbá. (A) Laginha Quarry outcrop with the approximate stratigraphic positions of the squares where the clasts were counted. (B) Angular granite clast. (C) Rounded quartzite clast. (D) Pocket of white sparry calcite. (E) Reddish sandstone clast.

damage zone, the breccia comprises angular and fractured ooid grainstone, sandstone and dolomudstone fragments that have frequent points of contact with each other (Fig. 6A), supporting an incipient calcite-rich matrix.

In the transition between the damage zone and the core of the Veneza Fault, the matrix proportion of the fault breccia is greater than 60% and lower than 90%. Matrix shows a well-developed foliation deflected around bigger dolomudstone fragments (Fig. 6). These fragments present small-scale faults, which are indicative of shear and rotation. Petrographic details reveal that the matrix is composed of oriented calcite crystals (Figs. 7A, 7B and 7C). In this portion, contacts between fragments are less common.

The fault core presents a highly oriented calcitic matrix, with proportion greater than 90% (Fig. 6D). Sparry calcite in veins is common in both matrix and fragments (Figs. 6C and 7D). The Veneza Fault rocks evolve from mosaic breccias to ultracataclasites, as they edge towards the fault core (Fig. 6F). The cataclasite nomenclature was chosen instead of mylonite

due to the interpretation of cataclasis as the main deformation mechanism, although ductile processes likely took place as well.

Corumbá region

The polymictic breccia at the base of the Tamengo Formation holds different characteristics in the Serra da Bodoquena and Corumbá regions, despite its occurrence at the same stratigraphic position in both locations (Fig. 3). The most exposed sections of the Tamengo basal breccia in Corumbá are located in the Laginha Quarry and in the Noroeste do Brasil Railway, 1.3 km apart, with only a few sedimentological differences. No cataclastic breccias associated to the Tamengo Formation were found in the Corumbá region.

