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Chapter 45

Glacially influenced sedimentation of the Puga Formation, Cuiabá Group and Jacadigo Group, and associated carbonates of the Araras and Corumbá groups, Paraguay Belt, Brazil

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Abstract: Discontinuous exposures of diamictite (>1000 km) termed the Puga Formation (Fm.) and interpreted as being related to a late Cryogenian glacial event are known in the Paraguay Belt (Brazilian–Pan-African Orogeny) and part of the Amazon craton and Rio Apa Block. These diamictite units and a mixed assemblage of sandstone, conglomerate and claystone were first named the Jangada Group. Recent interpretations have shown that the diamictite of the Puga Formation passes laterally into metasediments of the Cuiabá Group, interpreted as glacially influenced turbidites. The correlative Jacadigo Group in the southern Paraguay Belt includes a thick succession of banded iron formation (BIF) bearing large boulders that have been interpreted as recording glacially influenced sedimentation. The diamictite of the Puga Fm. is overlain by two different carbonate-bearing successions, the Corumbá Group (Cadieus, Cerradinho, Bocaina, Tamengo and Guaicurus formations) in the south and the Araras Group (Mirassol d'Oeste, Guia, Nobres formations) in the north. Evidence of glaciation in the Puga Fm. consists of striated and faceted pebbles and blocks, and dropstones in the turbidites. Sedimentary and geochemical data from the associated carbonate reinforce the interpretation of a glacial origin. C, O and Sr isotope data from the northern Paraguay Belt are consistent with the proposed late Cryogenian age for the Puga Fm. sedimentation.

Discontinuous outcrops of the Puga Fm. extend for more than 1000 km along the Paraguay Belt and over the Amazonian Craton and Rio Apa Block (Fig. 45.1). The glacial diamictite succession was first described from the isolated Puga Hill (19° 37′ 20.03″S, 57° 31′ 40.01″W), SE of Corumbá (Fig. 45.1; Maciel 1959), but its best exposures are located in the northern Paraguay Belt, where the diamictite of the Puga Fm. passes laterally into turbidites with dropstones of the Cuiabá Group (Fig. 45.2) (Alvarenga & Trompette 1992). A glaciogenic origin was first proposed by Maciel (1959), but Alvarenga & Trompette (1992) were the first to suggest a glaciomarine setting; they interpreted the fine-grained sediments of the Cuiabá Group as glacially influenced turbidites.

The diamictite exposures in the northern Paraguay Belt were first described by Almeida (1964*a*, *b*) as part of Acorizal, Engenho, Bauxi and Marzagão formations within the Jangada Group. The type section was described between Jangada and Bauxi (Fig. 45.1). Quartzite and sandstone units below the diamictite (Puga Fm.) and above the slate (Cuiabá Group) were described as the Bauxi Fm. (Almeida 1964*a*; Vieira 1965), whereas diamictite and associated conglomerate, quartzite and slate were named the Jangada Group (Almeida 1964*a*, *b*; Rocha-Campos & Hasuí 1981). The name 'Jangada Group' is not used in the current nomenclature.

In the southern Paraguay Belt, glacial deposits include the Jacadigo Group and the Puga Fm. These two units occur in isolated hills making it difficult to confirm the stratigraphic relationships between them. The Jacadigo Group (Almeida 1945; Dorr II 1945; Almeida 1946) is exposed in some hills south of the town of Corumbá extending into Bolivia. The Urucum Fm. (lower unit) is characterized by conglomerate and arkose and is overlain by the economic manganesiferous bed and banded iron formation (BIF) of the Santa Cruz Fm. (type section, 19° 11′ 24.36″S, 57° 36′ 31.45″W). Fe formations bearing large granite boulders have been interpreted as recording a glacial influence (Barbosa 1949; Walde *et al.* 1981; Hoppe *et al.* 1987; Urban *et al.* 1992; Klein & Ladeira 2004; Walde & Hagemann 2007). The Jacadigo Group, in contrast to the huge exposure area of the Puga Fm. and Cuiabá Group in the northern Paraguay Belt, is restricted to a few hills on the border of Bolivia and Brazil near Corumbá (Fig. 45.1).

There are two Fe formation units in the southern Paraguay Belt. The most significant is the economic Fe formation and Mn ore deposits of the Jacadigo Group in Urucum Hill (Almeida 1945l Dorr II 1945); the second is an Fe formation in diamictite of the Puga Formation (Boggiani *et al.* 2006; Piacentini *et al.* 2007).

Carbonate rocks of the Araras Group and mixed clastic-carbonate rocks of the Corumbá Group overlie diamictite of the Puga Fm. and in some areas are interpreted as cap carbonate (Nogueira *et al.* 2003; Boggiani *et al.* 2003; Alvarenga *et al.* 2004, 2008). Historically, 'Corumbá and Arara Limestones' were the first names given to these carbonate rocks in the Paraguay Belt (Evans 1894). Most studies about carbonate rocks that overlie the diamictite of the Puga Fm. focus on isotope geochemistry, chemostratigraphy (Boggiani *et al.* 2003; Alvarenga *et al.* 2004, 2008; Font *et al.* 2006; Nogueira *et al.* 2007; Riccomni *et al.* 2007) and palaeomagnetic data (Trindade *et al.* 2003).

Outcrops of the Araras Group extend for more than 600 km along the Northern Paraguay Belt. This group is subdivided into three carbonate formations (Fig. 45.1, Table 45.1): (i) the Mirassol d'Oeste Fm., described as a cap dolomite (Nogueira *et al.* 2003;

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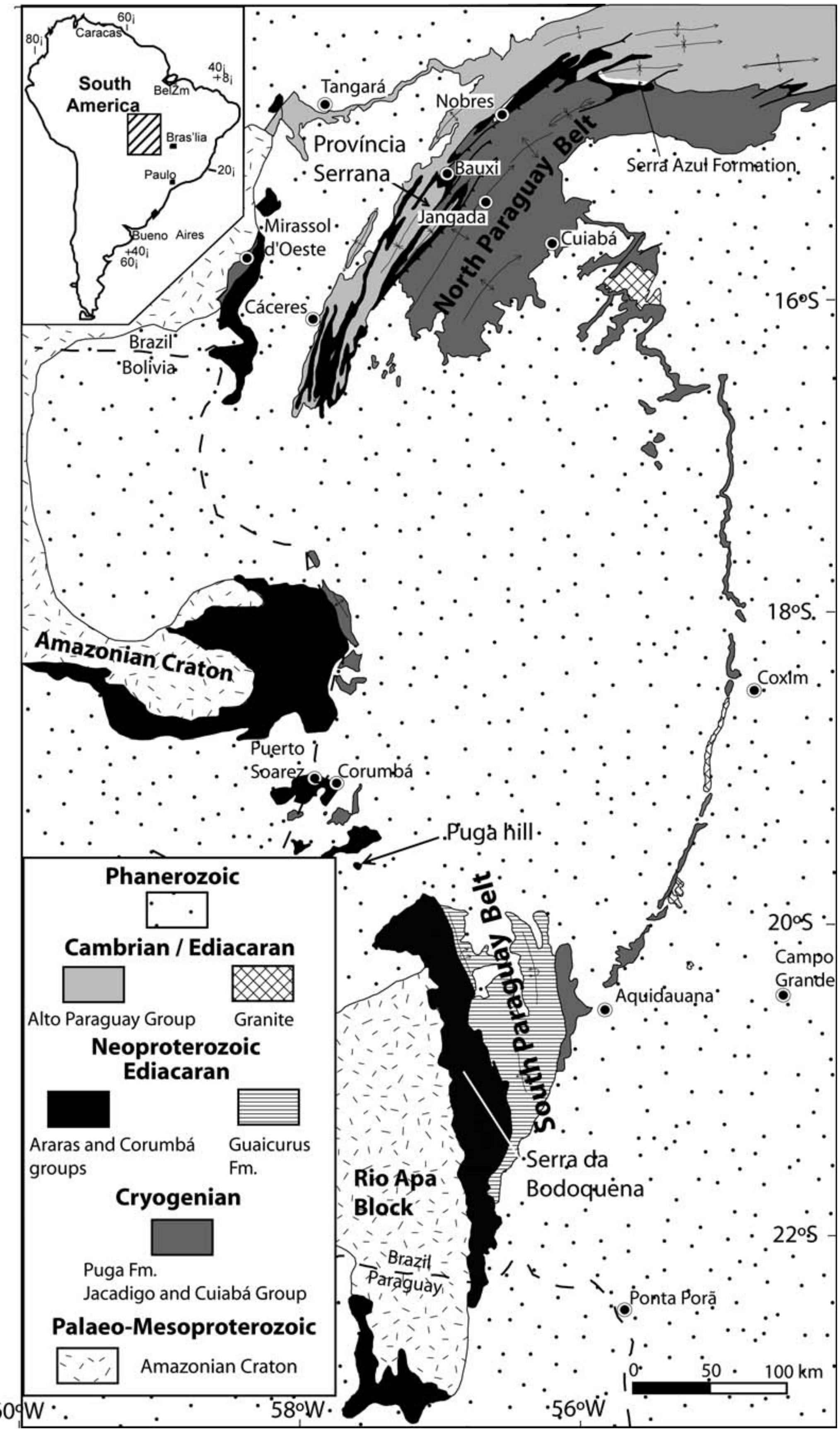

