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Facies architecture of the fluvial Missão Velha Formation (Late Jurassic–Early Cretaceous), Araripe Basin, Northeast Brazil: paleogeographic and tectonic implications

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ABSTRACT:

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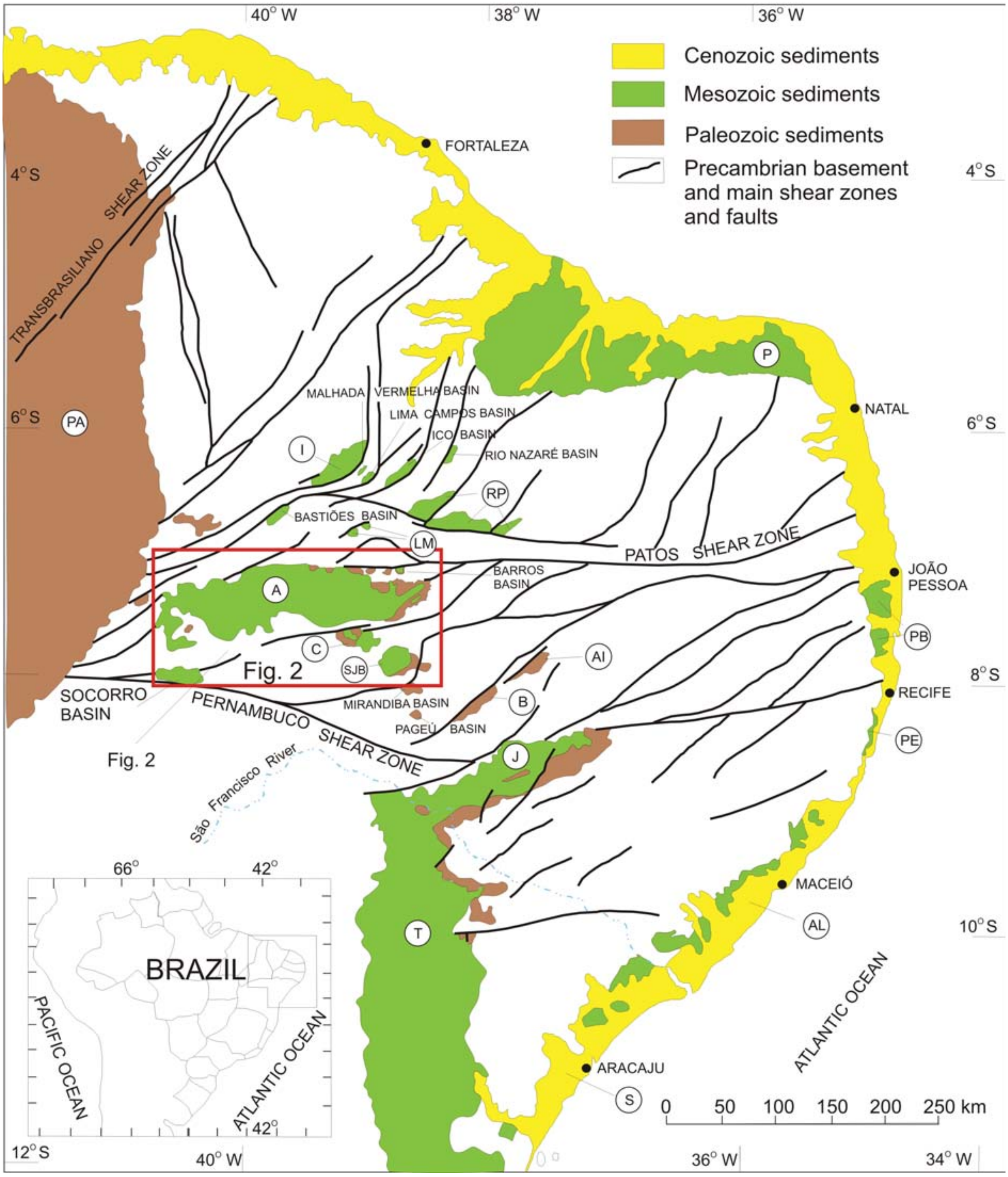
Sedimentological analysis of the Missão Velha Formation (Araripe Basin, northeast Brazil) is the aim of this paper through detailed facies analysis, architectural elements, depositional systems and paleocurrent data. The main facies recognized were: (i) coarse-grained conglomeratic sandstones, locally pebbly conglomerates, with abundant silicified fossil trunks and several large-to-medium trough cross-stratifications and predominantly lenticular geometry; (ii) lenticular coarse-to-medium sandstones with some granules, abundant silicified fossil wood, and large-to-medium trough cross-stratifications, cut-and fill features and mud drapes on the foresets of cross-strata, (iii) poorly sorted medium-grained sandstones with sparse pebbles and with horizontal stratification, (iv) fine to very fine silty sandstones, laminated, interlayered with (v) decimetric muddy layers with horizontal lamination and climbing-ripple cross-lamination. Nine architectural elements were recognized: CH: Channels, GB: Gravel bars and bed forms, SB: Sand bars and bedforms, SB (p): sand bedform with planar cross-stratification, OF: Overbank flow, DA: Downstream-accretion macroforms, LS: Laminated sandsheet, LA: Lateral-accretion macroforms and FF: Floodplain fines. The lithofacies types and facies associations were interpreted as having been generated by alluvial systems characterized by (i) high energy perennial braided river systems and (ii) ephemeral river systems. Aeolian sand dunes and sand sheets generated by the reworking of braided alluvial deposits can also occur. The paleocurrent measurements show a main dispersion pattern to S, SE and SW, and another to NE/E. These features imply a paleodrainage flowing into the basins of the Recôncavo-Tucano-Jatobá.