In the Laginha Quarry, the breccia bed is nearly 12 m thick and shows both the basal erosional contact with dolomites of the Bocaina Formation and the superior contact with ooid wackestones, presenting a general orientation of N70º/40ºSE (Fig. 2A). Ramos (2019) described a 25 cm thick friable yellowish-brown muddy sandstone with lithoclasts and argillaceous
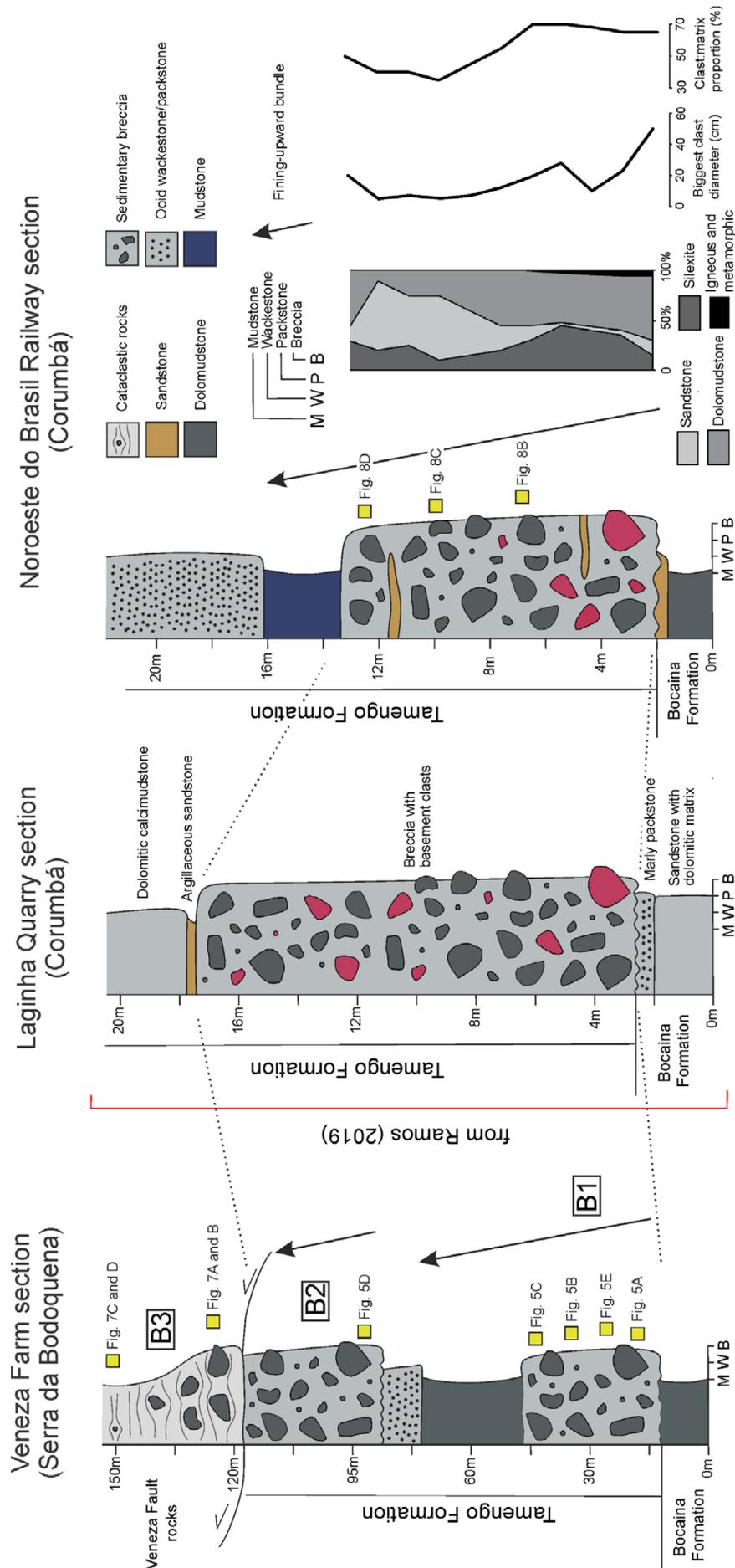
Figure 3. Columnar sections of the Bocaina – Tamengo limit at the Veneza Farm (Serra da Bodoquena), Laginha Quarry (Corumbá, from Ramos 2019) and Noroeste do Brasil Railway (Corumbá). Yellow squares indicate the stratigraphic position of photomicrographs of Figures 5, 7 and 8. Red blocks represent basement clasts.
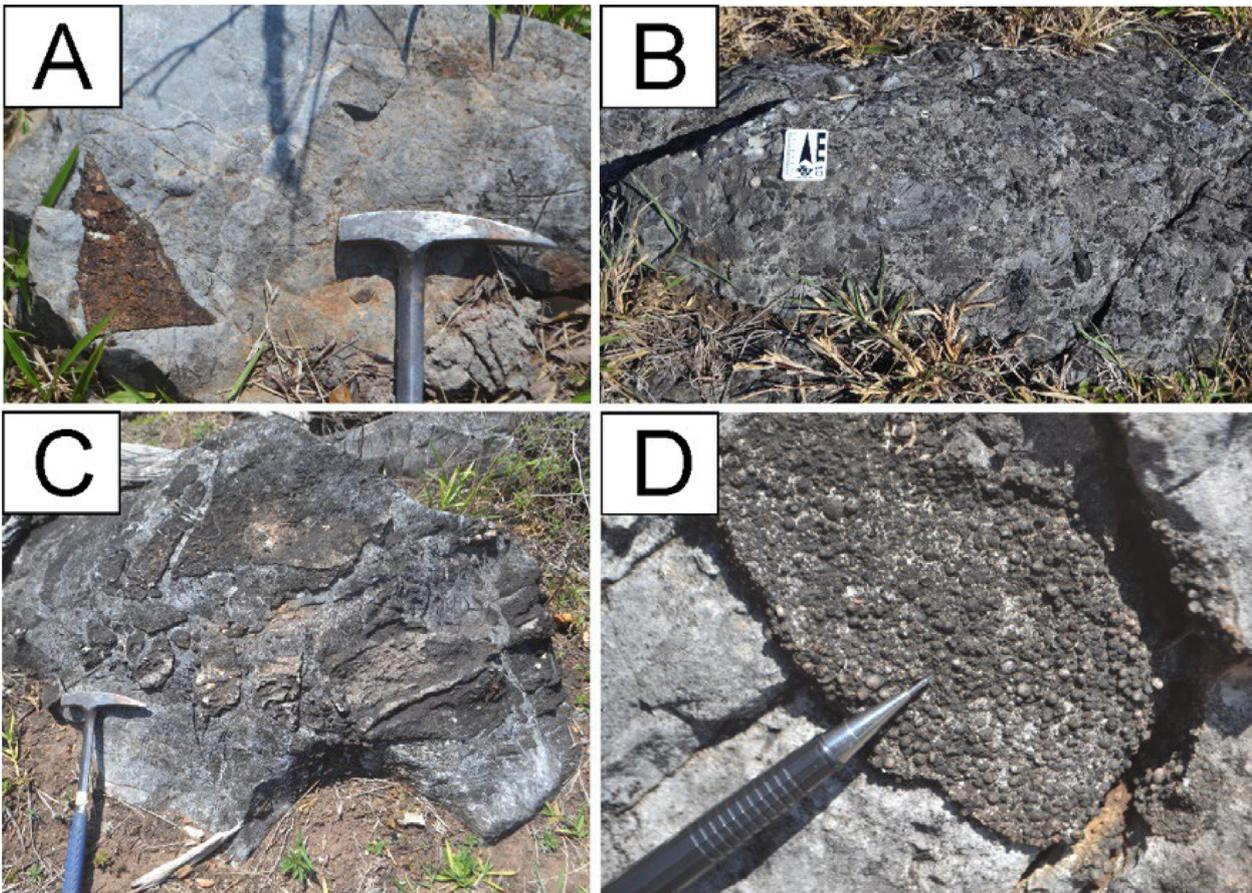
Figure 4. Photographs of the Tamengo Formation sedimentary breccia at the Serra da Bodoquena region. (A) Angular sandstone clast amidst abundant dolomudstone matrix. (B) Orthobreccia facies with grayish dolomudstone and silexite clasts. (C) Parabreccia facies with blackish angular silexite clasts. (D) Rounded ooid grainstone clast.

matrix right above the breccia layer in the same section. The breccia contains a calcitic matrix, occasionally recrystallized (Fig. 8). The clasts consist of several lithologies, including silexite, dolomudstone, limestone, sandstone, gneiss, phyllite, granite, shale, conglomerate, quartzite (Figs. 2B to 2E), and phosphorite (Fig. 8A). Clasts are subrounded to angular and some are up to 60 cm in diameter. The clast counting shows that changes on lithologies within the breccia bed are not evident (Fig. 9), with nearly all types of clasts being present in all stratigraphic positions.

In the Noroeste do Brasil Railway section, the breccia is nearly 11 m thick. The matrix is calcitic in nature, locally recrystallized, and with a great proportion of quartz grains, up to 60% (Fig. 8B). The matrix proportion also increases to the top, from 30 to 70% (Fig. 2). The main clast types are dolomudstone, sandstone, silexite and lithologies from the crystalline basement (granite, gneiss and quartzite). Their proportions change stratigraphically, with basement clasts occurring only in the first 5m. In thin section, silicified ooid fragments are present (Fig. 8C). Paleocurrent and imbrications structures are absent, but the entire breccia body comprises a fining-upwards bundle, once the biggest clast diameter decreases to the top, from 55 cm to 20 cm (Fig. 2).