Fig. 45.1. Geological map of the Paraguay Belt (modified from Alvarenga & Trompette 1993; Boggiani 1998).

Alvarenga *et al.* 2004, 2008), (ii) the Guia Fm. (Almeida 1964*a*; Hennies 1966), and (iii) the Nobres Fm. (Hennies 1966; Luz & Abreu 1978). Good exposures of the Mirassol d'Oeste Fm. overlying the Puga Fm. in the Northern Paraguay Belt can be found at the Terconi (15° 40′ 41.87″S, 58° 04′ 18.22″W) and Tangará (14° 44′ 13.7″S, 57° 49′ 52.45″W) quarries and in a drill core from the Bauxi region (15° 09′ 06.14″S, 56° 41′ 00.74″ W). The Guia Fm. can be found in the Terconi and Tangará quarries as well as at the Cimento Tocantins Mine (14° 38′ 12.02″S, 56° 15′ 57.50″W) in the Nobres region and the Nossa Senhora

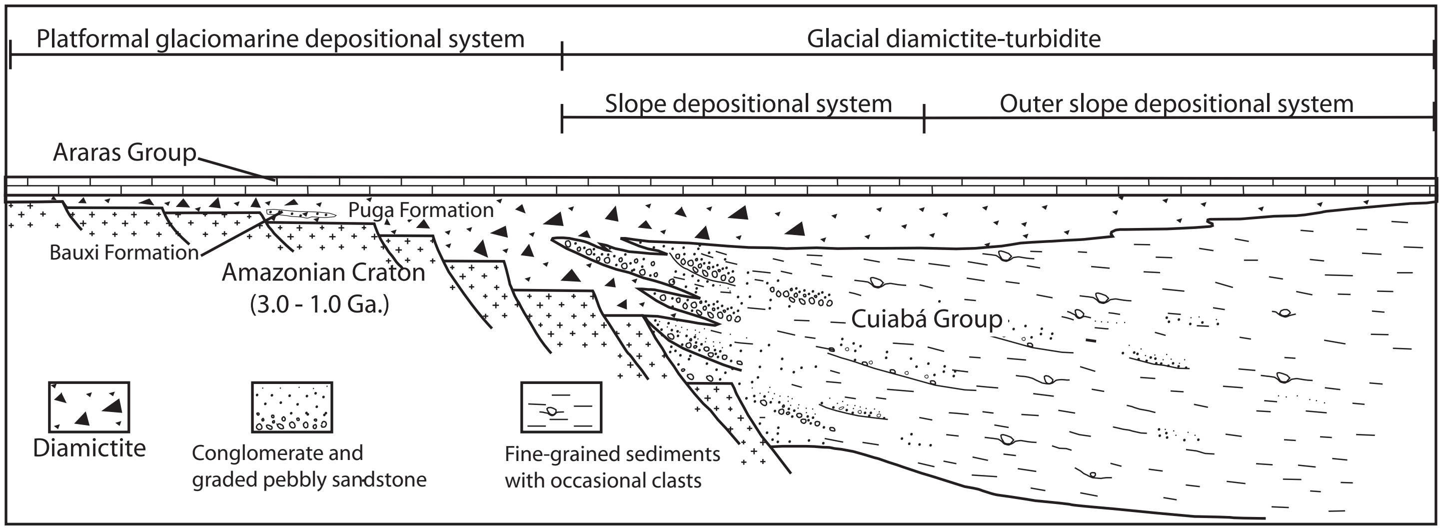

Fig. 45.2. Schematic cross-section showing the glacial facies relationships for the late Cryogenian glacial event (*c.* 635 Ma) along the southeastern edge of the Amazonian Craton (modified from Alvarenga & Trompette 1992). Diamictites of the Puga Fm. are in the platformal glaciomarine system, while the diamictites of the Cuiabá Group are in the slope and outer slope depositional system.

da Guia Quarry (15° 21′ 15.07″S, 56° 11′ 24.47″W). The Nobres Fm. is exposed in the Província Serrana.

The Corumbá Group, in the southern Paraguay Belt, is subdivided into five formations (Tables 45.2 & 45.3). The basal Cadieus and Cerradinho formations occur only in the Serra da Bodoquena (Fig. 45.1, Table 45.2; Boggiani 1998). Above this unit lies the grey dolomite of the Bocaina Fm. (Almeida 1945), which is exposed in the Serra da Bodoquena and Corumbá regions and which outlines the geographical extent of exposures of the Corumbá Group in the southern Paraguay Belt. The pink carbonate of the Bocaina Fm. overlies the Puga Fm. at Puga Hill (Table 45.3). The uppermost two units of the Corumbá Group are the Tamengo and Guaicurus formations (Almeida 1965) exposed in the Corumbá region and in the eastern part of Serra da Bodoquena.

In the northern Paraguay belt, two Neoproterozoic diamictite-bearing glacial intervals are described (Table 45.1): the units described in this chapter and attributed to a late Cryogenian glaciation (*c.* 630 Ma), as well as the Serra Azul Fm. attributed to the Ediacaran glaciation (580 Ma; Alvarenga *et al.* 2007; Figueiredo *et al.* 2008, 2011). Most rocks in the region have experienced low-grade metamorphism. In order to facilitate subsequent rock descriptions, the prefix 'meta' has been omitted.

