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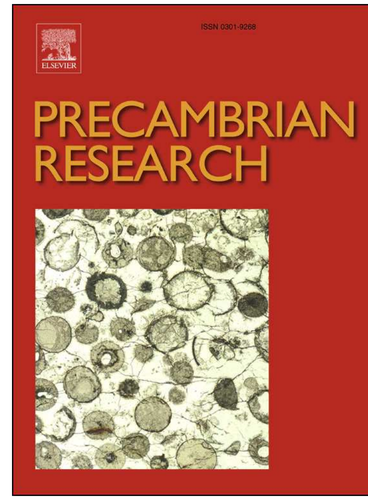

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Wind-pattern circulation as a palaeogeographic indicator: case study of the 1.5-1.6 Ga Mangabeira Formation, São Francisco Craton, Northeast Brazil

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Abstract

The preserved deposits of dune-scale aeolian bedforms provide valuable palaeoenvironmental indicators of atmospheric circulation patterns and the latitudinal position and distribution of land masses. However, no attempts to use palaeowind directions and palaeogeographic reconstructions of ancient land mass distribution have been published to model Precambrian atmospheric circulation. The Mangabeira

Formation is a large Mesoproterozoic aeolian erg succession (1.6 to 1.5 Ga) composed of two aeolian units that accumulated in the São Francisco Craton, Brazil. The Lower Unit records multiple drying-upward depositional cycles, each of which represents an episode of erg expansion and contraction driven by climate changes. The Upper Unit is composed dominantly of stacked aeolian dune strata that lack intervening interdune deposits and which record extreme aridity. Palaeowind directions recorded from cross-strata of transverse, crescentic aeolian dunes of the Lower and Upper Units record dune migration under the influence of two dominant winds that blew to the southeast and northwest. Analysis of these palaeowind data in relation to assessment of regional palaeogeographic reconstructions for the period 1.6 to 1.5 Ga reveals a correlation between atmospheric circulation and land mass distribution. At this time the São Francisco Craton was located between the mid-latitudes and the equatorial zone. The wind regime determined from analysis of dip azimuths of cross-strata of the Lower Unit (1.6 to 1.54 Ga) are consistent with a palaeogeographic position between 25º to 35º S. Analysis of cross-strata dip azimuths of the Upper Unit indicate northwest-directed palaeowinds and a dominant monsoonal wind pattern from 1.54 to 1.5 Ga. During this time the large land mass of the São-Francisco-Congo and Siberian cratons drifted northwards through the equatorial zone from palaeolatitude 30º S to 30ºN.

Keywords: Mesoproterozoic erg; Mangabeira Formation; Palaeowinds; Palaeogeography, Wind-pattern model

1. Introduction

Large aeolian dune deposits and related facies are the primary indicators of extensive Precambrian desert environments. It has been argued that large examples of such sedimentary systems were only been present at mid-palaeolatitudes (within 30 degrees of the palaeo-equator) during the Precambrian (Eriksson et al., 2013). Indeed, present-day large desert systems (>12.000 km^2, Pye and Tsoar, 2009) occur mostly between 15º and 30º latitude. Numerous post-1.8 Ga Precambrian aeolian successions have been documented (e.g. Ross, 1983; Pulvertaft, 1985; Deynoux et al., 1989; Chakraborty, 1991; Chakraborty, 1993; Simpson and Eriksson, 1993; Clemmensen, 1988; Tirsgaard and Øxnevad, 1998; Bose et al., 1999; Biswas, 2005; Rodríguez-López et al., 2014). Eriksson and Simpson (1998) proposed that the occurrence of these ancient aeolian successions was related to the assembly of large land masses, which encouraged the evolution of major aeolian erg (dune field) systems. Based on the identification of diagnostic sedimentary structures, such as wind-ripple strata and large-scale sets of cross strata, Precambrian aeolianites are generally associated with extensive erg environments that developed in a broad range of climatic settings (Eriksson and Simpson, 1998; Simpson et al., 2004; Heness et al., 2014). Although Precambrian aeolian successions are widely recognised and correlated with various tectonic settings and climatic regimes (e.g. Pulvertaft, 1985; Jackson et al., 1990; Soegaard and Callahan, 1994; Tirsgaard and Øxnevad, 1998; Simpson et al., 2002), no attempts have hitherto been published to show how the record of aeolian accumulation and palaeogeographic reconstructions of the land mass distribution can be used to model Precambrian atmospheric circulation.

Ancient aeolian landforms (e.g. dunes, draas and sand seas) reflect the directions and intensity of palaeowinds – a major component of atmospheric circulation. In turn, atmospheric circulation is dominated by the latitudinal distribution of solar radiation and the distribution of land masses. Several models of atmospheric circulation, based on palaeowind directions recorded by the deposits of aeolian sandstones and on the palaeogeographic reconstructions of land masses in Pangaean times, have been published (Parrish and Peterson, 1988; Peterson, 1988; Loope et al., 2001, 2004; Scherer and Goldberg, 2007). Modelling of this type is particularly difficult for Precambrian times because of the fragmentary nature of the sedimentary record and the relatively poorly constrained palaeogeography (e.g. Li et al., 2008; Zhang et al., 2012; Evans, 2013; Pisarevsky et al., 2003, 2014).

The Mangabeira Formation is a Proterozoic erg located on the São Francisco craton in north-eastern Brazil. This large Proterozoic aeolian accumulation has a preserved area of ~50.000 km^2 and is up to ~700 m thick. The formation comprises two units, each of which is characterized by a distinct depositional architecture and each of which provides a detailed record of palaeowind directions via the preservation of sets of inclined cross strata that represent aeolian dune lee slope deposits.

The aim of this study is to present palaeocurrent data to enable the reconstruction of dominant palaeowind patterns in low (equatorial) and middle (~30^0S) palaeolatitudes during the Mesoproterozoic (1.6 - 1.5 Ga). This wind-pattern model is based on the analysis of aeolian cross-strata in the Mangabeira Formation and on recent palaeogeographic reconstructions for these times (Pisarevsky et al., 2014). Specific research objectives are (i) to understand the stratigraphic evolution of the Mesoproterozoic erg of Mangabeira Formation, (ii) to present global-scale palaeogeographic maps showing the distribution of major aeolian units, and (iii) to discuss the wind regime and propose a wind-pattern model for the time period 1.6 to 1.5 Ga.

2. Geological Setting

The São Francisco Craton is located in north-eastern Brazil and comprises Archaean Palaeoproterozoic basement with metamorphic and supracrustal rocks that are overlain by Palaeoproterozoic to Phanerozoic platform-type cover deposits (e.g., Almeida, 1977; Barbosa et al., 2004; Cruz and Alkmim, 2006; Alkmim and Martins-Neto, 2012). Two physiographic features in the northern part of the craton – the Northern Espinhaço Range and Chapada Diamantina Range – expose Proterozoic sedimentary successions. In the Chapada Diamatina Range, the Espinhaço Supergroup and the São Francisco Supergroup are the main sedimentary units; the former is of Palaeoproterozoic to Neoproterozoic age and is composed dominantly of siliciclastic rocks; the latter is characterized mainly by carbonate successions of

Neoproterozoic age (Fig.1). The Espinhaço Supergroup spans an age range from approximately c. 1.75 to 0.9 Ga based on radiometric age constraints (Schobbenhaus et al., 1994; Babinski et al., 1999). This unit is composed principally of clastic sedimentary rocks of continental and coastal origin (Pedreira and De Waele, 2008; Danderfer et al., 2009; Alkmim and Martins-Neto, 2012), and associated volcanic deposits (Schobbenhaus et al., 1994; Babinski et al., 1999).

As proposed by Chemale et al. (2012), three megasequences termed the Lower, Middle and Upper sequences characterize the Espinhaço Supergroup, and these sequences are related to the superimposition of numerous basins (Fig. 2). The Lower Megasequence is represented by the Rio dos Remédios Group, which comprises a volcanic-sedimentary succession related to an extensional tectonic event between ca. 1.80 and 1.68 Ga, and includes continental clastic sequences of the Serra da Gameleira, Lagoa de Dentro and Ouricuri do Ouro formations associated with volcanic rocks of the Novo Horizonte Formation. The Middle Espinhaço megasequence developed in a rift-sag basin that became filled with continental and coastal deposits. This thermal sag phase spans an age range from 1.6 to 1.38 Ga (Pedreira, 1994; Pedreira and De Waele, 2008; Guimarães et al., 2008; Alkmim and Martins-Neto, 2012; Guadagnin et al., 2015a). The Paraguaçu Group and the lowermost Tombador Formation of the Chapada Diamatina Group comprise this sequence. The Paraguaçu Group (c. 1.6 to 1.5 Ga) is represented by the Mangabeira and Açuruá formations. The ca. 1.45 - 1.38 Ga Tombador Formation represents the superposition of multiple depositional systems that accumulated in response to a basin sag phase (Magalhães et al., 2015). The Upper Espinhaço Megasequence (ca. 1.19 - 0.9 Ga) is the uppermost sedimentary succession of the Espinhaço Supergroup and is related to the fill of a rift-sag basin. The Caboclo and Morro do Chapéu formations, the uppermost two units of the Chapada Diamantina Group, comprise this sequence.

The Mangabeira Formation, which is the focus of this study, was formally defined by Schobbenhaus and Kaul (1971), and described by Pedreira (1994). This

700 m-thick sedimentary succession (as measured in this study) records the accumulation of a palaeo-desert environment that was characterized by aeolian dunes, sandsheets and wadi deposits. Bállico et al. (2017) proposed a stratigraphic architecture for the Lower Unit of the Mangabeira Formation, which is characterized by drying-upward cycles. Provenance data for this unit were presented by Guadagnin et al. (2015b) who demonstrated that sediments of the Mangabeira Formation were recycled from sedimentary sources linked to a collisional tectonic setting. Analyzed zircon grains were formed in the Paleoproterozoic Era, as a result of palaeoplate amalgamation. Based on the chronostratigraphic distribution of detrital zircon ages (Guadagnin et al. (2015b; Guadagnin and Chemale, 2015), the Mangabeira Formation has an age of 1.5 to 1.6 Ga. Radiometric dates acquired from analysis of mafic sills and dyke swarms that cut the base of the Mangabeira Formation (Babynski et al., 1999; Silveira et al., 2013) reveal an age of ca. 1.5 Ga; the latter authors interpreted 1.5 Ga to be the likely minimum depositional age for this unit.