Regarding diagenetic features, stylolites surfaces are frequent in the breccia matrix, as well as portions with sparry calcite and fluorite as centimetric venules and pockets. Moreover, elliptic ooids are recorded in the ooid wackestone facies right above the breccia layer, indicating mechanical compaction.

DISCUSSION

The sedimentary and tectonic breccias of the upper Corumbá Group differ greatly regarding petrographic and structural aspects, recording processes of different natures, as discussed below.

Tamengo Formation sedimentary breccia

Depositional setting

Previous investigations developed on the Tamengo Formation display different viewpoints and explanations regarding the genesis of the breccia interval. Oliveira *et al.* (2019) proposed a carbonate ramp model for the Tamengo Formation, in which the breccia would be formed in a wave-dominated inner ramp. However, reworking by wave alone could explain neither the occurrence of angular igneous and metamorphic clasts nor the abundance of a fine matrix, as well as the wide regional distribution of the breccia. Amorim *et al.* (2020), on the other hand, proposed the ramp model only for the Tamengo Formation above the basal breccia, without including it in the model. Regardless of the proposed interpretation, the stratigraphic position of the breccia layer at the basal Tamengo
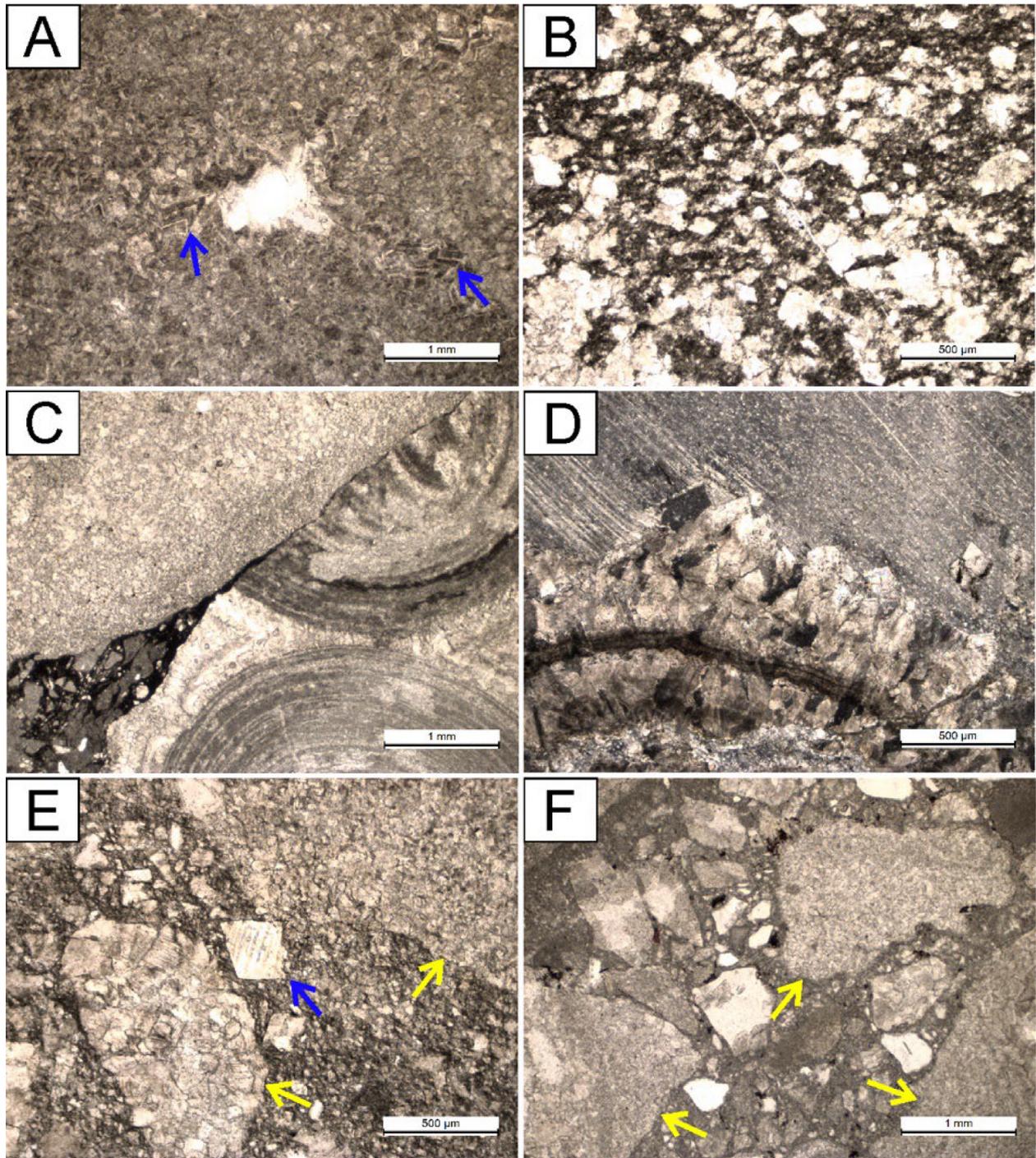
Figure 5. Photomicrographs of the Tamengo Formation sedimentary breccia at the Serra da Bodoquena region. (A) Recrystallized dolomitic matrix, with rhombohedral dolomite (blue arrows) and quartz. (B) Partially recrystallized dolomitic matrix, with incipient rhombohedral dolomite and dark dolomicrite. (C) Contact between the dolomitic matrix and an ooid grainstone clast with giant ooids (> 2 mm). (D) Bladed calcite crystals in B2 facies. (E) Dolomudstone clasts (yellow arrows) in dolomitic matrix with sparry dolomite (blue arrow). (F) Dolomudstone clasts in dolomicritic quartz-rich matrix. Only (D) is planepolarized.