Structural framework

Outcrops of the Neoproterozoic rocks extend along the southeastern border of the Amazonian Craton as well as along the eastern margin of the Rio Apa Block, and contain a thick sequence of glaciomarine, turbidite, carbonate and siliciclastic sedimentary rocks formed on an extensional continental margin. In the northern Paraguay belt, the Puga Fm. is mostly subhorizontal and *c.* 100 m thick on the craton, whereas in the central part of the belt, in the deepest part of the basin, the glacially influenced sediments (Cuiabá Group) are more than 3000 m thick (Alvarenga & Saes 1992; Alvarenga & Trompette 1992, 1993; Dantas *et al.* 2009). In the southern Paraguay Belt, the NE–SW-trending extensional structures, with sub-vertical faults of a half-graben system, were filled by conglomerate, arkose sandstone and jaspilite of the Jacadigo Group. The present landscape in the south is due to a later tectonic event and erosion during the Neogene subsidence of the Pantanal Basin, with blocks defined by vertical faults (Trompette *et al.* 1998).

The overlying Corumbá and Araras groups were deposited in a passive margin environment. The total thickness of the sedimentary pile increases from *c.* 200 m in the western cratonic area

Table 45.1. *Neoproterozoic lithostratigraphy nomenclature in the northern Paraguay Belt*

Period	Group	Formation	Lithology	Ages
Ediacaran	Alto Paraguay	Diamantino	Siltstone and arkose sandstone	
		Sepotuba	Siltstone	Rb–Sr: 569 ± 20 Ma
		Raizama	Sandstone	
		Serra Azul	Diamictite and mudstone	
	Araras	Nobres	Dolostone and sandy dolostone	
		Guia	Limestone and mudstone	
		Mirassol d'Oeste	Pink dolostone	Pb/Pb: 633 ± 25 Ma
Cryogenian	Puga Formation / Cuiabá Group		Diamictite / Diamictite, conglomerate, sandstone and fine-grained rocks	

Table 45.2. *Neoproterozoic lithostratigraphy nomenclature in the Serra da Bodoquena region, southern Paraguay Belt*

Period	Group	Formation	Lithology	U–Pb Ages
Ediacaran	Corumbá	Guaicurus	Shale	543 ± 2 Ma
		Tamengo	Limestone, mudstone and shale	
		Bocaina	Dolostone	
		Cerradinho	Limestone, shale, sandstone	
		Cadieus	Conglomerate, arkose and shale	
Cryogenian		Puga	Diamictite	

(inner-shelf domain in Mirassol d'Oeste region) to more than 1000 m eastwards (middle-outer shelf domain) along the Província Serrana (Alvarenga & Saes 1992; Alvarenga & Trompette 1993; Trompette 1994; Alvarenga *et al.* 2008, 2009).

The Neoproterozoic rocks along the Paraguay Belt were folded and metamorphosed to very low-grade metamorphism during the Brasiliano/Pan-African Orogeny, in the Ediacaran–Cambrian Period (Alvarenga 1990; Trompette 1994; Pimentel *et al.* 1996; Trindade *et al.* 2003; Tohver *et al.* 2006). This event was followed by post-orogenic sub-alkaline granitic magmatism at *c.* 500 Ma (Almeida & Mantovani 1975).

Deformation and metamorphism increase from imperceptible effects on flat-lying rocks overlying the stable Amazonian craton border to low-grade metamorphism within the Paraguay Belt, determined by folding and crystallization of the illite parallel to cleavage planes (Alvarenga *et al.* 1990; Alvarenga & Trompette 1993). Despite low metamorphism, diamictite, quartzite, slate and phyllite of the Cuiabá Group and Puga Fm., as well as the limestone, marl, dolostone and shale of the Araras and Corumbá groups, have well-preserved sedimentary structures in most outcrops.

Stratigraphy

The Puga Fm. and the Cuiabá and Jacadigo Groups include diamictite and fine-grained rocks with outsized clasts. In the north Paraguay Belt, the Puga Fm. and Cuiabá Group are overlain by the carbonate rocks of the Mirassol d'Oeste Fm., Araras Group (Table 45.1; Nogueira *et al.* 2003; Alvarenga *et al.* 2008, 2009). In the south Paraguay Belt glaciogenic deposits are named the Puga Fm. and the Jacadigo Group; these are in turn overlain by mixed clastic and carbonate rocks of the Corumbá Group (Tables 45.2 & 45.3).

Puga Fm. and Cuiabá Group

The diamictite lying concordantly below the dolomite of the Bocaina Fm. originally described in the southern Paraguay Belt at Puga Hill (Maciel 1959) has been found in other areas of the Paraguay Belt, and is also named Puga Fm.

In the northern Paraguay Belt, the Puga Fm. consists of diamictite, sandstone and claystone units that are part of a

Table 45.3. *Neoproterozoic lithostratigraphy nomenclature in the Corumbá and Puga hill region, southern Paraguay Belt*

Period	Group	Formation	Lithology	U–Pb Ages
Ediacaran	Corumbá	Guaicurus	Shale	543 ± 2 Ma
		Tamengo	Limestone, mudstone and shale	
		Bocaina	Dolostone	
Cryogenian		Puga*	Diamictite	
	Jacadigo	Santa Cruz	BIF, Mn beds and arkose	
		Urucum	Conglomerate and arkose	

*Puga Fm. is thought to be coeval with the sedimentation of the Jacadigo Group, although isolated outcrops make it difficult to confirm their stratigraphic relationship.

marine succession (*c.* 100 m thick) close to the western border of the Neoproterozoic basin. To the east, in the deeper parts of the basin, layers of diamictite intercalated with conglomerate, sandstone and fine-grained rocks of the Cuiabá Group (*c.* 3000 m thick) were deposited as sediment gravity flows (Table 45.1; Alvarenga & Trompette 1992).

In the Bauxi region (Fig. 45.1), the Puga Fm. contains diamictite associated with conglomerate, sandstone and siltstone in its lower part followed by a massive diamictite. At this site, the massive diamictite, interbedded with conglomerate and sandstone, passes to the east into a thick fine-grained facies with a few isolated clasts of the Cuiabá Group.

The exposed section of the Puga Fm., at its type section on Puga Hill (Fig. 45.1), consists of a 95-m-thick massive diamictite with a sandy matrix, which in the lower 50 m, contains a sandstone layer intercalated with a clay matrix massive diamictite (Maciel 1959). A pink limestone of the Bocaina Fm. rests on the diamictite (Table 45.3; Maciel 1959) and was interpreted as a cap carbonate typical of other Neoproterozoic successions (Boggiani & Coimbra 1996; Boggiani *et al.* 2003).

Diamictite of the Puga Fm. at the Serra da Bodoquena (Fig. 45.1, Table 45.2) are found along the axis of folded rocks, overlain by carbonate rocks of the Corumbá Group (Almeida 1965). To the east of the Serra da Bodoquena a massive foliated diamictite with a ferruginous matrix is intercalated with centimetre-thick hematite and magnetite layers, and sub-millimetre layers of quartz and chert (Piacentini *et al.* 2007).

Jacadigo Group

Between Corumbá and Puga Hill (Fig. 45.1), the Neoproterozoic exposures of the Jacadigo Group occur in isolated hills (up to 900 m high), surrounded by lowlands of the wetland Pantanal plain (Neogene Basin). The Jacadigo Group (Fig. 45.3) differs from the Puga Fm. in the presence of significant ferruginous and manganesiferous chemical deposits and the absence of diamictite. The lower unit of the Jacadigo Group (Urucum Fm.) comprises conglomerate and arkose sandstone, with discontinuous conglomerate interbeds, *c.* 200 m thick. The Santa Cruz Fm. is *c.* 400 m thick, and forms the upper part of the Jacadigo Group. The lower part of this formation starts with a continuous layer of red-violet ferruginous-manganese arkose with a jaspilite/hematite cement along Urucum Hill (Almeida 1945; Walde & Hagemann 2007); this unit was named the Banda Alta Fm. by Dorr II (1945). Towards the top of the Santa Cruz Fm., there are bedded hematite-rich rocks and jasper (BIF) with arkose and manganese ore intercalations bearing large granite boulders. In Bolivia, the lower part of the Boqui Group has been interpreted as correlative to the Jacadigo Group (Litherland *et al.* 1986).