FIGURE 1

FIGURE 2

2.2. São Francisco-Congo craton and the Mesoproterozoic palaeogeography

Nuna or Columbia (e.g., Hoffman, 1997; Meert, 2002; Pesonen et al., 2003; Zhao et al., 2002; Pisarevsky et al., 2014) was a Proterozoic supercontinent, components of which included the Congo-São Francisco craton and other large cratons, such as Siberia, India, Baltica, Laurentia and N. China. Stratigraphic correlation, geochronological and palaeomagnetic data suggest that the São Francisco and Congo cratons composed a single continent from ca. 2050 Ma until the opening of the Atlantic Ocean, ca. 130 Ma (e.g., Trompette, 1994; D'Agrella Filho et al., 1996; Deckart et al., 1998; Feybesse et al., 1998; Côrrea-Gomes and Oliveira, 2000; Pedrosa-Soares et al., 2001, Zhao et al., 2002; Janasi, et al., 2011).

Pisarevsky et al. (2014) compiled a palaeomagnetic and geological database using data from many continents, and reconstructed global palaeogeography from 1770 to 1270 Ma. The global-scale maps of Pisarevsky et al. (2014) show that the Congo-São Francisco craton was located in southern mid-latitudes at 1.58 Ga and in equatorial position at 1.5 Ga.

The palaeoposition of Congo-São Francisco at 1.5 Ga is supported by palaeomagnetic and geological data. Silveira et al. (2013) dated the dike swarm at the base of the Mangabeira Formation at 1506.7±6.9 Ma age (U–Pb baddeleyite). Ernst et al. (2013) noted a good match between Large Igneous Province (LIP) “barcodes” of the Congo-São Francisco and Siberia at 1500 Ma and at 1380 Ma and suggested the affinity of these cratons at 1500-1380 Ma. This fit is also supported by palaeomagnetic data (Ernst et al., 2013 and references therein). Pisarevsky et al. (2014) used this match in their 1580 to 1270 Ma global reconstructions. Unfortunately, there are no reliable ca. 1580 Ma palaeomagnetic poles from Siberia and Congo-São Francisco (Pisarevsky et al., 2014), which implies that the suggested palaeo-positions of these cratons at that time might be reconsidered if they contradict some new geological data.

3. Study Area and Methods

The Mangabeira Formation crops out over a large area (~50.000 km^2) on the São Francisco Craton. For this study, the detailed sedimentology of the Mangabeira Formation was documented along a series of roadside cuttings in the southern part of the Chapada Diamantina Range, over an area of ~1200 km^2. It is in this region that the outcrops are best preserved. The main road has a north to south orientation and provides a dip-oriented section. Strata dip at 5 to 10° to the south and the sections exhibit little deformation. For this study, 18 detailed sedimentological sections of the Mangabeira Formation were measured and logged at 1:100 scale. Graphic logs record grain size, physical sedimentary structures and palaeocurrent data (328 readings) based on cross-strata dip and dip-direction. All measurements were corrected by removing structural dip to negate the influence of tectonic overprint. Resultant foreset dip azimuths were plotted on rose diagrams and on palaeogeographic maps. These maps were corrected to remove the component of rotation known to have been experienced by São Francisco Craton through time (see Pisarevsky et al., 2014). The Euler rotation parameters were based on those provided by Pisarevsky et al. (2014).

4. The Mangabeira Formation: palaeowinds and stratigraphic architecture

In the southern area of the Chapada Diamantina, the Mangabeira Formation can be subdivided into two units, each of which preserves a distinct stratigraphic architecture and which records evidence for palaeowind directions.

4.1. Lower Unit

4.1.1. Description

The Lower unit is ~500 m thick and records a variety of aeolian facies. The succession is arranged into vertically stacked depositional cycles that are each 2 to 20 m thick. Each preserved cycle is characterized by a well-defined facies succession (Fig. 3). The base of each cycle is characterized by deposits of very fine- to medium-grained, moderately sorted sandstone that occurs as tabular beds that are laterally continuous for 0.6 to 6 metres (Fig. 4). The tabular bodies display horizontal to low-angle cross-stratification (<5º), composed of three types of lamination. The first lamination type comprises millimetric, inverse graded, horizontally to low-angle translatent lamination, made up 0.1 to 0.2 m-thick beds (Fig. 3a). The base of laminae is formed of very fine-grained sandstone that grade upward to medium-grained sandstone, forming pin-stripe lamination (Fryberger and Schenk, 1988). The second lamination type is formed by millimetric to centimetric interlayered sandstone and mudstone, with crinkled-lamination, 5- to 100 mm thick (Fig. 3b). The third lamination type is 2 mm-thick lenticular and laterally discontinuous compounded wind-ripple lamination that occurs within sets of tangential cross-stratified sandstone. Other lithofacies associated with the low-angle cross-stratificated sandstones comprise fine- to medium-grained sandstone characterized by ripple cross-stratification (Fig. 3c). These low-angle cross-stratificated sandstones occur as 0.1 m-thick sets, groups of which occur collectively as stacked co-sets that are themselves 1 to 2 m thick and up to 5 m in lateral extent. Rare, small-scale (< 0.2 m thick) soft-sediment deformation structures and thin lenses and drapes of massive mudstone (up to 10 mm thick) are also rarely observed. These deposits are overlain by 0.2 to 3 m thick fine- to medium-grained, well-sorted sandstones, with trough-tangential cross-stratification. The foresets are formed by wedges of sand flow (i.e. grainflow) deposits, each 10- to 80 mm thick, that pinch out down-dip into milimetrical wind-ripple laminae (Fig. 3d). The cosets display two arrangements: sets that are 0.2 to 0.5 m thick and sets up to 1.5 m thick. Individual sets are wedge shaped. In orientations transverse to palaeoflow (as revealed by cross strata azimuths), cross beds and their basal bounding surfaces are characterized by troughs. These troughs display a spread of foreset azimuths from 005° to 050° in a single set (Fig. 4). In orientations parallel to palaeoflow, cross-strata dip up to 30^0 and are tangential to planar basal bounding surfaces, which are themselves sub-horizontal or inclined <5° in an upwind direction. Internally, the cross-bedded sets are subdivided by inclined bounding surfaces that truncate the strata below, whereas the strata above are concordant with these surfaces. These bounding surfaces, which occur internally within sets, dip up to 15º (Fig. 4). Foreset dip orientations are variable, with most foreset azimuths occurring in the range 045º to 335º (Fig. 4). The main foreset dip is <20º, varying between 18º and 30º. Very fine- to fine-grained sandstones with inversely graded, horizontal lamination or wavy-crinkled lamination (Fig. 3e) and millimetric and irregular laminae of mudstone occur intercalated with inclined cross-strata in places. These set of beds are discontinuous and irregular; thicknesses vary from 0.1 to 0.2 m; widths vary from 10 to 20 metres (Fig. 3f).

4.1.2. *Interpretation*

Each of the depositional cycles of the Mangabeira Formation records an upward change from aeolian sandsheet to aeolian dune and interdune deposits. The tabular sandstones with low-angle stratification are interpreted as aeolian sandsheets (Hunter, 1977; Kocurek and Nielson, 1986). The thin, horizontally to low-angle translatent lamination with inverse grading laminae represent wind-ripple deposits formed by the migration and climbing of wind ripples over a dry depositional surface (Hunter, 1977; Fryberger and Schenk, 1988). The millimetric to centimetric interlayered sandstones and mudstones with the crinkled-lamination are interpreted as adhesion ripples that accumulated on a damp or wet surface (Kocurek, 1981; Kocurek and Fielder, 1982; Chakraborty and Chaudhuri, 1993; Scherer and Lavina, 2005). Small-scale tangential cross-beds with wind-ripple lamination and laterally discontinuous are interpreted as residual deposits of aeolian dunes (Hunter, 1977) that accumulated in sand-availability limited, dry conditions (cf. Kocurek and Nielson, 1986). The fine- to medium-grained sandstones with ripple-cross stratification are interpreted as aqueous 2D- or 3D-ripple deposits. The thin massive mudstones indicate settling of suspended sediments in a low-energy aqueous environment, probably related to the final stages of ephemeral floods (Miall, 2006). Soft-sediment deformation structures as interpreted as formed by fluid escape in unconsolidated sediments, probably as result of groundwater fluctuation (Owen, 2003). Sets and cosets of trough cross-stratification, composed of sandstone with well-sorted and well-rounded grains that are organized into grainflow and wind-ripple laminae indicate migrating aeolian dunes (Hunter, 1977). The down-dip pinch-out of packages of grainflow strata into wind-ripple lamination are interpreted as lee-slope grainflow avalanches that reached dune toesets, whereas wind ripples migrated over dune plinth areas (cf. Mountney, 2006; Scherer, 2000). Subhorizontal to low-angle inclined, upwind-dipping surfaces (as seen in sections parallel to paleoflow) are interpreted as interdune migration bounding surfaces (Kocurek, 1996). The trough geometry of the interdune surfaces observed in sections transverse to palaeoflow indicates that the main bedforms possessed sinuous crestlines (Rubin, 1987). Inclined downwind-dipping bounding surfaces that occur within the cross-bedded sets are reactivation surfaces, generated as a result of episodic erosion of the partial lee-side of the bedforms during short term changes in wind direction and/or strength (Brookfield, 1977; Hunter and Rubin, 1983; Mountney, 2006; Rubin and Hunter, 1982; Scherer and Lavina, 2005). Common trough-tangential cross-stratification combined with high dispersion values of the foreset dip is typical of crescentic dunes with moderate to highly sinuous crestlines. Discontinuous and irregular beds with translatent and wavy crinkled lamination that occur between and intercalated with sets of aeolian dune cross-strata are interpreted as aeolian interdune deposits. Inversely graded, horizontal lamination is interpreted as subcritical climbing wind-ripple strata (Hunter, 1977), indicating dry interdunes, which accumulated under conditions where the water table was below the accumulation surface. Wavy crinkled laminations are interpreted as adhesion structures that developed on damp interdune surfaces; these structures indicate a context where the water table was located close to the accumulation surface (Mountney and Thompson, 2002; Paim and Scherer, 2007). An alternative interpretation of the crinkled lamination is a microbial origin (Eriksson et al., 2010; Souza, 2012; Simpson et al., 2013; Bállico et al., 2017). The thin beds of interdune origin with irregular geometry indicate dry or damp interdune hollows or corridors, that occupied spatially isolated hollows between the dunes (Mountney and Jagger, 2004).