Key words: Araripe Basin; Missão Velha Formation; Fluvial facies; Architectural elements; Rift basins.

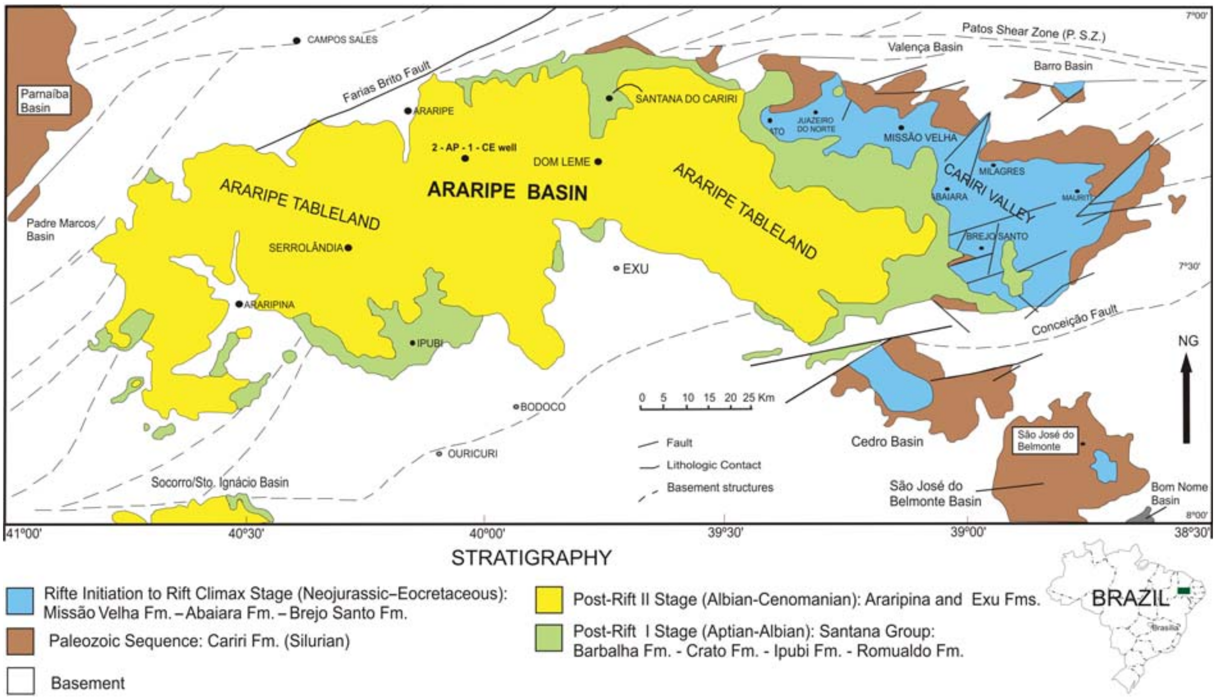
INTRODUCTION

The Araripe Basin represents the most complete intracontinental basin of northeast Brazil. Its stratigraphic column spans Paleozoic and Mesozoic deposits (Upper Jurassic–Upper Cretaceous). The origin and geological evolution of the Mesozoic rocks of the Araripe Basin are related to the tectonic