Formation and above the Bocaina Formation seems to be consensus. Therefore, the stratigraphic and sedimentological similarities, as will be shown, indicate that the breccia facies at Corumbá and Serra da Bodoquena are genetically related.

The poorly sorted nature of the breccia, with subrounded to angular clasts, points to relatively short reworking distances and rapid deposition. In addition, high energy is also required to displace and movement meter-scale clasts. The lack of tractive sedimentary structures suggests a high-density cohesive flux, which is endorsed by the abundance of fine carbonate matrix in most outcrops. We propose that the sedimentological data presented herein are consistent with reworking by gravity flows downslope, such as slumps, slides and debris flows. Such mass fluxes occur on the steep margins of carbonate platforms, are poorly channelized (Nichols 2009) and can be triggered by several processes, such as earthquakes, wave or tidal loading, pore-water pressure, subaerial exposure and sediment accumulation (Spence and Tucker 1997, Locat and Lee 2005) in deepwater environment. Sea-level fall exposes the underlying units and causes sediment instability at the
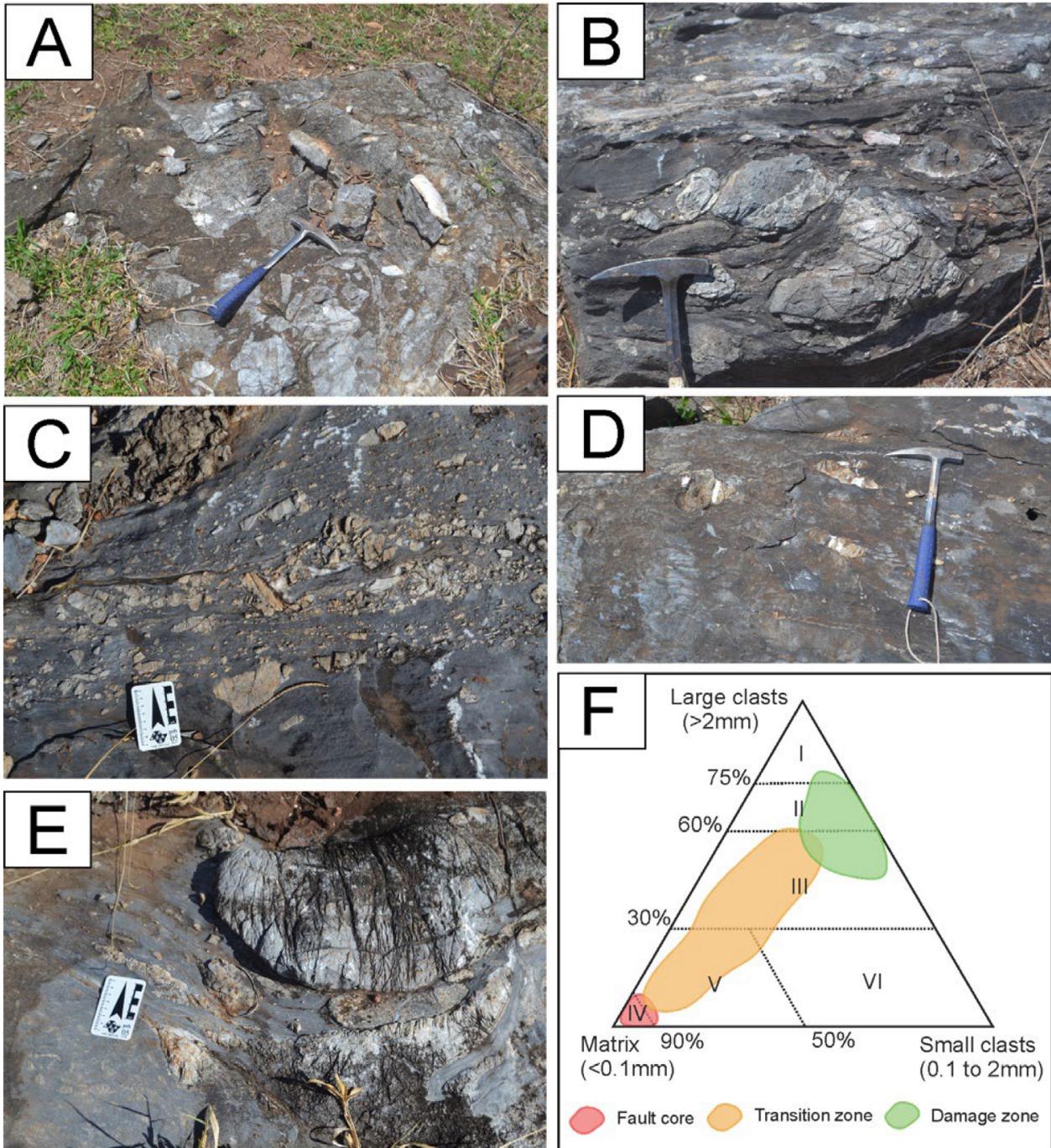
Figure 6. Veneza Fault rocks, in the Serra da Bodoquena region. (A) Damage zone with fractured dolomitic host rock. (B) Transition zone with foliated matrix and dolomudstone fragments. (C) Transition zone with dolomudstone fragments of different sizes and white sparry calcite filling fractures. (D) Transition zone with elongated dolomudstone fragments and abundant matrix. (E) Deflected matrix and fragments around a bigger dolomudstone fragment. (F) Classification of the Veneza Fault rocks from estimated proportion of grain sizes (nomenclature from Woodcock and Mort 2008).

top of the slope. Moreover, the normal faulting rate also influences the timing of depositional cycles and the initiation of the gravity flows on carbonate slopes by steepening the topography (Quiquerez *et al.* 2013, Jo *et al.* 2015), although there are no evidences of synsedimentary faulting for the Tamengo Formation. The steepened palaeotopography could also be inherited from the Bocaina Formation carbonate shelf, which may have generated a steep reef slope. As Ramos (2019) suggests, the genesis of the breccia is related to rapid sediment infill in grabens formed by normal faulting, both sea-level fall and high faulting rate may have controlled the gravity flows

that formed the basal beccia facies. The diverse and complex clast composition also does not point to a single control to trigger these fluxes (Reijmer *et al.* 2015).