FIGURE 3

FIGURE 4

4.2. Upper Unit

4.2.1. Description

The Upper Unit is ~200 m thick. The basal contact with Lower Unit is covered and not exposed in the studied area. Two main facies associations characterize this unit (Fig. 5). The majority of deposits are fine- to coarse-grained sandstones that are well sorted, with subrounded to rounded grains, arranged in cross-stratified sets.

Individual sets are 2 to 10 metres thick. In orientations transverse to paleoflow, simple sets of cross bedding and their basal bounding surfaces reveal trough-shaped element geometries (Fig. 6; troughs are 50 to 200 m wide). By contrast, in orientations parallel to the direction of dip of the cross-strata, inclined cross bedding is tangential to basal set bounding surface (Fig. 5a). Internally, foresets within sets have uppermost parts that are composed of massive sandstone or inversely-graded grainflow lenses that dip at ~20º (Fig. 5b). Toeset deposits are characterized by inversely graded wind-ripple laminae, each up to 3 mm thick (Fig. 5c). In some places, the laminations are armoured by very coarse-grained sandstone to granules, deposits of which form wedge-shaped lenses (Fig. 5d). Some sets exhibit concordant cyclic cross-bedding, composed of packages of grainflow strata that are separated by thinner packages of wind-ripple laminae. These cyclic sets of cross-bedding are regularly spaced, each package being 0.2 to 0.8 m thick in orientations parallel to sand transport (Fig. 7). Internally, the cross-bedded sets can be subdivided into sub-sets bounded by surfaces that truncate the strata below, whereas the strata above are concordant with the dipping bounding surfaces. The dipping bounding surfaces are themselves inclined up to 16º. Palaeocurrent directions are variable; most of the wind currents are in the range 225º SW to 270º W based on foreset dip azimuths (Fig. 6).

The second facies association occurs in a specific interval of the succession and is composed by four lithofacies: (i) fine- to medium-grained sandstones with low-angle stratification; (ii) fine-grained sandstone with millimetric spaced wrinkled lamination (Fig. 5e); (iii) very fine- to fine-grained sandstone with ripple-cross stratification in packages up to 25 mm thick; (iv) heterolithic beds of massive mudstone and fine-grained sandstone with wavy-ripple lamination up to 50 mm thick (Fig. 5f). Rare small-scale deformation structures are present in a few places. These sedimentary structures occur interlayered as composite cosets of strata which themselves form 0.7 to 2.5 m-thick and 10 m-wide tabular bodies (Fig. 5g).

4.2.2. Interpretation

The medium- to large-scale cross-strata sandstones compounded by grain flow and wind-ripple strata are interpreted as formed by the migration of large aeolian dunes. The presence of grainflow strata indicates high-angle, well-developed slipfaces (Hunter, 1977). The unimodal trend of the cross-bed dip azimuths, and their occurrence in trough-shaped sets indicates crescentic dunes with sinuous crestlines (Rubin, 1987). The regularly spaced cyclic sets of cross-bedding with the alternation of grain-flow and wind-ripple lamination suggests periods where grain flow lamination were developed by avalanche in lee-faces dunes followed by intervals of erosion and deposition of wind-ripple laminations. This most commonly occurs in response to seasonal changes in wind direction (Hunter and Rubin, 1983; Kocurek et al., 1991; Chan and Archer, 2000; Loope et al., 2001; Scherer and Lavina, 2005; Mountney, 2006; Kocurek et al., 2007; Scherer and Goldberg, 2007). Thicker packages of grainflow strata that dip to the southeast, as revealed in sections parallel to sand transport direction, were transported by the stronger winds that dictated the dune orientation. By contrast, the wind-ripple lamination records the action of weaker oblique to reverse winds. The laminations characterized by armoured very coarse-grained sandstones to granules are granule ripple deposits; these deposits likely accumulated in response to changes in effective wind direction and strength (Fryberger et al., 1992). The concave-up surfaces that truncate the foresets are interpreted as reactivation surfaces, which reflect frequent changes in the wind flow. The association of water-laid sedimentary structures that occur in bodies with a tabular geometry suggests unconfined, high-energy, ephemeral flash flood deposits (Miall, 1996). The sandstones with low-angle-inclined stratification are interpreted to record sediment transport in a flow that undertook a transition from lower to upper flow regime conditions (Miall, 1977, 1996). The presence of wavy-ripple sandstone indicates fair-weather waves on wide and shallow, ephemeral lakes. The very fine- to fine-grained sandstones with ripple-cross stratification are interpreted as 2D- or 3D-ripples formed in lower flow regime (Miall, 1977). The wavy crinkled lamination is interpreted as adhesion structures accumulated on damp or wet surfaces by the adhering of dry sand to a wet or damp surface (Kocurek and Fielder, 1982).

FIGURE 5

FIGURE 6

5. Discussion

5.1. Stratigraphic Evolution

The Mangabeira Formation records prolonged aeolian sedimentation and subordinate ephemeral fluvial systems (Fig. 8). The Lower Unit is ~500 m thick and records multiple hiatuses of aeolian deposition and deflation expressed in drying-upward cycles (Bállico et al, 2017). The Upper Unit is ~200 m thick and comprises the deposits of large aeolian dunes that developed in a dry aeolian system with only rare examples of fluvial deposition. The contact between these units was not exposed in the studied area. However, based in the distinct depositional architecture and reconstructed palaeowind directions, we suggest that these units are separated by an unconformity. Both units accumulated in an intracratonic basin in the São Francisco craton as part of the Supergroup Espinhaço (Guimarães et al., 2008; Guadagnin et al, 2015; Magalhães et al., 2015).

The Lower Unit records multiple drying-upward cycles that record cyclical changes in depositional conditions (Fig. 8). These cycles have been interpreted as episodes of erg expansion and retraction driven by climate changes (Bállico et al., 2017), with each cycle characterized by aeolian sandsheet and water-lain deposits that are replaced upward by aeolian dune and interdune deposits. Each cycle is bounded at its top by laterally extensive supersurfaces. The aeolian sandsheets and water-laid deposits accumulated in a relatively humid setting. The presence of closely associated adhesion strata and wind-ripple strata suggest a near-surface water table (Kocurek and Havholm, 1993). Moreover the presence of the water-laid deposits interlayered with the sandsheets suggests periods of intense precipitation, which resulted in fluvial activity whereby streams entered the erg via interdune corridors. A consequence of this flood-related fluvial activity was an associated rise in water table level within the aeolian dune field (Langford and Chan, 1989). During humid periods, the sand availability and the transport capacity of the wind were limited, whereas sediment supply suitable for later aeolian reworking was generated by fluvial sediment influx (Kocurek, 1999; cf Almasrahy and Mountney, 2015). As the climate shifted to more arid conditions, the aeolian sandsheets and water-laid deposits were replaced by aeolian dunes and interdunes. In contrast to the aeolian sandsheets, the aeolian dunes and interdunes developed in conditions where the water table was significantly below the accumulation surface, which implies that all sediments were potentially available for aeolian transport (Kocurek and Havholm, 1993). Accumulation was associated with a positive sediment budget, controlled by aerodynamic factors (e.g. compression of streamlines over dune stoss slopes which resulted in flow acceleration and erosion, followed by flow deceleration and deposition on the downwind lee slope). The presence of small-scale sets that grew into medium-scale sets of cross-strata can be explained by an increasing availability of dry sand for aeolian construction, and a consequent increase in the size of dunes or an increase in the angle of climb of the dunes as they accumulated (Kocurek and Havholm, 1993; Mountney, 2006). Minor occurrences of damp interdune deposits between aeolian dunes suggest an oscillation of the water table, which sometimes intercepted the accumulation surface. The simple crescentic dunes and well-developed slipfaces (with grainflow and wind-ripple strata), allied to unimodal trends of the palaeowind indicators suggests a persistent wind regime, which was associated with continuous sand availability. The unimodal wind regime behaviour was punctuated by annual fluctuations, as revealed by the regularly spaced reactivation surfaces present in the aeolian dune strata. Cycles of aeolian dune and interdune strata are bounded by supersurfaces, which are interpreted as deflation surfaces (Kocurek and Havholm, 1993; Bállico et al., 2017). The climax of each episode of aridity was likely associated with the onset of the erg deflation. With increasing aridity, the upwind sediment supply in the form of the dry sand became exhausted and the wind transport system became undersaturated with respect to its potential sand carrying capacity, thereby inducing a change from accumulation to deflation of the erg.

The Upper Unit is composed mainly of aeolian dunes deposits without intervening interdune deposits; this implies extreme aridity (Fig. 8). The absence of damp/wet interdune deposits implies conditions in which the water table and its capillary fringe lay deeply below the accumulation surface. The Upper Unit is therefore representative of a dry aeolian system (terminology of Kocurek and Havholm, 1993). In dry aeolian systems, accumulation occurs when the transport rate decreases downwind and dune bedforms grow to a size whereby they occupy the entire accumulation surface at the expense of intervening interdune flats (Kocurek and Havholm, 1993). The onset of accumulation of dry aeolian systems requires a high availability of sand for aeolian transport; climbing of aeolian dunes commences when the depositional surface reaches a saturated condition (i.e. interdune flats are eliminated – Kocurek and Havholm, 1993).

The presence of cyclic cross-bedding pattern suggests an annually oscillation in the wind regime (Hunter and Rubin, 1983; Kocurek et al., 1991; Chan and Archer, 2000; Loope et al., 2001; Scherer and Lavina, 2005; Mountney, 2006; Kocurek et al., 2007; Scherer and Goldberg, 2007). The common occurrence of these annual cycles indicates a variable wind regime during the accumulation of the Upper Unit. Although persistent SSW winds were likely responsible for the main component of aeolian dune migration, reversing or oblique winds (NNE winds?) apparently reworked the frontal face of the aeolian dunes, forming the wind-ripple strata and the common reactivation surfaces. The presence of granule ripples (interpreted as megaripples) provides additional evidence about the wind regime. Many authors have suggested that megaripples form in response to a strong wind regime (Sakamoto-Arnold, 1981;

Fryberger et al., 1992; Yizhaq, 2008; Milana, 2009), which implies that during the accumulation of the aeolian dunes of the Mangabeira Formation, the SSW winds were strong and persistent, punctuated by seasonal oscillation. The relationship of the localized fluvial package to the aeolian dune strata is not clear due a paucity of data. The nature of these deposits indicates that the fluvial accumulation occurred in response to multiple, successive flooding events that frequently entered into the erg along interdune corridors, possibly in response to short-lived relatively humid conditions (Fig. 8). The presence of mudstones with wavy lamination suggests that these flooding events were confined to interdune depressions, forming small ponds, similar to processes observed today in Skeleton Coast of the Namib Desert (Langford, 1989; Langford and Chan, 1989; Stanistreet and Stollhofen, 2002; Al-Masrahy and Mountney, 2015).