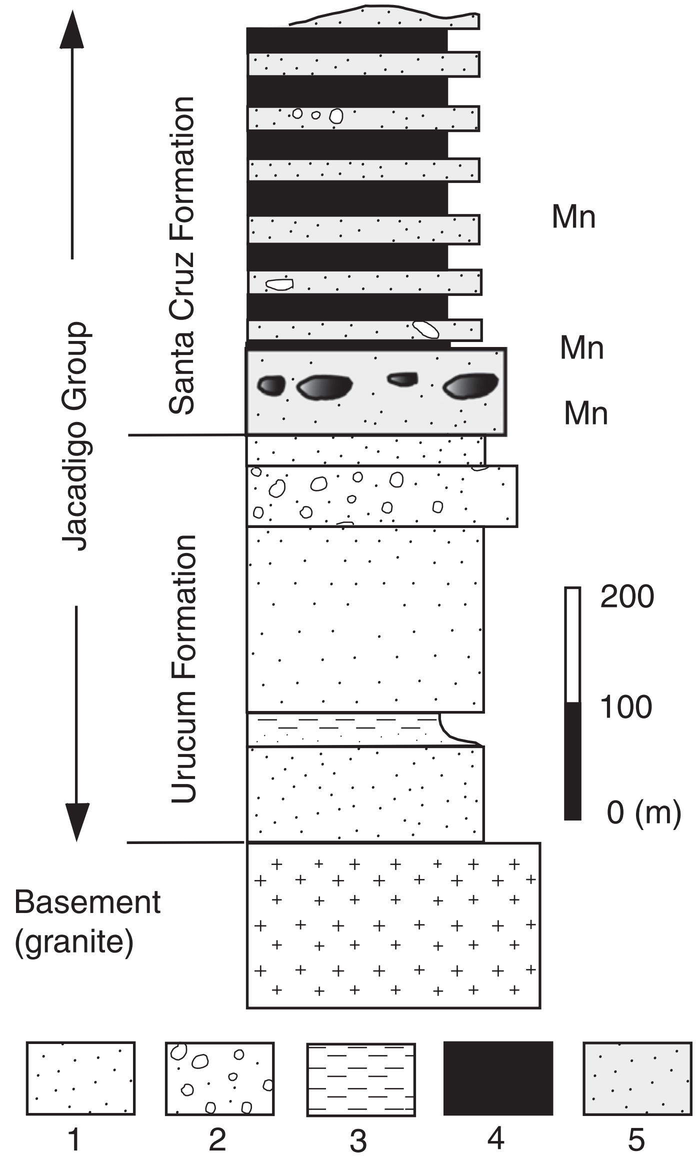

Fig. 45.3. Lithostratigraphy of the Jacadigo Group (modified from Almeida 1945). 1, Arkose sandstone; 2, conglomerate and arkose sandstone; 3, siltstones; 4, BIF with five Mn beds; 5, ferruginous arkose sandstone, sometimes with boulders and clasts.

Araras Group, northern Paraguay Belt

The thickness of the Araras Group varies from 100 to 150 m in the western area, overlying the cratonic region (inner shelf), to more than 1300 m eastwards and in the middle-outer shelf domain. Deeper-water rocks are chiefly marl limestone, rhythmite and siltstone that mark the slope deposits of the basin (Alvarenga *et al.* 2008). This unit was subdivided into three formations (Table 45.1). The lower Mirassol d'Oeste Fm. consists mostly of dolostone. The 18- to 32-m-thick type section at the Terconi Quarry is characterized by laminated dolostone associated with microbialites, giant wave ripples, tube-like structures and fan-like crystals (Nogueira *et al.* 2003; Nogueira & Riccomini 2006; Alvarenga *et al.* 2008).

The overlying Guia Fm. consists of dark grey laminated micrite limestone with thin interbedded shale or marl laminae. This formation reaches *c.* 250 m in thickness in the Nobres region. In the Terconi and Tangará quarries (inner shelf carbonate basin), this unit overlies the dolostone of the Mirassol d'Oeste Fm. and presents at its base fan-like crystals interpreted as aragonite pseudomorphs (Alvarenga *et al.* 2008). Interbedded graded grainstone and cross-bedded grainstone occur in the middle part of this formation. Locally, in the fore slope basin, an interbedded 12-m-thick layer of dolostone (grainstone and breccia) was described at the Nossa Senhora da Guia Quarry (Alvarenga *et al.* 2004, 2008).

The uppermost Nobres Fm. consists of a uniform, light grey dolostone (*c.* 1100 m) that forms the main karstic relief of the region. This formation is exposed in the Província Serrana but is absent in the eastern part of the Paraguay Belt (Fig. 45.1). The base of this unit is characterized by 2–4 m of dolomite brecciated layers intercalated with fine-grained and laminated dolomite. Most of the sequence consists of a thick succession of grainstone and packstone dolostone (Alvarenga *et al.* 2000, 2004).

The Corumbá Group, southern Paraguay belt

The Corumbá Group is exposed both in unfolded and folded domains. In the unfolded domains, this unit overlies the Rio Apa Craton, located on the western margin of the Paraguay River, whereas in the folded domains, it crops out in the eastern part of the Serra da Bodoquena (Fig. 45.1). The Corumbá Group is the uppermost Neoproterozoic succession exposed in the southern Paraguay Belt and was subdivided into five formations: Cadieus, Cerradinho, Bocaina, Tamengo and Guaicurus (Tables 45.2 & 45.3).

The Cadieus and Cerradinho formations occur only in the Serra da Bodoquena (Fig. 45.1) and comprise a mixed assemblage of clastic and carbonate rocks that unconformably overlies the Rio Apa Craton (Boggiani 1998). The Cadieus Fm. consists of conglomerate and arkosic sandstone that was deposited in an alluvial fan atop the igneous-metamorphic basement. The proximal facies of this fan grades upwards and laterally into the arkosic sandstone, shale and grainstone that comprises the more distal alluvial facies of the Cerradinho Fm. (Boggiani *et al.* 1993; Boggiani 1998). Cross-bedding and hummocky cross-stratification found within grainstone facies in the upper portion of the Cerradinho Fm. suggest a rise in sea level at the end of the rift phase (Boggiani 1998).

The Bocaina Fm. is present in the Serra da Bodoquena, Corumbá region and in Puga Hill, where it may reach thicknesses up to 300 m (Maciel 1959). This unit is placed directly above the limestone of the Cerradinho Fm. at the Serra da Bodoquena and the diamictite of the Puga Fm. at Puga Hill.

The Tamengo Fm. is up to 100 m thick and consists of dark, organic-rich limestone and shale rhythmically interbedded with uncommon limestone grainstone. In the Corumbá area, the organic-rich limestone and shale of this formation contain a rich Ediacaran microfossil assemblage that will be described below. The dominance of shale in the Bodoquena region suggests deeper waters when compared to the Corumbá region (Boggiani 1998), thus explaining the absence of *Cloudina lucianoi* in the Serra da Bodoquena limestone-shale.