The fining-upwards tendency at the Noroeste do Brasil Railway section suggests that the breccia was formed in a single sedimentation pulse, with decrease in the supply of coarse clasts (*e.g.* Surlyk 1978, Eyles and Januszczak 2007). On the other hand, in the Serra da Bodoquena region, each facies (B1 and B2) likely record several pulses, once thicker beds are more likely to represent multiple flows (Eyles and Januszczak 2007). This difference and the variable thickness of the breccia layers
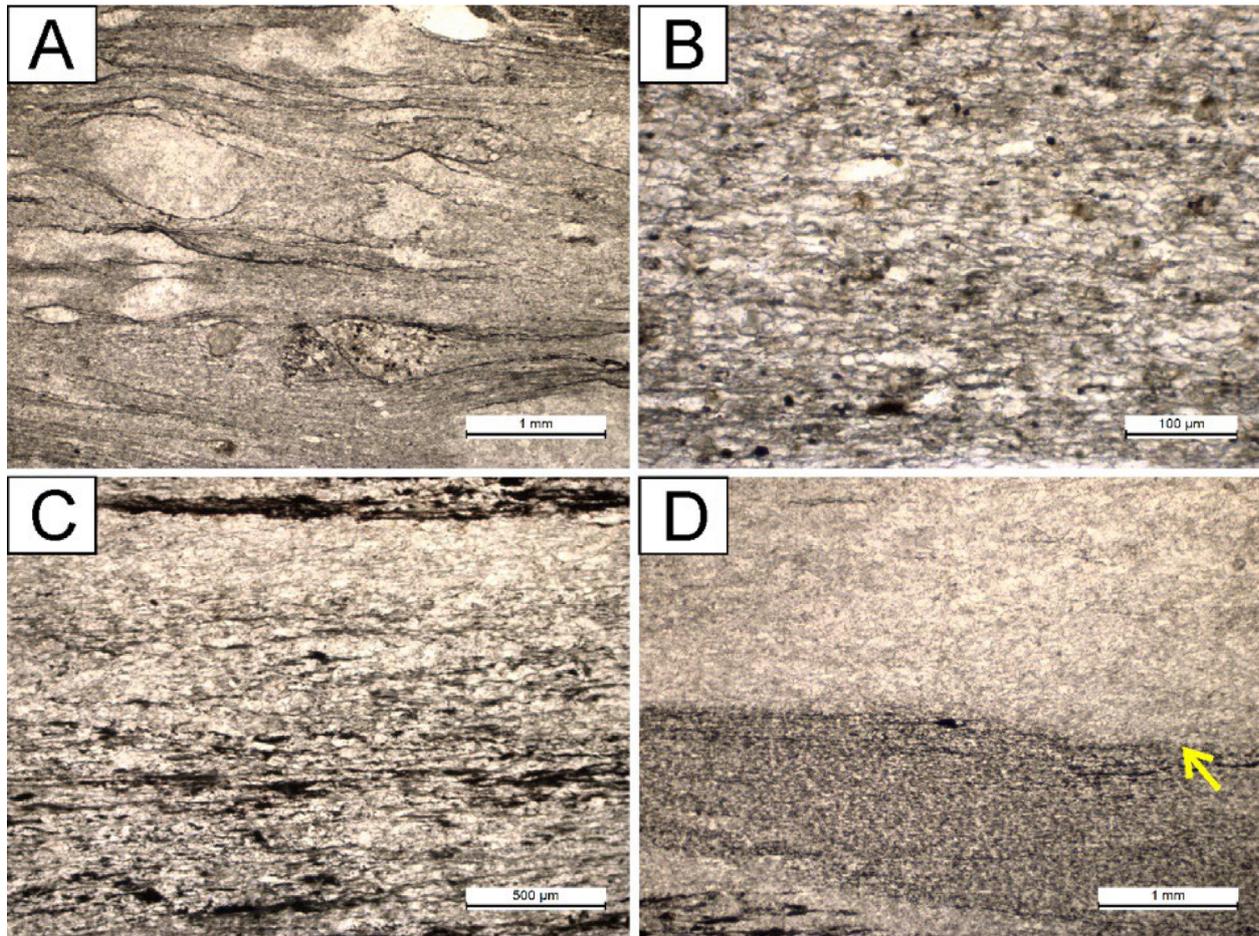
Figure 7. Photomicrographs of the Veneza Fault rocks. (A) Cataclastic breccia from the transition zone, with dolomudstone fragments and oriented calcitic matrix. (B) Highly oriented calcite crystals from the matrix. (C) Ultracataclasite portion, with highly oriented small calcite crystals. (D) Contact (yellow arrow) between a calcite vein and the ultracataclasite.

denote a highly heterogeneous process, despite its lateral continuity of over 250 km, indicating that the flows occurred in slope aprons, not being fed by discrete points, such as localized submarine fans or turbidite channels (Mutti 1985).

The breccia also underwent several diagenetic processes. Neomorphism is the most evident, with wide matrix recrystallization in both the Corumbá and Serra da Bodoquena regions. Stylolites indicate pressure dissolution due to chemical compaction. Mechanical compaction can be inferred by the elliptical ooids in the ooid wackestone facies right above the breccia bed in the Corumbá sections. Bladed calcite crystals indicate cementation under phreatic or vadose marine conditions (Dias-Brito 2017), preferentially with little Mg^{2+} in solution (Badiozamani *et al.* 1977). Furthermore, venules of sparry centimetric calcite and fluorite indicate fluid circulation.