FIGURE 8

5.2. Reconstruction of palaeowinds and implications for 1.6 - 1.5 Ga palaeogeographic reconstruction of SF-Congo craton and surrounding palaeoplates

In this section, we correlate and discuss the wind patterns recorded in the aeolian strata of the Mangabeira Formation with the 1.6 to 1.5 Ga regional and global palaeogeography. Our analysis focuses predominantly on the following: (i) the interpreted wind regime and consequent suggestions about circulation cells and their effects on the accumulation of aeolian sand seas; and (ii) the response of aeolian sand seas to the palaeolatitudinal position of the São Francisco-Congo craton.

In both hemispheres, the ascending and descending branches of Hadley, Ferrell and Polar cells are driven by the distribution of solar heating and the distribution of landmasses, which controls the atmospheric circulation along the latitudes (Webster, 2004). In this way, a zonal generic circulation model consists of trade winds in both hemispheres that converge from subtropical, high pressure zones, to tropical, low-pressure zones, resulting in high humidity and intense precipitation at the equator, and flow away to subtropical zone, with a dry air mass, forming the great deserts at mid-latitudes (Charney, 1975; Parrish and Peterson, 1988; Parrish, 1993; Gasse and Roberts, 2004; Webster, 2004). This zonal circulation pattern dominates at present and influences most modern desert regions around the world. Subordinate to this zonal wind circulation, there is a strongly seasonal monsoonal circulation that presently occurs in South Asia, West Africa and Australia, where the winds cross the equatorial zones due the high- and low-pressure gradient (Charney, 1975; Cook, 2003; Gasse and Roberts, 2004; Park et al., 2011).

The Mesoproterozoic Mangabeira Formation records crescentic aeolian dunes that developed in response to two main winds directions. The southeastern and the northwestern mean directions (palaeowinds directions in the past geographic coordinate system) of the lower and upper units, respectively, reflect changes in the atmospheric circulation probably caused by changes in the palaeo-positions of continents. From 1.60 Ga to ~1.54 Ga, the São Francisco craton occupied a mid-latitude position (Fig. 9). The wind regimes recorded by the aeolian deposits of the Lower Unit are consistent with the reconstructed palaeo-position of the craton at 25º to 35º S. This position mimics that of major, present-day deserts (e.g. the Namib Desert) and is also shown to have operated in Phanerozoic palaeo-deserts (e.g. Mountney et al., 1998; Chan and Archer, 2000; Loope et al., 2001; Mountney and Jagger, 2004; Scherer and Goldberg, 2007, 2010; Pye and Tsoar, 2009). The easterly and southeasterly migration of aeolian dunes is consistent with a zonal pattern of the atmospheric general circulation in the southern subtropics. The descending branch of the Hadley cell flowed towards the southeast (Charney, 1975; Webster, 2004), bringing dry air which is favorable for a high evaporation in the oceans and an accumulation of deserts in the landmasses. Palaeo-positions of other interpreted 1.6 to 1.5 Ga deserts (e.g., Dala Sandstone, ~1.6 Ga, Fennoscandian Shield, Pulvertaft, 1985; Lundmark and Lamminen, 2016; Mukun Group, 1.58 - 1.50 Ga, Siberian craton, Petrov, 2011,

2014) also correlate with palaeoclimate conditions and reconstructed atmospheric circulation. For example, one succession that developed coeval to the Mangabeira Formation is the Mukun Group in the Siberian Craton (1.58 to 1.50 Ga; Petrov, 2011, 2014). This succession is also characterized by alluvial, aeolian–fluvial, and fluvial–sabkha successions (Petrov, 2011, 2014). The palaeowind directions of the aeolian deposits of the Mukun Group exhibit a mean vector to the north (see Petrov, 2014; past coordinate system), which is consistent with the zonal circulation pattern proposed for the Lower Unit of the Mangabeira Fm. The Siberian craton is the northern neighbor of the São Francisco Craton in palaeogeographic reconstructions for 1.60 and 1.54 Ga (Fig. 9). Both land masses were located in the southern hemisphere, between subtropical and tropical zones. Between 30ºS and the equator, the southeasterly trade winds blew from southeast to northwest toward the equatorial zone (Fig. 9). Petrov (2011) concludes that the Mukun Group accumulated in humid to semi-arid zones, and this interpretation is consistent with the palaeogeographic reconstruction at 1.6 to 1.54 Ga (Fig. 9) and with the atmospheric conditions. Similar cyclicity is observed in both the Lower Unit of Mangabeira Formation (São Francisco) and in the fluvial-aeolian succession of the Mukun Group (Siberia; Petrov, 2011). However, the Lower Unit of the Mangabeira Formation is represented by multiple cycles of drying-upward aeolian sandsheets and dunes, whereas the Mukun Group records multiple cycles of fluvial-aeolian deposits. We relate these drying-upward cycles to allocyclic controls on sedimentation caused by climatic oscillations. The types of deposits in both the Lower Unit of the Mangabeira Formation and in the Mukun Group suggest accumulation in different environments but where both systems were influenced by the position of a Hadley cell and by global climate. For example, during episodes of semi-arid climates the formation of aeolian dunes was likely in subtropical zone (São Francisco); by contrast, in the tropical zone (Siberian craton) accumulation of fluvial-aeolian deposits was dominant.

FIGURE 9

Between 1.54 and 1.50 Ga, São-Francisco, Congo and Siberia had drifted farther north (Fig. 10). São Francisco was located between 5º S and 5º N (Pisarevsky et al., 2014). At present, the near-equatorial region is known as the Intertropical Convergence Zone (ITCZ) – a narrow belt characterized by the meeting of moist trade winds characterized by intense precipitation (Charney, 1975; Loope et al., 2001; Webster, 2004; Tsoar et al., 2009; McGee et al., 2014). Usually the trade winds in the ITCZ are weak and variable, due to the Coriolis Effect.

The Upper Unit of the Mangabeira Formation records pervasive northwesterly directed palaeowind directions, which is more consistent with the southeasterly winds that flow across the subtropical zones in a general westward equatorial direction (Webster, 2004). This implies a different palaeo-position for the São Francisco craton during the accumulation of the Upper Unit, consistent with the palaeo-reconstruction at 1.54 to 1.50 Ga (Fig. 10). However, if we assume that 1.54 to 1,50 Ga palaeogeographic map is more consistent with the wind pattern recorded in the Upper Unit, how might we explain the accumulation of large sand seas in an equatorial zone without any evidence of "wet deposits", as observed in the Mukun Group? The monsoonal wind pattern that prevailed at 1.54 to 1.50 Ga can explain this. The large land masses of São Francisco-Congo and Siberia in mid-latitudes and near the equator could have controlled the monsoonal pattern in low-latitudes. The monsoonal pattern was characterized by cross-equatorial winds, moving from a high pressure centre in the winter hemisphere to a low pressure center in the summer hemisphere, similar to what happens today in southeastern Asia (Webster, 1987; Cook, 2003; Gasse and Roberts, 2004; Park et al., 2011). A similar regime could have existed over the Pangaea supercontinent between the Permian and Jurassic periods (Parrish and Peterson, 1988; Parrish, 1993; Loope et al., 2001, 2004; Rowe et al., 2007; Scherer and Goldberg, 2007, 2010). The monsoonal regime at that time is recorded in many aeolian deposits in both hemispheres (Navajo Sandstone, Loope et al., 2001, 2004; Sergi Formation, Scherer and Goldberg, 2010). The consistent northwestern palaeowind directions recorded in the Upper Unit of the Mangabeira Formation, and the palaeoposition of the ~50.000 km^2 Mangabeira erg in the central part of a large land mass (São-Francisco-Congo and Siberian cratons) forced the winds to cross the equatorial zone (~5ºN), creating a strong monsoonal pattern. Even without a general circulation model for the Mesoproterozoic, we can suggest that the aeolian dunes were built by strong monsoonal winds that originated in high-pressure zones above the São-Francisco-Congo craton in winter and directed towards the low-pressure zone above the Siberian Craton in boreal summer (Fig. 10). We suggest that the ITCZ in boreal summer was located above Siberia, at about 20ºN. On the contrary, in the austral summer and boreal winter, the ITCZ was shifted by several degrees of latitude farther south above the São Francisco craton, at ~15ºS. This explains the absence of wet interdunes and other features such as slumps in the lee face of the dunes as recognized in Jurassic aeolian dune deposits of the Navajo Sandstone, USA (cf. Loope et al., 2001). These authors identified common slump deposits in the lee faces of the aeolian dunes that were interpreted as deformation features developed in response to intense rainfall events that occurred as a consequence of annual monsoon rainfall beneath the northern margin of ITZC. For example, in the present-day, the Lençóis Maranhenses – a coastal aeolian dune field in northern Brazil – experiences a seasonal latitudinal positioning of the ITCZ, which determines the incidence of dominant winds and rainfall precipitation (Tsoar et al., 2009).

Cyclic cross bedding in the aeolian cross strata provides additional evidence of the monsoonal wind regime (Hunter and Rubin, 1983; Kocurek et al., 1991; Chan and Archer, 2000; Loope et al., 2001; Scherer and Goldberg, 2010). The presence of cyclic cross-bedding in the Upper Unit of the Mangabeira Formation, marked by sets of grainflow strata alternating with sets of wind-ripple strata, suggests an alternation of northwesterly directed winds, followed by reversed transverse or oblique northeasterly directed winds, which caused slipface degradation, reworking, and production of reactivation surfaces and the related formation of wind-ripple wedges. Thus, the dunes migrated under the influence of strong and dominant winds, in this case during the austral winter the southern hemisphere, when the trade winds blew from the high-pressure zone above the Congo craton and crossed the equator towards the low-pressure zones over the center of the Siberian craton. In turn, during the seasonal wind shift in the boreal winter, the northern hemisphere winds blew from the high-pressure zone over the Siberian craton towards the low-pressure zone in southern hemisphere, reworking the frontal face of the aeolian dunes.