The Guaicurus Fm. was first described by Almeida (1965) as a thick shale succession on the top of the Corumbá Group that extends over the eastern part of the Serra da Bodoquena and along the Miranda River valley. It consists of fine-grained siliciclastic rocks, mainly shale. Diamictite and pelite with clasts that occur as lenses in the pelite of the Guaicurus Formation at Laginha Mine, Corumbá, Mato Grosso do Sul, have been interpreted as sediment gravity-flow deposits in a slope setting (Boggiani *et al.* 2004). There are no equivalents of both the Tamengo and Guaicurus formations in the northern part of the Paraguay belt (Fig. 45.1; Tables 45.1, 45.2 & 45.3).

Glaciogenic deposits and associated strata

Puga Fm.

In the northern Paraguay Belt, the Puga Fm. consists of a succession of diamictite units intercalated with sandstone, conglomerate and mudstone. The matrix of the diamictite varies from sandy to clayey. Diamictite is massive or stratified and contains clasts from a few centimetres up to 1 m in diameter. Clasts mainly of basement rocks (granite, gneiss, quartzite, quartz, schists, etc.), some of them deflecting the underlying laminae, faceted and striated, and abundant detrital mica, are found in outcrop, close to the Palaeoproterozoic basement rocks. Massive diamictite shows great variations in the relative proportions of matrix (muddy sand) and clasts. Occasionally, a crude stratification can be observed. Some stratified diamictite consists of few-centimetres-thick, massive diamictite beds associated with mudstone with graded bedding and outsized clasts clearly deflecting the underlying laminae.

The mudstone comprises an alternation of silt-shale, siltstone and very fine-grained sandstone, with clasts cutting or disturbing the bedding (Alvarenga & Trompette 1992). Some thin beds and lenses, up to 0.3 m thick, made up of clast-rich diamictite, have erosive basal contacts. Lenses of fine-grained sandstone commonly show load structures. Some massive or laminated sandstone intercalations, up to 15 m thick, include isolated clasts.

Cuiabá Group

The Cuiabá Group includes a thick sequence of fine-grained rocks, sandstone, conglomerate and diamictite (Fig. 45.2; Alvarenga & Trompette 1992). Diamictite in this group is massive, with an abundant clay-silt matrix. Most clasts are millimetre to centimetre scale, although a few reach 1 m in diameter. Some clasts of carbonate rocks are found in clast-poor diamictite.

Sandstone and coarse-grained rocks are widely distributed in this group. Conglomerate with beds 0.3–15 m thick is commonly interbedded with sandstone and diamictite. The clast size ranges from less than 1 cm to *c.* 10 cm. The matrix represents less than 10%, and consists of a clay-silt-sand mixture (Alvarenga & Trompette 1992). Pebbly sandstone exhibits normal grading, starting with a pebbly conglomerate and passing upward to a fine-grained conglomerate followed by sandstone. The individual graded bed is normally 0.5–3.0 m thick, with a sharp erosive basal contact. Clasts include quartz, feldspar, quartzite, mudstone, limestone and some granite. Flame, load casts and ball and pillow structures are observed at the contact between two graded sequences, with an injection of sandy material into the overlying pebbly sandstone layer. Fine-grained sandstone layers grade upwards into mudstone. Occasionally, isolated clasts can be found cutting the underlying layers of laminated claystone.

In the Puga Fm., east of the Serra da Bodoquena, a BIF occurs as a bed, *c.* 2 m thick, confined within a massive diamictite with a ferruginous matrix. The BIF is formed by centimetre-thick layers of hematite and magnetite, alternating with millimetre-thick layers of quartz and chert (Piacentini *et al.* 2007).

Jacadigo Group

A BIF at the top of the Jacadigo Group (Santa Cruz or Banda Alta formations) consists of a thick succession (up to 450 m thick) of interbedded (i) ferruginous arkose sandstone, (ii) hematite-rich jaspilite (BIF), (iii) arkose and feldspathic sandstone, sometimes containing isolated granite blocks and boulders, (iv) siltstone and ferruginous mudstone, (v) mudstone with banded jaspilite, and (vi) four manganese ore beds between 0.3 and 4 m thick (Fig. 45.3). Beds vary from centimetres to a few metres in thickness. Arkose and feldspathic sandstone ranges from massive to bedded, and is rarely graded. Some arkose beds exhibit isolated granite-gneiss boulders, some of them bigger than 1.5 m in diameter. Deformation around the boulders is generally more pronounced above them (Trompette *et al.* 1998).

Mirassol d'Oeste Fm.

The Mirassol d'Oeste Fm. (20–32 m thick) is the basal pink dolostone of the Araras Group, resting on the diamictite of the Puga Fm. (Nogueira *et al.* 2003). The first 8 m of the formation consists of laminated pinkish dolostone that grades upward through a diffuse and transitional contact to a grey laminated dolostone. The basal dolostone has stratiform and wave microbialite with dispersed tube-like structures (Nogueira *et al.* 2003; Font *et al.* 2006; Elie *et al.* 2007). The upper part of the dolostone has an enigmatic wave bed form that was interpreted as a giant wave ripple by Allen & Hoffman (2005) but described as a tepee-like structure by Nogueira *et al.* (2003). Fan-like crystals interpreted as aragonite pseudomorphs are commonly found in the upper part of the dolostone and in the overlying limestone of the Guia Formation (Nogueira *et al.* 2003; Alvarenga *et al.* 2008). Carbonate has also been described from a drill core in the Bauxi area (Fig. 45.1) in the middle-outer shelf domain where the Araras Group is *c.* 1300 m thick. In this area, 18-m-thick white laminated dolostone overlies the diamictite of the Puga Formation in sharp contact (Alvarenga *et al.* 2008). Other common sedimentary structures found in this dolostone include stromatolite, and breccia.

Basal member of the Bocaina Fm.

Maciel (1959) was the first to describe the carbonate of the Bocaina Fm. that overlies the diamictite of the Puga Fm. at Puga Hill. The succession starts with a succession of 4-m-thick massive pink limestone overlaid by *c.* 10 m of a purple limestone/dolostone, mudstone and sandstone that grade upwards to grey dolostone and light grey dolostone. This upper dolostone is the common rock of the Bocaina Fm., which also presents grainstone, packstone, breccia and stromatolites with poorly developed stratification (Almeida 1945; Boggiani *et al.* 1993).

Boundary relations with overlying and underlying non-glacial units

The basal diamictite of the Puga Fm. lies unconformably above the Palaeoproterozoic metamorphic rocks, in the western part of the basin, around Mirassol d'Oeste (Fig. 45.1). This contact is usually poorly exposed, but a road cut section exhibits 12 m of massive diamictite above the unconformity, followed upwards by mudstone with isolated cobbles and pebbles, including some intercalations of massive diamictite, up to 0.80 m thick (Alvarenga 1990; Alvarenga & Trompette 1992).

Good exposures of the upper contact of the Puga Fm. with the Araras Group can be found at the Terconi and Guia quarries and in a drill core in the Bauxi region (Alvarenga & Trompette 1992; Nogueira *et al.* 2003; Alvarenga *et al.* 2004, 2008). The best exposure of this contact (Terconi Quarry) exhibits dolostone of the Mirassol d'Oeste Fm. overlying diamictite along a conformable sharp contact. This contact exhibits soft-sediment deformation (Nogueira *et al.* 2003). In the southern Paraguay Belt, the pink limestone from the Bocaina Fm. overlies the diamictite at Puga Hill (Maciel 1959; Boggiani *et al.* 2003).