Therefore, the sedimentation model for the Tamengo Formation basal breccia comprises the following main processes:
- sea level fall and/or increased faulting rate exposes rocks of underlying units, causing fracturing and displacement of clasts, creating a steepened topography;
- slumps, slides and debris flows on a reef slope apron, likely inherited from the Bocaina Formation palaeotopography, reworks these clasts amidst a micritic/dolomicritic matrix;
- the breccia is deposited at the lower slope, where it locally undergoes seafloor cementation.

Provenance and regional relevance

The polymictic nature of the breccia reflects the complexity of the source area (McIlreath and James 1978) and allows for interpretation of its provenance. Dolomudstone, phosphorite, silexite and ooid grainstone, with giant ooids, are all facies of the Bocaina Formation that appear as clasts in the breccia, implying that this formation was likely a source unit. The same logic can be applied to sandstone, shale and phyllite facies for the Cerradinho Formation, and granite, gneiss and quartzite for the igneous and metamorphic basement, with the difference that these lithologies appear less frequently as clasts in the breccia. Some of the sandstone clasts may be syndepositional. The basement rocks in the Corumbá region occur in the northernmost part of the Rio Apa Cratonic Terrane (Faleiros *et al.* 2016). They present K-Ar (biotite) ages of 1730 ± 22 Ma, K-Ar (K-feldspar) ages of 889 ± 7 Ma for granites (Hasui and Almeida 1970) and U-Pb SHRIMP ages of 1808 ± 7 Ma for felsic gneiss (McGee *et al.* 2018). These are in accordance with the obtained ages for detrital zircon, from 900 to 1900 Ma, for the Tamengo Formation (Babinski *et al.* 2008). Therefore, the occurrence of igneous and metamorphic clasts in the basal breccia represents further evidence indicating that the Rio Apa is the basement source for the lower Tamengo Formation.

The studied sedimentary breccia marks the change in the sedimentation regime and chemistry, from dolomitic tidal plain
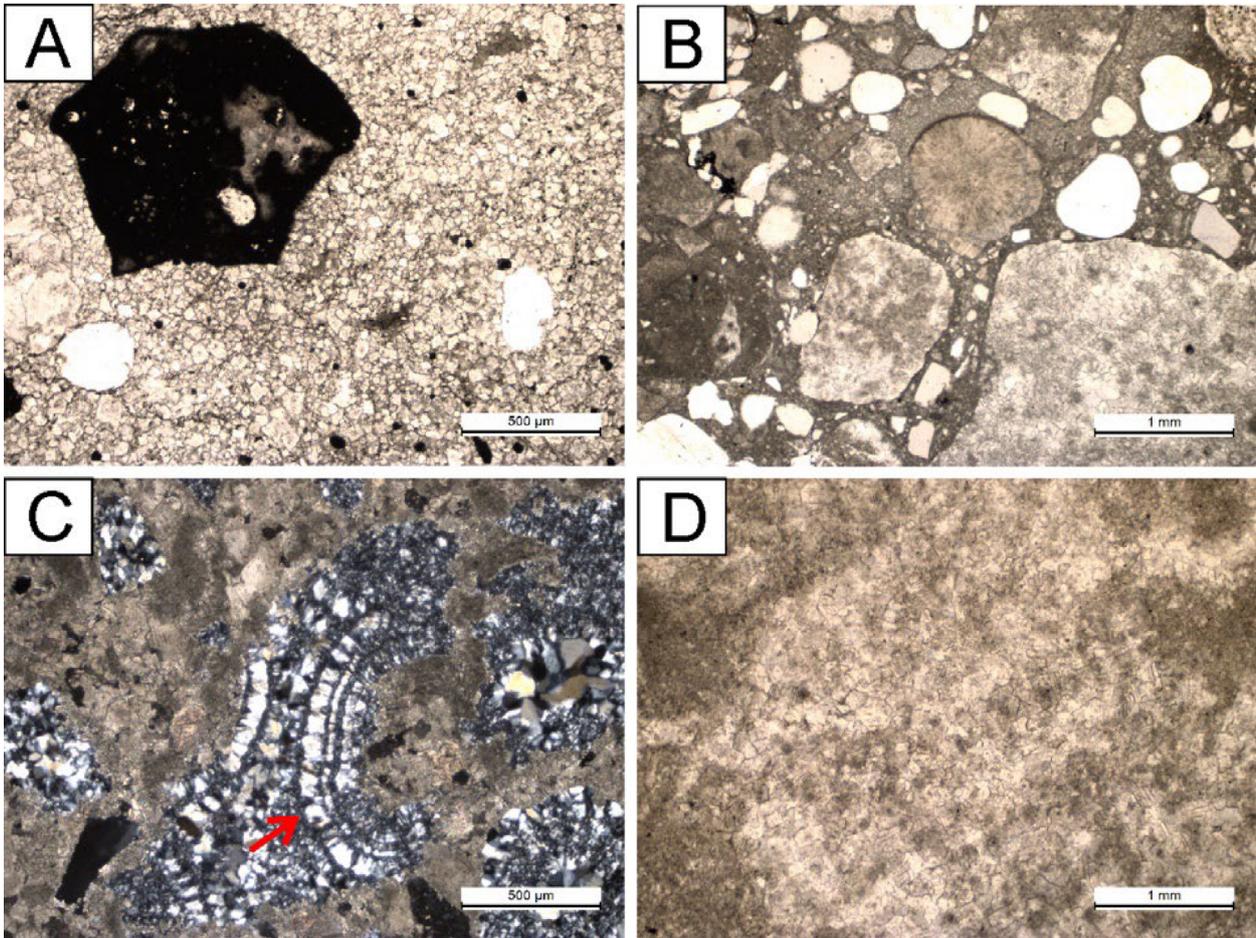
Figure 8. Photomicrographs of the Tamengo Formation sedimentary breccia in the Corumbá region. (A) Angular phosphorite clast in recrystallized calcitic matrix. (B) Dolomudstone matix amidst micritic quartzrich matrix. (C) Silicified ooid structure (red arrow) amidst micritic matrix. (D) Partially recrystallized calcite matrix. Only (C) is plane-polarized.
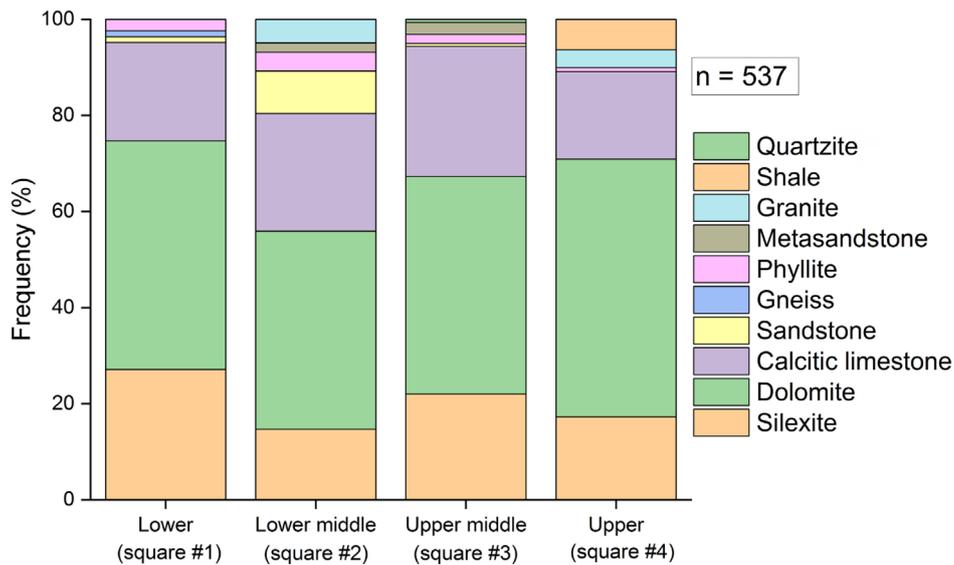
Figure 9. Relative distribution of clasts lithology in the sedimentary breccia of Tamengo Formation at the Laginha Quarry section, Corumbá.