The palaeowind reconstructions presented above are based on sedimentological evidence acquired from a succession that potentially could represent a relatively small fraction of the total time span being considered (1.6 to 1.5 Ga) by the study. Moreover, the wind conditions that prevailed during episodes of aeolian accumulation might conceivably differ from those that prevailed during episodes of deflation or bypass for which no sedimentary record exists. Thus, the palaeowind reconstructions are, by necessity, based on a highly fragmentary sedimentological record that potentially could lead to a biased interpretation.

FIGURE 10

7. Conclusions

The Mangabeira Formation of the São Francisco craton represents deposits of an aeolian erg system and is represented by two distinct units. The Lower Unit records multiple, stacked depositional cycles, each of which records a drying-upward trend. Each cycle records an episode of erg expansion and contraction driven by climate changes. The aeolian sandsheet and water-laid deposits that characterize the lowermost deposits of each cycle accumulated in relatively humid environments, whereas the aeolian dunes and interdunes that characterize the upper part of each cycle are related to arid conditions. The Upper Unit is composed mainly of aeolian dune deposits that lack associated interdune deposits and records extremely arid conditions. Distinct palaeowind directions are observed: the Lower Unit shows that aeolian dunes migrated towards the southeast (past coordinate system), whereas the large aeolian dunes of the Upper Unit migrated towards the northwest (past coordinate system). The geochronological data provide a maximum and minimum depositional age of the Mangabeira Formation: it accumulated during the Calymmian period, between 1.6 and 1.5 Ga. The peculiarities of these aeolian deposits likely relate to the palaeo-position of the Mesoproterozoic continents (Pisarevsky et al., 2014). Our new 1.6 to 1.54 Ga palaeogeographic maps demonstrate a good correlation with the sedimentological record in the Lower Unit. At that time, the São Francisco-Congo craton and the Siberian Craton were located between the mid-latitudes and the equatorial zone. The wind regime recorded from cross-strata of the Lower Unit is consistent with the palaeogeographic positions of São Francisco between 25º to 35º S. The eastern and southeastern migration of aeolian dunes is consistent with a zonal atmospheric circulation pattern. In the subtropics of the southern hemisphere, the descending branch of the Hadley cell blew toward the southeast, bringing dry air favorable for the development of deserts on the landmasses.

Our new reconstruction and the proposed model of atmospheric circulation also explains the record of palaeowinds in the Mukun Group of northern Siberia (Petrov, 2011, 2014). Between 1.54 to 1.50 Ga the large land mass that comprised the São-Francisco-Congo and Siberian cratons had drifted farther north reaching palaeolatitudes between 30º S and 30ºN. At that time, the São Francisco Craton was located in the equatorial zone. This palaeogeography is consistent with northwesterly directed palaeowind directions recorded in the Upper Unit. The presence of a large landmass in the mid-latitude and equatorial regions could explain the monsoonal pattern in low-latitudes.

The presence of cyclic aeolian cross bedding in the Upper Unit of the Mangabeira Formation provides additional evidence of the proposed monsoonal wind regime. As the dunes migrated under the influence of strong and dominant winds during the austral winter of the southern hemisphere, the southeasterly trade winds blew from the high-pressure zone above the Congo craton and crossed the equator towards the low-pressure zone over the centre of the Siberian Craton. In turn, during the seasonal wind shift in the boreal winter, the winds of the northern hemisphere blew from the high-pressure zone over the Siberian Craton towards the low-pressure zone in southern hemisphere, reworking the frontal face of the aeolian dunes.

The present work is the first attempt to correlate the palaeogeographic configuration with aeolian deposits in Precambrian times. Future research might involve the construction of new palaeogeographic models for this period, as new palaeomagnetic and geochronological data become available, which implies that the suggested palaeopositions of these cratons at that time might be reconsidered if they contradict some new geological data. Although there are currently no global circulation models for Mesoproterozoic, this work serves to contribute to an initial integration between sedimentology – mainly sedimentary environments that are sensitive palaeoclimatic indicators – and the evolution of the supercontinents and their position around the globe, mostly in a time for which the sedimentary record is extremely fragmentary.

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Figure Captions

FIGURE 1. (A) Location of the São Francisco craton and the Chapada Diamantina Range. (B) Geological map of the Chapada Diamantina Range and the location of the study area. Geological map based on Geological Survey of Brazil (CPRM). (C) Location of vertical profiles.

FIGURE 2. Stratigraphic chart for the Proterozoic Espinhaço Supergroup (based of Guadagnin et al., 2015a).

FIGURE 3. Representative log for the Lower Unit. The main characteristics of the Lower Unit identified: (A) Millimetric, inverse graded, horizontally to low-angle translatent lamination; (B) Millimetric to centimetric interlayered sandstone and mudstone with crinkled-lamination; (C) ripple cross-stratification; (D) Aeolian dunes formed by wedges of grainflow deposits that pinch out down-dip into milimetrical wind-ripple laminae; (E) Interdunes deposits composed by very fine- to fine-grained sandstones with wavy-crinkled lamination; (F) Relationship between aeolian dune and interdune deposits.

FIGURE 4. Lateral panel showing the depositional architecture of the Lower Unit. Aeolian dunes and aeolian sandsheets are the main architectural elements. Rose diagrams show the orientation of aeolian dunes in present-day coordinates.

FIGURE 5. Representative log for the Upper Unit. The main characteristics of the Lower Unit identified: (A) Tangential cross-stratification; (B) Foresets within sets composed of massive sandstone or inversely-graded grainflow lenses that dip at ~20º; (C) Inversely graded wind-ripple laminae; (D) Granule ripples; (E) Fine-grained sandstone with wrinkled laminations; (F) Heterolithic beds of massive mudstone and fine-grained sandstone with wavy-ripple lamination; (G) Fluvial sandstones.

FIGURE 6. Lateral panel showing the depositional architecture of the Upper Unit. Large and simple aeolian dune deposits compose this unit. Rose diagrams show the orientation of aeolian dunes in present-day coordinates.

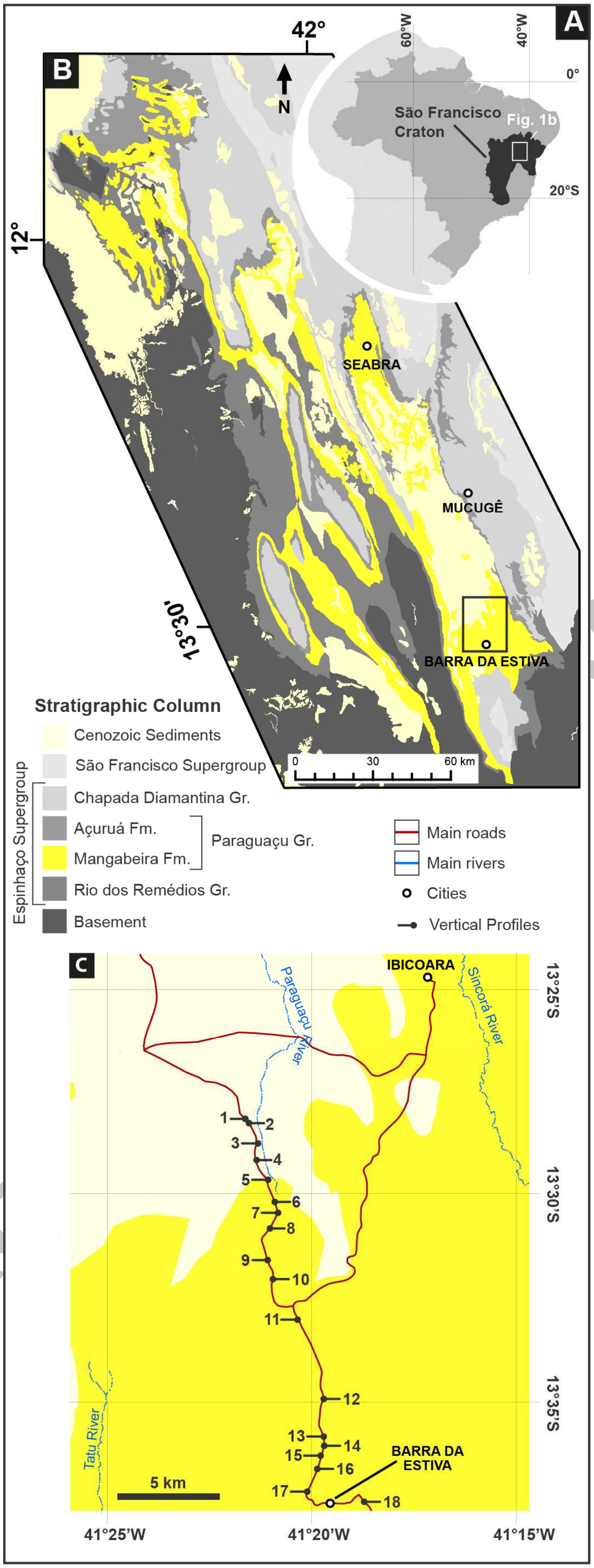
FIGURE 7. Cyclic sets of cross-bedding in the Upper Unit. The sets are regularly spaced each package is 0.2 to 0.8 meters thick composed of alternating between grainflow and wind-ripple laminae.