Chemostratigraphy

The chemostratigraphic data discussed here take into account all available C, O and Sr isotope data from the Araras and Corumbá carbonate successions (Gaucher *et al.* 2003; Boggiani *et al.* 2003; Nogueira *et al.* 2003, 2007; Pinho *et al.* 2003; Alvarenga *et al.* 2004, 2008; Figueiredo 2006; Font *et al.* 2006; Misi *et al.* 2007; Riccomini *et al.* 2007). The discussion will focus on C isotopes, because they are more resistant to post-depositional alteration. The Sr-isotope ratios were also considered for those samples in which the Sr concentration was higher than 400 ppm.

Northern Paraguay Belt

The $\delta^{13}C$ profiles of the Mirassol d'Oeste Fm. were constructed from three sections in the northern Paraguay Belt: Terconi and Tangará quarries, both located on the western cratonic domain, and the João Santos borehole, which is located in the fold belt near Bauxi (Figs 45.1 & 45.4). While the $\delta^{13}C$ values of the first 20–30 m in the cratonic region range between −10.5‰ and −3.0‰, the $\delta^{13}C$ values along the profile located in the folded domain range from −4.8‰ to −1.7‰. Corresponding $\delta^{18}O$ ratios range from −8.2 to −1.3‰, whereas $^{87}Sr/^{86}Sr$ ratios are high and variable with low Sr content (44–96 ppm) and high Mn–Sr ratios (>18).

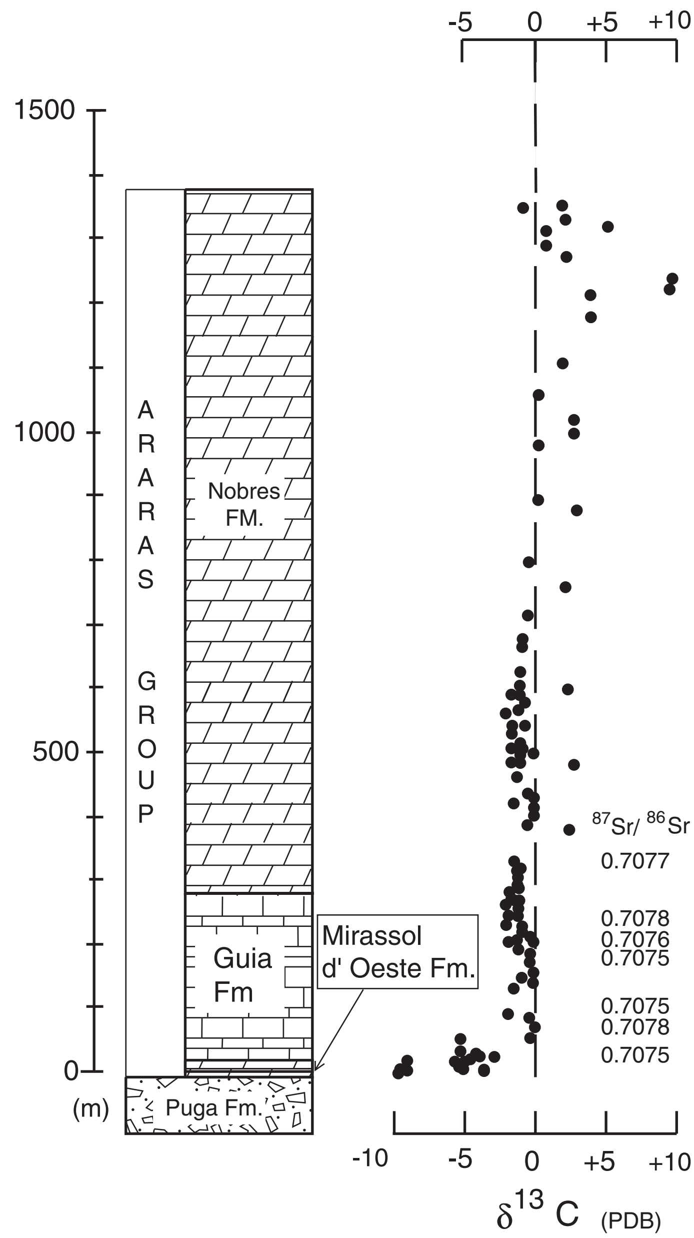

Fig. 45.4. Stratigraphic section and variations of $\delta^{13}C_{PDB}$ and $^{87}Sr/^{86}Sr$ for the Araras Group (data from Nogueira *et al.* 2003, 2007; Alvarenga *et al.* 2004, 2008; Font *et al.* 2006; Figueiredo 2006).

Dark grey laminated micritic limestone interbedded with the thin shale or marl layers of the Guia Fm. lie above the Mirassol d'Oeste Fm. This grey limestone presents increasing $\delta^{13}C$ values across the first 20 m from the base, with a narrow range of C-isotopic values (between −1.6 and +0.1‰; Fig. 45.4). The $^{87}Sr/^{86}Sr$ ratios for limestone samples with high Sr content (750–4351 ppm) and low Mn–Sr (<0.2) range between 0.70763 and 0.70780 (Fig. 45.4).

The dolostone of the overlying Nobres Fm. presents a wide range of C-isotopic values (Alvarenga *et al.* 2004; Nogueira *et al.* 2007). In the Bauxi-Nobres area, for instance (Fig. 45.1), the dolostone at the base of the sequence (900 m thick) is characterized by homogeneous and positive $\delta^{13}C$ values (+1.9 to +2.7‰), while the upper dolostone, which consists of thin layers of sandy dolostone, exhibit increasing $\delta^{13}C$ values up to +9.6‰ (Fig. 45.4; Alvarenga *et al.* 2004; Figueiredo 2006). On the other hand, in the Cáceres area, the lowermost 300 m of the dolostone placed on top of the Guia Fm. have $\delta^{13}C$ values ranging from −2.2 to +0.3‰ (Fig. 45.4; Nogueira *et al.* 2007).

Southern Paraguay Belt

Boggiani *et al.* (2003) presented $\delta^{13}C$ values close to −5‰ for the first 12 m of laminated carbonate rocks overlying the Puga Fm. in the Puga Hill (Fig. 45.5). In the Jacadigo Group, thin limestone intercalations in the BIF show $\delta^{13}C$ ratios between −5.2 and −7.0‰ (Klein & Ladeira 2004).

The Tamengo Fm. occurs in the Corumbá area and along the eastern part of the Serra da Bodoquena. The isotopic data of limestone from this unit were obtained at the Laginha, Saladeiro and Corcal quarries, located in the Corumbá area (Figs 45.1 & 45.5; Boggiani 1998; Boggiani *et al.* 2003; Misi *et al.* 2007). Limestone of the lower part of the Tamengo Formation records a negative $\delta^{13}C$ excursion (−3.3 to −2.5‰), which is followed by limestone with positive $\delta^{13}C$ values (up to +5.8‰). In the Serra da Bodoquena, located about 200 km SE of Corumbá, limestone correlated to the Tamengo Fm. shows homogeneous $\delta^{13}C$ values around +3‰ (Boggiani 1998). The $^{87}Sr/^{86}Sr$ ratios of the Tamengo carbonate rocks from both areas are clustered between 0.7084 and 0.7085 (Boggiani 1998; Babinski *et al.* 2008).

Other characteristics

Mn and Fe ore bodies with 36 billion metric tonnes of hematite, and estimated Mn ore reserves of 608 million metric tonnes (Urban *et al.* 1992) are known around south Corumbá.

This mineralization occurs throughout the Santa Cruz Fm., as banded, hematite-rich, jaspilite with arkose sandstone intercalations (Walde *et al.* 1981; Hoppe *et al.* 1987; Trompette *et al.* 1998; Walde & Hagemann 2007). The manganese deposits consist of four individual layers ranging from 0.3 to 4.0 m in thickness. Beds of Mn ore, up to 5 m thick, are mined in the underground Urucum Mine. Isolated granite clasts up to 1.5 m in diameter have been identified in the arkose intercalations (Trompette *et al.* 1998; Walde & Hagemann 2007).