of the Bocaina Formation (Boggiani 1998, Fontaneta 2012) to calcitic storm-dominated ramp, which coincides with the first appearances of the *Cloudina* fossils in the Tamengo Formation (Oliveira *et al.* 2019, Amorim *et al.* 2020). As paleogeographic studies indicate that the Rio Apa and Amazonia cratons were

likely at high (Li *et al.* 2008) to mid paleolatitudes (Tohver and Trindade 2014) around 550 Ma, carbonate sedimentation of the Tamengo Formation and breccia deposition on steep slopes are relevant paleogeographic indicators that may question the validity of these magnetic poles and paleogeographic

models. The possible link between the breccia deposition and the Corumbá Basin inversion, from passive margin to foreland setting, as proposed by Campanha *et al.* (2011), cannot be ruled out, although further studies regarding sedimentary provenance must be carried on.

U-Pb ages of ash beds at the top of both Bocaina and Tamengo formations place the erosional episode responsible for the breccia formation between 555 and 542 Ma (Parry *et al.* 2017). The breccia represents a key unconformity within the carbonate units of the Corumbá Group, matching some of the criteria to place it as a first-order sea-level change, such as its great areal extent, the magnitude of the deepening of sea-level and the degree of change in sedimentary regime (Catuneanu *et al.* 2005). Thus, the Tamengo Formation basal breccia may contribute to the correlation with its counterparts in Southwestern Gondwana as similar stratigraphic patterns are recognized in other Ediacaran units (Misi *et al.* 2007) and geochronologial markers are often scarce.

Correlations

Possible counterparts for the Tamengo Formation basal breccia may be found in the Arroyo del Soldado, Sierras Bayas, Nama and Cango Caves groups. In the Arroyo del Soldado Group (Uruguay), the Polanco Formation records sea-level fall and negative δ^{13}C values in Cloudina-bearing carbonates (Gaucher *et al.* 2004, Frei *et al.* 2011), similarly to the basal Tamengo Formation (Boggiani *et al.* 2010, Spangenberg *et al.* 2014). Due to its mid-shelf depositional environment, deeper than the Tamengo Formation, it did not come to breccia deposition, only cross-bedded calcarenite. The Barriga Negra Formation is a thick breccia and conglomerate unit in the Arroyo del Soldado Group, also interpreted as gravity flows on faulted margins (Demarco *et al.* 2019). However, it is now considered the base of the group, related to older (Paleoproterozoic) carbonates, characterized by low ^{87}Sr/^{86}Sr ratios (0.7044 – 0.7050) (Frei *et al.* 2013, Gaucher 2014). In the Sierras Bayas Group (Argentina), carbonate, phosphate-bearing breccias assigned to the Avellaneda Formation (Arrouy *et al.* 2015) overlie limestones of the Loma Negra Formation (Barrio *et al.* 1991, Gaucher and Poiré 2009). The occurrence of Cloudina in the Loma Negra Formation (Gaucher *et al.* 2005) suggests an age similar to the Tamengo Formation.