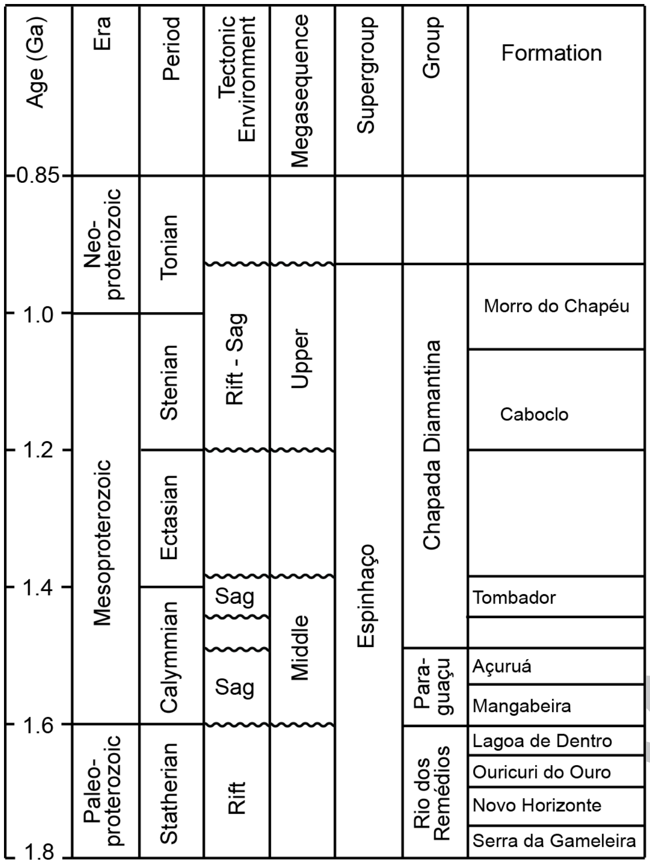
FIGURE 8. Sedimentological log of the Mangabeira Formation. The Lower Unit (~500 m) records multiple drying-upward cycles and the Upper Unit (~200 m) is composed mainly by aeolian dune deposits, without intervening interdune deposits. Rose diagrams show the orientation of aeolian dunes in present-day coordinates (black color) and in coordinates inferred at the time of sedimentation (yellow color). Number of

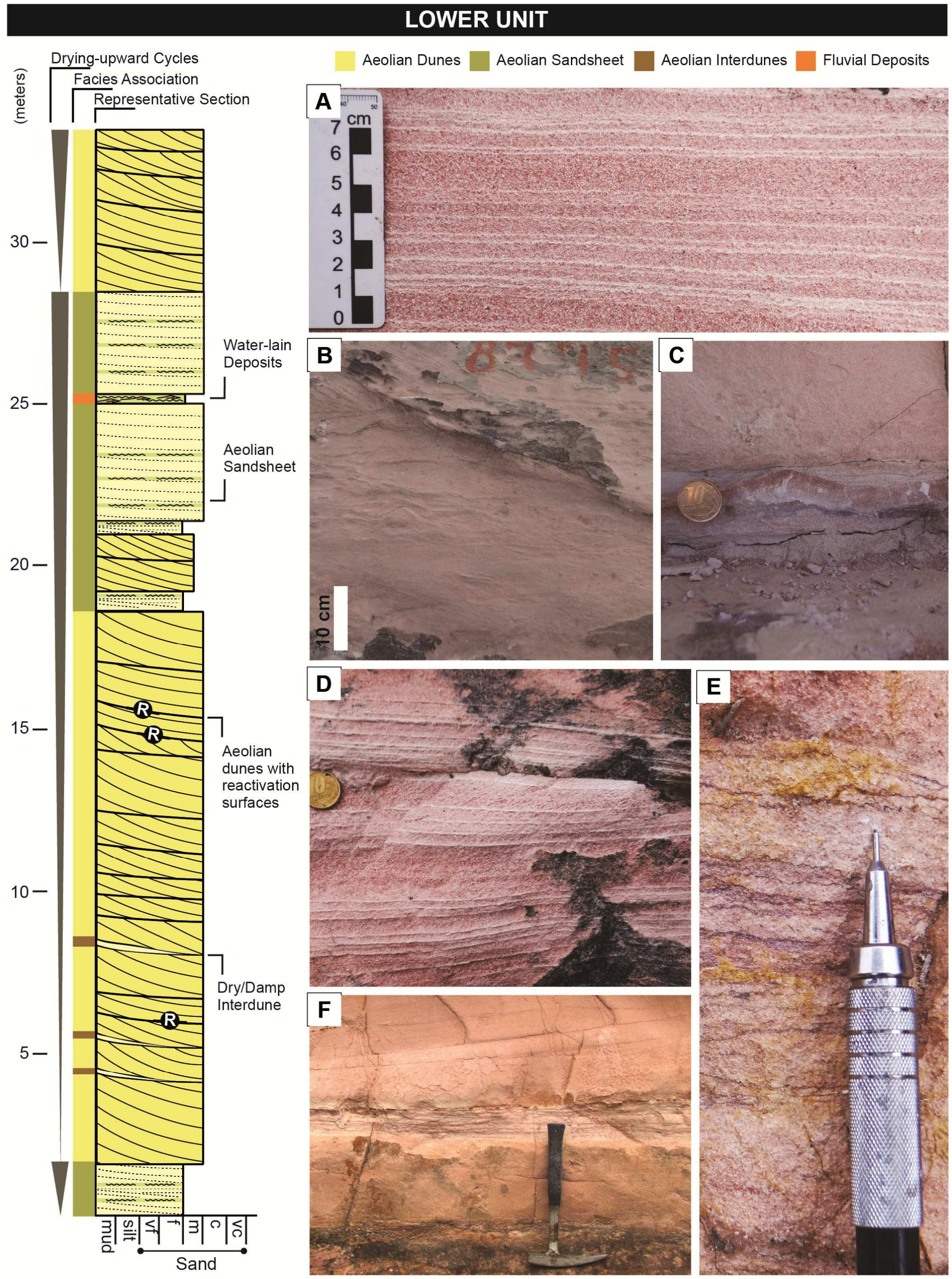
readings: 281 for the Lower Unit and 47 for the Upper Unit. The Euler rotation parameters utilized to rotate the rose diagrams were based on those provided by Pisarevsky et al. (2014).

FIGURE 9. Palaeogeographic map for 1.6 to 1.54 Ga. At this time the São Francisco craton occupied a mid-latitude position. East and southeast migration of aeolian dunes (past coordinate system) of the Lower Unit is consistent with a zonal circulation model in the southern subtropics (see text for explanation). La = Laurentia, Ba = Baltica, In = India, NAC = North Australian craton, WAC = West Australian Craton, SAC = South Australian Craton, Sb = Siberia, SF = São Francisco, Kal = Kalahari, C = Congo, NC = North China.

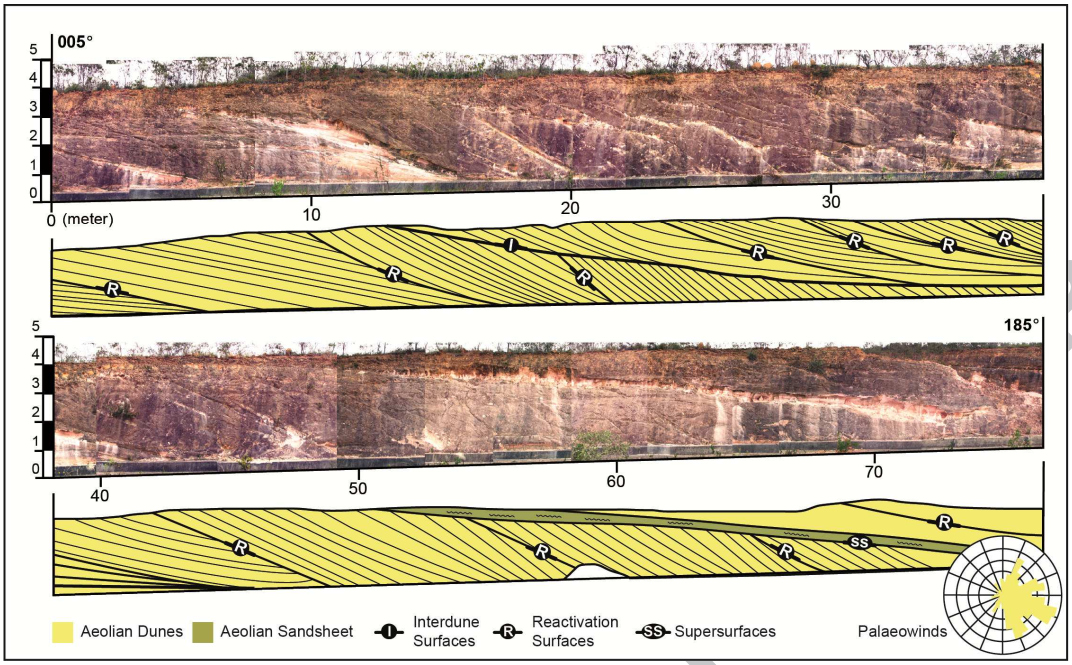
FIGURE 10. Palaeogeographic map between 1.54 Ga to 1.5 Ga (Pisarevsky et al., 2014). At this time the São Francisco Cratons in an equatorial zone. This palaeogeography is consistent with the northwesterly directed palaeowinds directions recorded in the Upper Unit. The occurrence of a large landmass in the mid-latitudes and equatorial area could explain the monsoonal pattern in low-latitudes (see text for explanation). La = Laurentia, Ba = Baltica, In = India, NAC = North Australian craton, WAC = West Australian Craton, SAC = South Australian Craton, Sb = Siberia, SF = São Francisco, Kal = Kalahari, C = Congo, NC = North China.