The BIFs in the eastern part of the Serra da Bodoquena are thin beds (2–3 m thick) in a massive diamictite with a ferruginous (magnetite) matrix, suggesting the relationship of these sediments with Fe precipitation (Piacentini *et al.* 2007). The magnetite matrix has an Fe content ranging from 15 to 72%, with an average of 27% (Piacentini 2008).

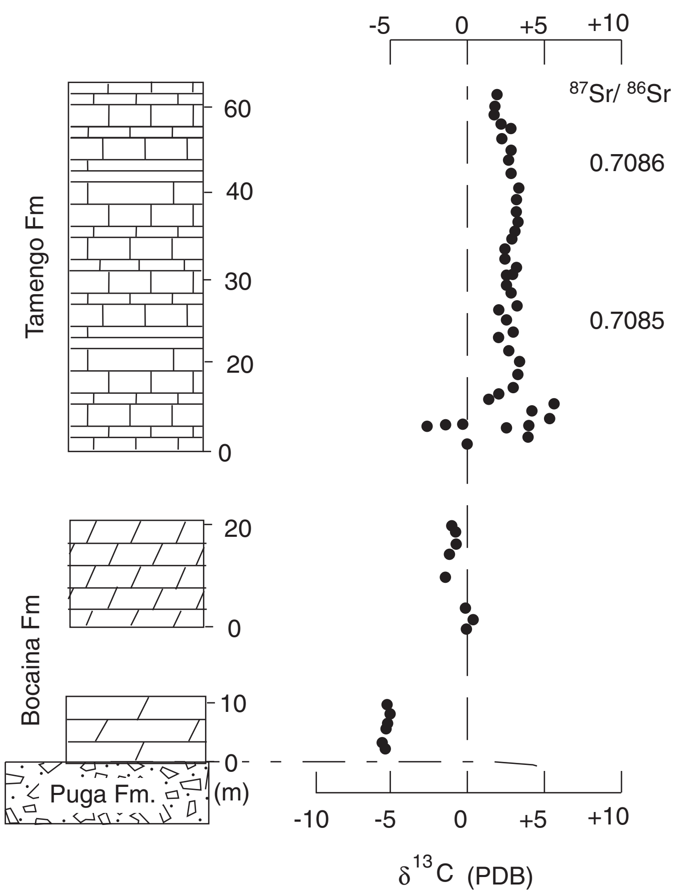

Fig. 45.5. Composite of $\delta^{13}C_{PDB}$ and $^{87}Sr/^{86}Sr$ record for the Corumbá Group from Corumbá area, Puga Hill and Serra da Bodoquena (data from Boggiani 1998; Boggiani *et al.* 2003; Misi *et al.* 2007 and unpublished data).

Palaeolatitude and palaeogeography

Palaeomagnetic data are only available for the Neoproterozoic Mirassol d'Oeste Fm. and are restricted to 19 samples from the Terconi Quarry, in the northern part of the Paraguay belt (Trindade *et al.* 2003). These palaeomagnetic data indicated five polarity reversals within the first 20 m of the dolomite, suggesting a primary magnetization and a low palaeolatitudes ($22 + 6/-5°$) for these rocks.

Geochronological constraints

A U–Pb zircon age of 543 ± 2 Ma (Ediacaran) has been obtained from an ash bed intercalated with the Cloudina bearing limestone of the Tamengo Fm. near Corumbá city (Babinski *et al.* 2008), thus providing a precise Upper Ediacaran age for this unit. In the northern Paraguay belt (Terconi Quarry), a Pb/Pb isochron age of 633 ± 25 Ma was obtained for the dolostone of the Mirassol d'Oeste Fm. and the limestone of the Guia Fm. (Babinski *et al.* unpublished). This age is interpreted as the time of deposition for these carbonate rocks. There are otherwise no radiometric data available to directly constrain the age of the Puga Fm.

Other radiometric ages include the Nd isotope signature obtained from clasts in diamictite, quartzite and phyllite in the Cuiabá Group and Puga Fm. by Dantas *et al.* (2009). The T_{DM} model ages display an irregular distribution. Diamictite present variable T_{DM} values (1.4–2.15 Ga), but homogeneous ε_{Nd} (*t*) around −8. The sandstone show T_{DM} model ages (*c.* 2.0–2.1 Ga) older than the ones determined for fine-grained rocks (T_{DM} values of 1.7 and 1.8 Ga). This difference of Nd isotopes may be related to variations in the source region or may be the result of mixing of material from different sources. Nevertheless, all of these data indicate sources within the Amazonian Craton, in agreement with the palaeogeographic interpretation, which points to the northwestern basement as the main source of detritus (Alvarenga & Trompette 1992; Dantas *et al.* 2009).

The limestone and shale of the Tamengo and Guaicurus formations near the city of Corumbá contain a record of Ediacaran fossils (Hahn *et al.* 1982; Walde *et al.* 1982; Zaine & Fairchild 1985, 1987; Gaucher *et al.* 2003). The microfossil assemblage is dominated by scyphozoan *Corumbella werneri* (Hahn *et al.* 1982; Walde *et al.* 1982), *Babvinella faveolata*, Vandalosphaeridium sp., *Cloudina lucianoi* (Zaine & Fairchild 1985, 1987), *Soldadophycus bossii*, *Titanotheca* and the vendotaenid *Eoholynia corumbensis* sp. (Gaucher *et al.* 2003). The presence of these fossils suggests a deposition during the 570–545 Ma period, consistent with the U–Pb age obtained in the Tamengo Fm.

Discussion

Northern Paraguay Belt depositional settings

The glacially influenced succession of the Puga Fm. and Cuiabá Group in the northern Paraguay Belt displays three main depositional settings: platform, slope and outer slope (Fig. 45.2). The platformal deposits are reworked by sedimentary gravity flows. The deposits on the inner shelf show dominant massive diamictite, alternating with sandstone and fine-grained sedimentary rocks that contain striated and faceted clasts (Alvarenga & Trompette 1992). On the outer shelf, there is an association of massive diamictite, stratified diamictite and fine-grained sedimentary rocks with some clasts disrupting the underlying beds. The outer shelf succession has been interpreted as a succession of resedimented glacial deposits with alternations of debris-flows and shallow water turbidite events (Alvarenga & Trompette 1992).

Glaciomarine deposits reworked by sediment gravity flows and related to submarine fans characterize the slope depositional system. Progressive sorting in the deeper portions of the fans are demonstrated by the transition from diamictite to massive conglomerate and sandstone with local inverse and/or normal grading and normally graded, fine-grained turbidites. Sandstone and siltstone intercalations are consistent with inter-channel deposits. Deposition on the outer slope system was dominated by fine-grained deposits related to low-density turbidity currents, in which a direct glacial influence is only indicated by isolated clasts (dropstones).

This type of basin-filling suggests that the sedimentary source was located on the Amazonian Craton (Alvarenga & Trompette 1992) and this was confirmed by Nd isotopic analysis (Dantas *et al.* 2009). Shelf reworking during the glacial event helped develop submarine channels and turbidite deposits on the slope and outer slope (Alvarenga & Trompette 1992). Diamictite at the top of this succession is interpreted as the final stage of glaciation, during which all deposits were transported into the basin by sediment gravity flows and iceberg melting.