Another important correlation is proposed by Germs and Gaucher (2012), associating the breccia in the Tamengo Formation to the Vingerbreek Unconformity, which is recognized in the upper Kuibis and lower Schwarzrand subgroups in the Nama Group (Namibia), as well as in the Kombuis Member of the Matjies River Formation in the Cango Caves Group (South Africa) (Praekelt *et al.* 2008). This unconformity was formed by a glacial event (Vingerbreek Glaciation; Hofmann *et al.* 2015) and is related to Cloudina-bearing limestones and negative δ^{13}C excursions down to –3‰ (Germs and Gaucher 2012). The Vingerbreek Unconformity is tightly constrained between 549 ± 1 Ma and 545 ± 1 Ma (Grotzinger *et al.* 1995, Germs and Gaucher 2012). Therefore, the sea-level drop responsible for the breccia at the base of the Tamengo Formation may be glacio-eustatic in origin and correlated to other units of the Southwestern Gondwana.

Veneza Fault's tectonic breccias

The tectonic breccias occur in the Veneza Fault zone, in the Serra da Bodoquena region. The main process responsible for their formation was cataclasis, which was caused by three major mechanisms:

- fracturing of the host rock (in this case, dolomudstone, dolomitic breccia and other facies of the Bocaina and Tamengo formations);
- rotation of fragments;
- matrix foliation.

As a result, a textural difference can be found in distinct parts of the fault zone, with increasing overall matrix proportion from the damage zone to the fault core.

Time evolution models of carbonate fault rocks can be widely found in the literature (e.g. Billi *et al.* 2003, Billi and Storti 2004, Ferraro *et al.* 2018), although models that consider foliated matrix are rare. Usually, the cataclasis onset is the fracturing of the host rock, which then progresses to brecciation, with formation of angular fragments and an incipient matrix. The matrix proportion, then, increases as the faulting proceeds and more comminution occurs in the grains, displacement of fragments and abrasion. The endmembers of fault rocks developed in this model are ultracataclasites and ultramylonites, with more than 90% of matrix. The rocks of Veneza Fault follow this model, with the addition of generating foliated matrix due to intense shear (Fig. 10). Although cataclasis
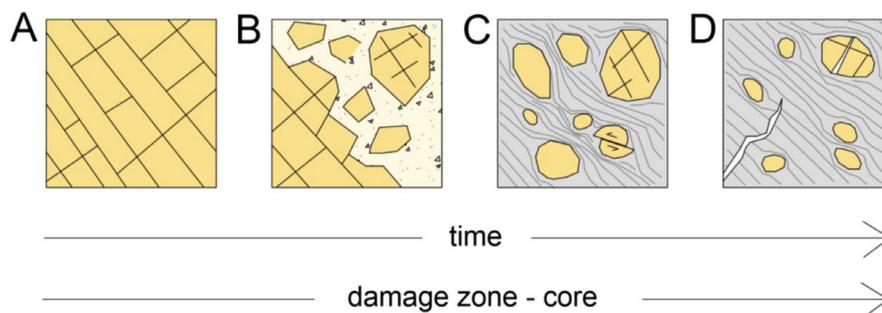
Figure 10. Time evolution model for tectonic breccias of the Veneza Fault. (A) Damage zone with orthogonal fractures in the dolomitic host rock. (B) Brecciation onset and comminution of fragments. (C) Fragmentation, rotation and rounding of fragments. It is also at this stage that occurs the dedolomitization and formation of foliated matrix. (D) More intense comminution, rounding and orientation of fragments according to foliation, with deposition of sparry calcite in veins.

was the main process of deformation, ductile mechanisms can also be inferred, mainly from the foliated matrix and elongated fragments, implying that these rocks were formed near the brittle–ductile transition for carbonates.

Moreover, these fault rocks likely underwent dedolomitization prior to, or during, matrix foliation, once comminution alone would not change the mineralogy of fine fragments that compose the matrix. In that sense, we presume that calcite substituted dolomite, a process that appears in the literature in the context of carbonate fault rocks (e.g. Tapp 1988, Erickson 1994, Hajri and Abdallah 2020). Therefore, percolation of calcite-rich fluids in the fault zone provided the dedolomitization at near-surface depths, and then deformation caused the matrix to foliate. The presence of sparry calcite in the veins is an indicator that fluids with this characteristic percolated within the matrix and the fragments of the fault breccias.

The age of the Veneza Fault is uncertain. McGee *et al.* (2018) proposed that final sedimentation and deformation of the southern Paraguay Belt took place during the early Cambrian (540–510 Ma). In that sense, the cataclastic rocks associated with reverse faults of the deformational front would be early Cambrian in age, up to 45 Ma younger than the Tamengo Formation basal sedimentary breccia. Furthermore, the Bocaina–Tamengo limit, marked by the sedimentary breccia, is a major discontinuity of the Corumbá Group, ideal to host deformation and form fault rocks as the fold-thrust belt developed. Therefore, this accounts for the close occurrence of these two types of breccia in the Serra da Bodoquena region.

CONCLUSION

- There are sedimentary and tectonic breccias in the Serra da Bodoquena region that, despite their close occurrence, are products of processes of distinct natures and times within the Corumbá Group;
- The sedimentary polymictic breccia marks the Bocaina–Tamengo limit and is an important stratigraphic mark for the Corumbá Group. The breccia was formed by submarine mass flows such as slumps, slides and debris flows. Sea level fall and/or increased faulting rates caused these processes on steep slope aprons;
- The clast lithologies of the sedimentary breccia imply that both Bocaina and Cerradinho formations, as well as the Rio Apa crystalline basement, acted as source units for the lower Tamengo Formation, which is in accordance with previous provenance studies;
- Tectonic breccias occur in the Veneza Fault, on the east side of Serra da Bodoquena. Their textural characteristics vary from the damage zone to the fault core. Cataclasis acted by fracturing and rotating fragments of the dolomitic host rock in relatively shallow depths. Their matrix underwent dedolomitization due to calcitic fluid percolation and foliation due to shear;
- The age of the sedimentary breccia at the base of the Tamengo Formation is placed between 555 and 542 Ma. The age of the rocks related to the Veneza Fault is unknown, but they are likely early Cambrian.

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