A
60°W
40°W
0°
20°S
São Francisco Craton
Fig. 1b
B
42°
N
12°
13°30'
SEABRA
MUCUGÊ
BARRA DA ESTIVA
0 30 60 km
Stratigraphic Column
Cenozoic Sediments
São Francisco Supergroup
Chapada Diamantina Gr.
Açuruá Fm.
Mangabeira Fm.
Paraguaçu Gr.
Rio dos Remédios Gr.
Basement
Espinhaço Supergroup
Main roads
Main rivers
Cities
Vertical Profiles
C
IBICOARA
Paraguaçu River
Sincorá River
Tatu River
5 km
BARRA DA ESTIVA
13°25'S
13°30'S
13°35'S
41°25'W
41°20'W
41°15'W

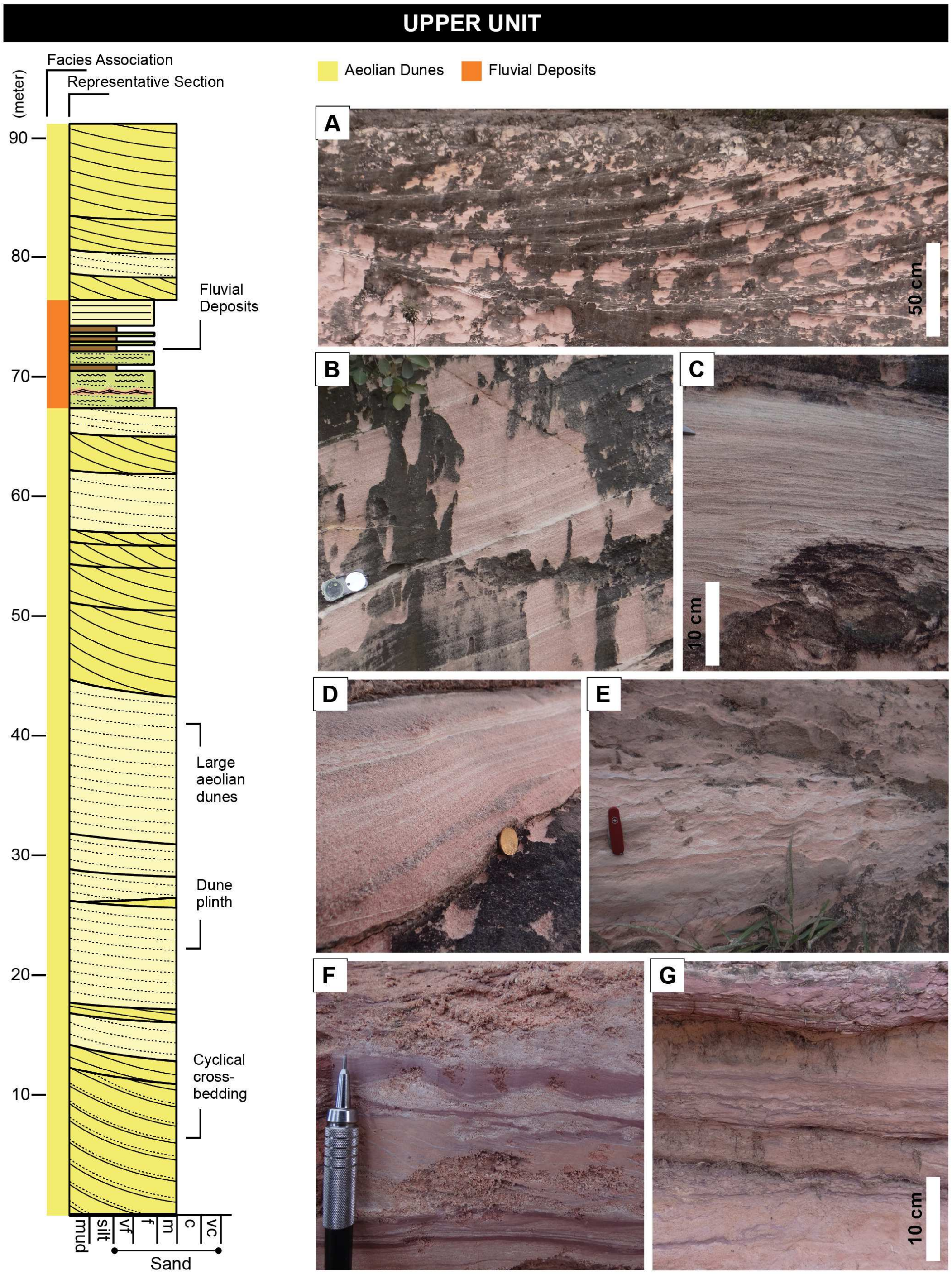

Age (Ga)
Era
Period
Tectonic Environment
Megasequence
Supergroup
Group
Formation
0.85
1.0
1.2
1.4
1.6
1.8
Neo-proterozoic
Mesoproterozoic
Paleo-proterozoic
Tonian
Stenian
Ectasian
Calymmian
Statherian
Rift - Sag
Sag
Sag
Rift
Upper
Middle
Espinhaço
Chapada Diamantina
Para-guaçu
Rio dos Remédios
Morro do Chapéu
Caboclo
Tombador
Açuruá
Mangabeira
Lagoa de Dentro
Ouricuri do Ouro
Novo Horizonte
Serra da Gameleira

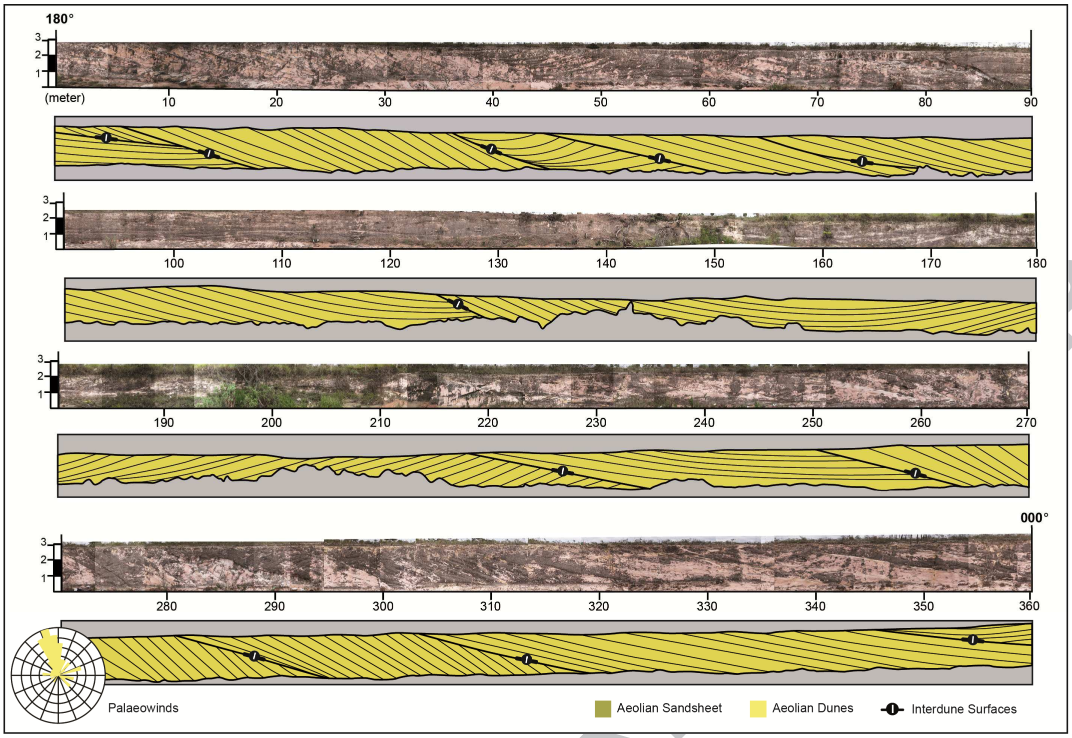


LOWER UNIT
Aeolian Dunes
Aeolian Sandsheet
Aeolian Interdunes
Fluvial Deposits
Drying-upward Cycles
Facies Association
Representative Section
(meters)
30
25
20
15
10
5
Water-lain Deposits
Aeolian Sandsheet
Aeolian dunes with reactivation surfaces
Dry/Damp Interdune
R
mud
silt
vf
f
m
c
vc
Sand
A
cm
7
6
5
4
3
2
1
0
B
10 cm
C
D
E
F

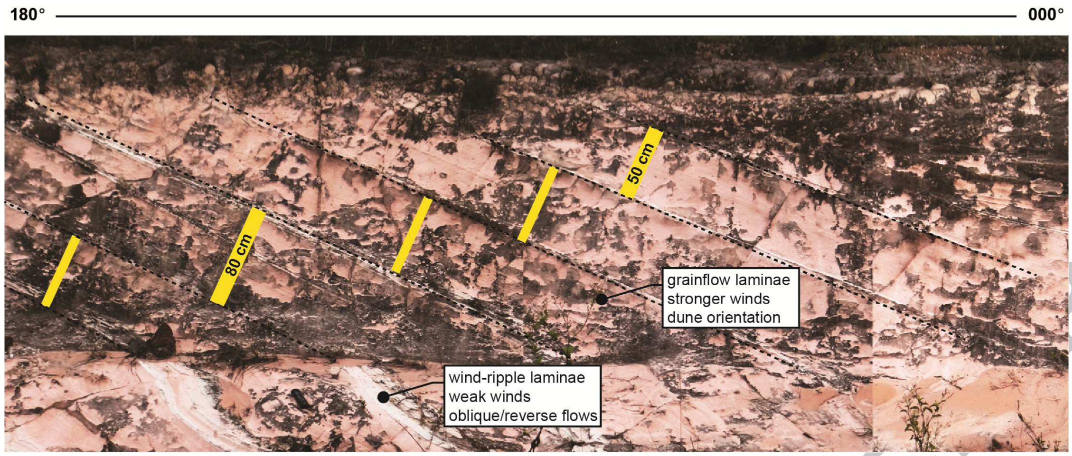


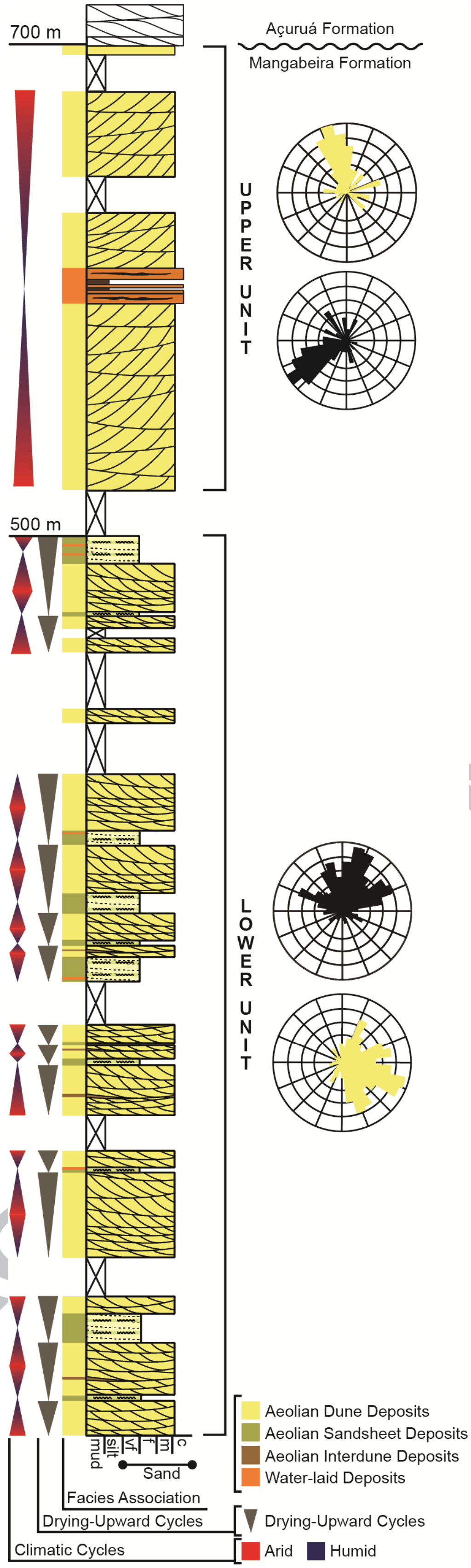
005°
5
4
3
2
1
0
0 (meter)
10
20
30
R
I
185°
40
50
60
70
SS
Aeolian Dunes
Aeolian Sandsheet
Interdune Surfaces
Reactivation Surfaces
Supersurfaces
Palaeowinds