The Araras Group records carbonate deposition and is divided into three lithostratigraphic units. The basal Mirassol d'Oeste Fm. was deposited directly on top of glacial diamictites of the Puga Fm., and is interpreted as a transgression over previously glaciated landscapes. The laminated limestone and shale of the middle Guia Fm. are related to a deep-water system. The upper carbonate unit, Nobres Fm., consists of more than 1100 m of shallow-shelf dolostone (breccia, grainstone and packstone) indicating high-energy environments (Alvarenga *et al.* 2004).

Southern Paraguay Belt depositional settings

In the southern Paraguay Belt (Fig. 45.1), the rocks interpreted as deposited during the late Cryogenian glacial event are the Jacadigo Group and the Puga Fm. The Jacadigo Group around Corumbá is interpreted as deposited in a Neoproterozoic tectonic graben system, coeval with the sedimentation of the Puga Formation (Trompette *et al.* 1998). The Santa Cruz Formation shows alternations of autochthonous chemical sediments and siliciclastic sediments (fine-grained and arkose sandstone), which have been interpreted as glacially influenced based on the presence of large granite boulders thought to be dropstones (Barbosa 1949; Walde *et al.* 1981; Urban *et al.* 1992; Klein & Ladeira 2004). Trompette *et al.* (1998), however, remarked that these granite pebbles and boulders generally do not cross-cut the underlying bedding, and the deformation around the boulders is associated with compaction from overlying strata, being more pronounced above the boulders rather than beneath them. These data were used to deny a glacial origin of these deposits, suggesting reworked gravitational fluxes (Trompette *et al.* 1998). The diamictite of the Puga Fm. in the southern Paraguay Belt does not show evidence of striated clasts or dropstones, but their widespread areal distribution underlying a carbonate succession (Araras and Corumbá groups) is strong evidence for their stratigraphic correlations to other glacial deposits of the Puga Fm. in the Paraguay Belt.

The Corumbá Group records mixed clastic and carbonate sedimentation in a passive margin setting. The Cadieus and Cerradinho formations record proximal and distal alluvial deposition. The pink limestone of the Bocaina Fm. has been described as a 'cap' carbonate (Boggiani *et al.* 2003; see discussion below). The Tamengo and Guaicurus formations comprise a trangressive–highstand sequence, which drowned the carbonate shelf of the Tamengo Fm. (Boggiani & Coimbra 1996). Diamictite and pelite with clasts that occur as lenses in the pelites of the Guaicurus Fm. at Laginha Mine, Corumbá, Mato Grosso do Sul, have been interpreted as sediment gravity flow deposits in a slope setting (Boggiani *et al.* 2004).

Correlations and geotectonic evolution of the Paraguay Belt

Despite the widespread areal distribution of diamictite underlying both carbonate successions (Araras and Corumbá groups), there is no consensus about the lithostratigraphic correlation between the northern and southern parts of the Paraguay Belt. In addition, the evolution of these two segments could have been diachronic. Some differences and similarities observed between the rocks from the north and south will be mentioned here in order to provide a picture of the current knowledge and controversies surrounding the geotectonic evolution of the Paraguay Belt.

Glacial episodes have been proposed for both sectors of the Paraguay Belt, but some differences are observed. In the northern Paraguay Belt, two glacial events can be found: an older one represented by the Puga Fm. and the Cuiabá Group rocks (Alvarenga & Trompette 1992), and a younger one represented by the Serra Azul Fm. and thought to be related to the Ediacaran glaciation (Alvarenga *et al.* 2007, 2009; Figueiredo *et al.* 2008, 2011). In contrast, the glacial origin of the Puga Fm. in the southern Paraguay Belt is debatable and no younger diamictite-bearing unit has been found there.

Whereas carbonate lithofacies and sedimentary structures typical of other Neoproterozoic cap-carbonate rocks have been described in the North (Nogueira *et al.* 2003), none have been found in the southern belt.

Although there is some evidence of diagenetic alteration of Sr values in the lower Mirassol d'Oeste Fm., the carbonate units found overlying diamictite of the Puga Fm. in both regions exhibit $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ values interpreted as representing original seawater geochemistry; these data are consistent with a north–south correlation for the Paraguay Belt and are typical of other Neoproterozoic cap-carbonate rocks.

In contrast, the upper part of the Corumbá and Araras Groups differ in their lithostratigraphy. The limestone and shale from the Tamengo and Guaicurus formations, both with microfossils (Gaucher *et al.* 2003), represent a transgressive phase at the top of Corumbá Group. This is contrasted with the 1300 m of carbonate-dominated deposition and no microfossils in the top of the Araras Group, in the northern part of the belt. A depositional age of 543 $\pm$ 2 Ma (zircon U–Pb SHRIMP dating) was obtained for the Tamengo Fm. (Babinski *et al.* 2008). If we consider that the Bocaina Fm. was deposited after the late Cryogenian glaciation, which is assumed to be 630 Ma, an unconformity would have to exist between the Bocaina and Tamengo formations, because the deposition of the Bocaina Fm. (200 m thick, at most) could not have taken such a long time (*c.* 100 Ma). In contrast, the 1300-m-thick carbonate succession between the two glacial units in the northern Paraguay Belt is thought to have lasted 50 Ma, assuming the two glacial units represent a late Cryogenian (*c.* 630 Ma) and an Ediacaran age glaciation (580 Ma), respectively (Alvarenga *et al.* 2007; Figueiredo *et al.* 2008).

Further evidence that undermines a north–south correlation for at least the upper part of the succession comes from the age of the Alto Paraguay Group, which overlies the Araras Group. Although it is poorly constrained, a Rb–Sr whole-rock isochron age of *c.* 569 Ma, was determined from the shale of the Sepotuba Formation (Table 45.1; Cordani *et al.* 1985), suggesting that the units of the uppermost formations of the northern part of the belt are older than the ones from the southern part (e.g. the Tamengo Fm., Table 45.2).

In addition, the geotectonic evolution of the two regions appears to differ during deposition of the upper part of the succession. $^{40}Ar-^{39}Ar$ ages ranging from 541 and 531 Ma were determined from the biotite of metavolcanics (Araés gold deposit in the eastern end of the belt) and interpreted as the cooling ages following regional metamorphism in the northern Paraguay Belt (Geraldes *et al.* 2008). In contrast, in the southern part of the belt, the deposition of carbonate rocks and shale from the Tamengo (*c.* 543 Ma) and Guaicurus formations was taking place in a passive margin environment. These drastic differences in the two segments of the belt are still not understood, and a more detailed and profound study is needed in order to better constrain the evolution of the Paraguay belt.

Radiometric constraints on the Puga Fm. are limited to Ediacaran ages (543 Ma) obtained from the Tamengo Fm. in the southern Paraguay Belt, although the significance of this data depends on stronger evidence for north–south stratigraphic correlations. In the end, the Puga Fm. and the correlated Cuiabá Group in the northern Paraguay Belt are interpreted as related to the late Cryogenian glaciation because of the overlying dolomite lithofacies, palaeomagnetic data and negative $\delta^{13}C$ values of the Mirassol d'Oeste Fm. (Nogueira *et al.* 2003; Alvarenga *et al.* 2004, 2008; Allen & Hoffman 2005). Limestone and mud-limestone deposited above the Mirassol d'Oeste Fm. have $^{87}Sr/^{86}Sr$ ratios between 0.70763 and 0.70780, consistent with a seawater composition from *c.* 630 Ma (Alvarenga *et al.* 2004, 2008). The age and glacial origin of the Puga Fm. in the southern Paraguay Belt awaits further study to resolve existing controversies.

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