UPPER UNIT
Facies Association
Representative Section
(meter)
Aeolian Dunes
Fluvial Deposits
90
80
70
60
50
40
30
20
10
Fluvial Deposits
Large aeolian dunes
Dune plinth
Cyclical cross-bedding
mud
silt
vf
f
m
c
vc
Sand
A
50 cm
B
C
10 cm
D
E
F
G
10 cm

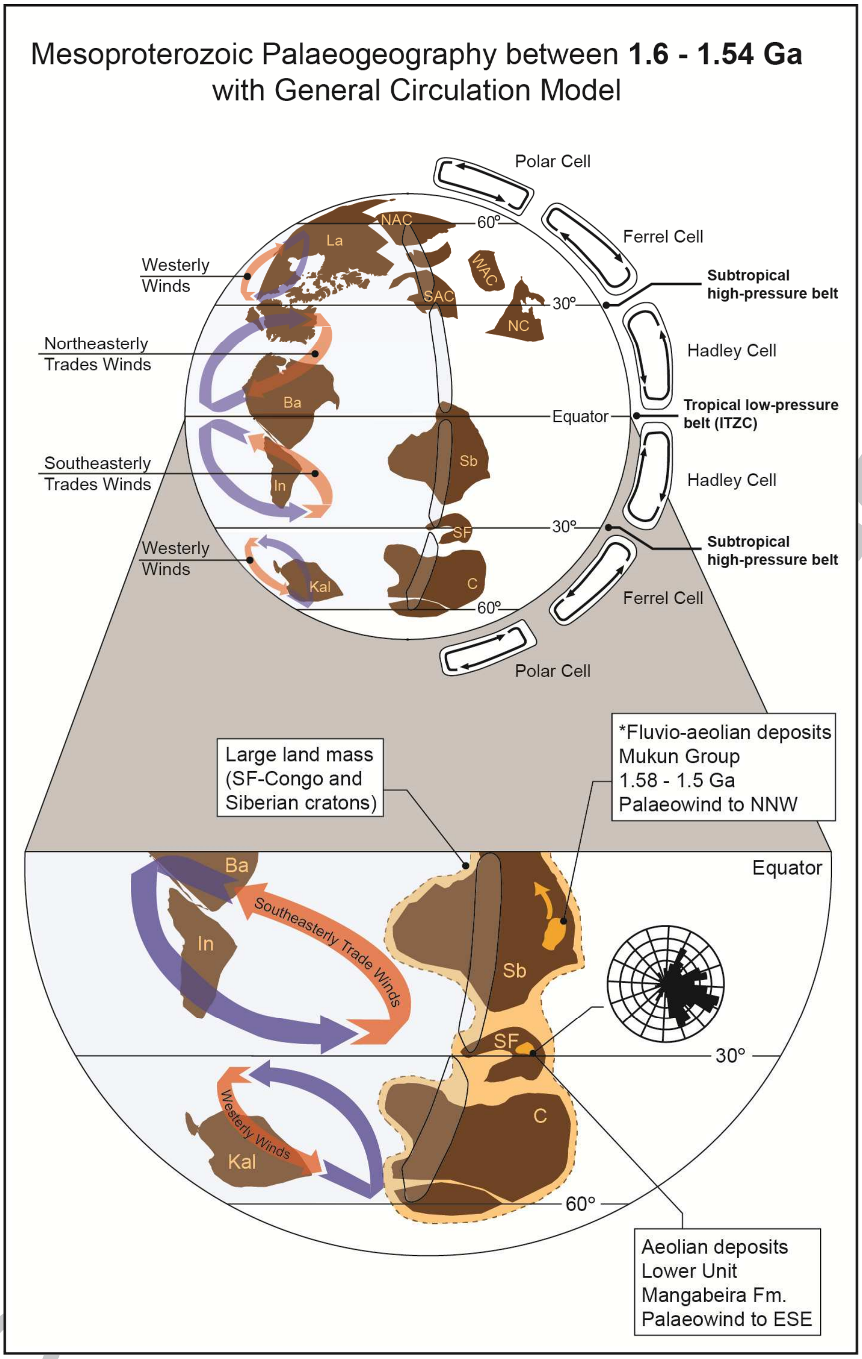


180°
3
2
1
(meter)
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
000°
280
290
300
310
320
330
340
350
360
Palaeowinds
Aeolian Sandsheet
Aeolian Dunes
Interdune Surfaces


180°
000°
50 cm
80 cm
grainflow laminae
stronger winds
dune orientation
wind-ripple laminae
weak winds
oblique/reverse flows

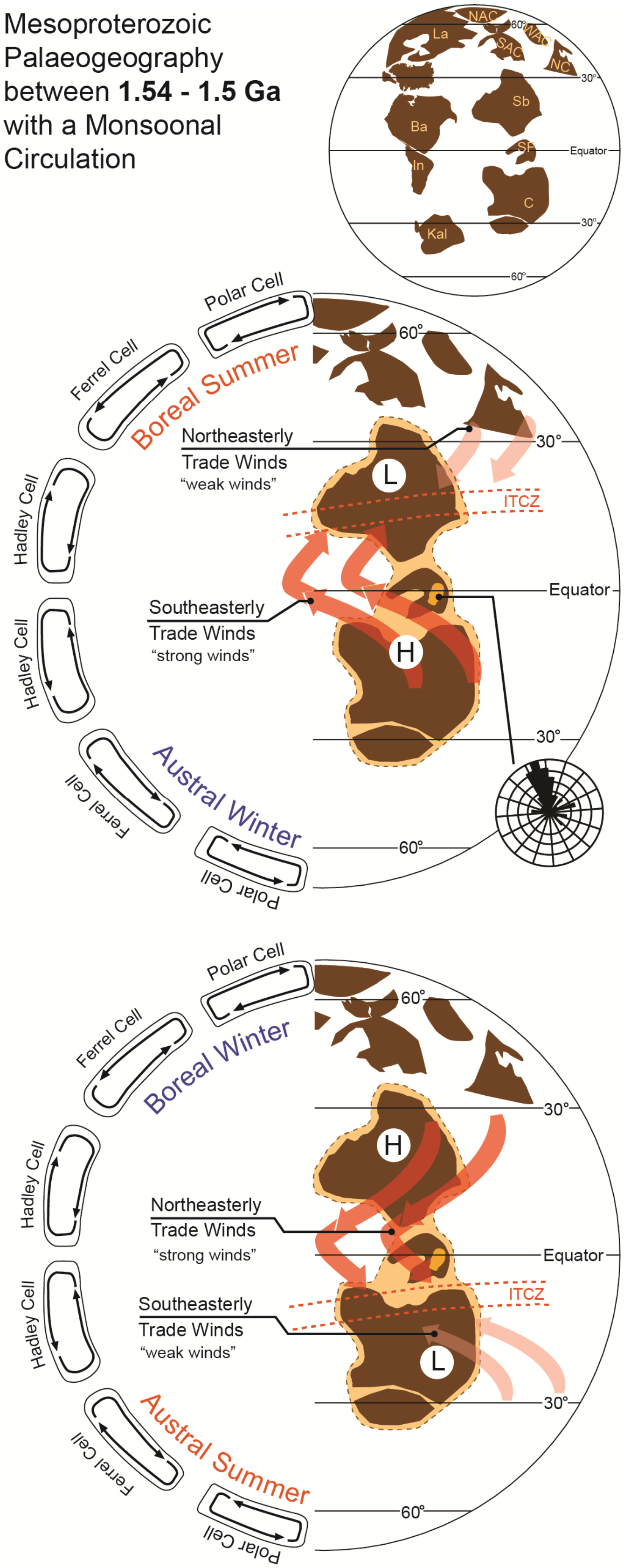


700 m
Açuruá Formation
Mangabeira Formation
UPPER UNIT
500 m
LOWER UNIT
mud
silt
vf
f
m
c
Sand
Facies Association
Drying-Upward Cycles
Climatic Cycles
Aeolian Dune Deposits
Aeolian Sandsheet Deposits
Aeolian Interdune Deposits
Water-laid Deposits
Drying-Upward Cycles
Arid
Humid



Mesoproterozoic Palaeogeography between **1.6 - 1.54 Ga**
with General Circulation Model
Polar Cell
Ferrel Cell
Subtropical high-pressure belt
Hadley Cell
Tropical low-pressure belt (ITZC)
Hadley Cell
Subtropical high-pressure belt
Ferrel Cell
Polar Cell
Westerly Winds
Northeasterly Trades Winds
Southeasterly Trades Winds
Westerly Winds
NAC
La
WAC
SAC
NC
Ba
Sb
In
SF
Kal
C
60º
30º
Equator
30º
60º
Large land mass (SF-Congo and Siberian cratons)
*Fluvio-aeolian deposits Mukun Group 1.58 - 1.5 Ga Palaeowind to NNW
Equator
Southeasterly Trade Winds
Westerly Winds
30°
60°
Aeolian deposits Lower Unit Mangabeira Fm. Palaeowind to ESE

Mesoproterozoic Palaeogeography between **1.54 - 1.5 Ga** with a Monsoonal Circulation



- First wind-pattern model for Mesoproterozoic (1.6 to 1.5 Ga);
- Mesoproterozoic aeolian erg succession in the São Francisco Craton;
- Palaeowinds directions as a palaeogeographic indicator