Text-fig. 1. Location and geological setting of the Araripe Basin, NE Brazil (modified after Assine 1992 and Schobbenhaus *et al*. 1984). Basins: A – Araripe; PA – Parnaíba; I – Iguatu; RP – Rio do Peixe; LM – Lavras da Mangabeira; C – Cedro; SJB – São José do Belmonte; B – Betânia; AI – Afogados da Ingazeira ou Fátima; J – Jatobá; T – Tucano; P – Potiguar; PB – Paraíba; PE – Pernambuco; AL – Alagoas; SE – Sergipe

events that resulted in the Gondwana Supercontinent breakup, and the opening of the South Atlantic Ocean (Asmus and Ponte 1973; Ponte and Asmus 1976, 1978; Matos 1992; Assine 1992; Mabesoone 1994; Ponte and Ponte-Filho 1996a, b; Matos 1999; Assine 2007; Fambrini *et al*. 2008, 2009, 2011a, b, 2012b, 2013; Scherer *et al*. 2014). These events ended in the middle Cretaceous. However, the stratigraphic

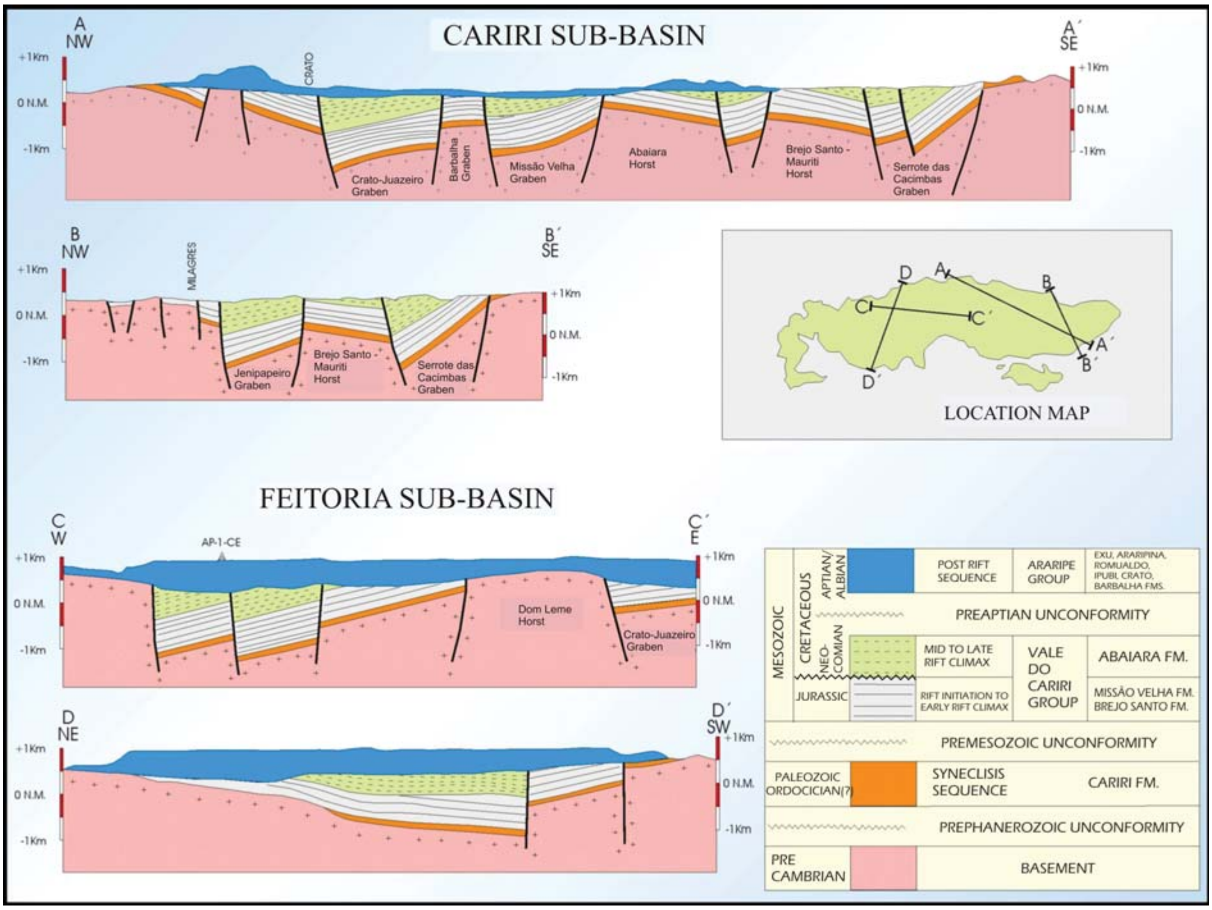


Text-fig. 2. Geological map of the Araripe Basin, NE Brazil (modified after Assine 1992, 2007)

record of these events remains little understood. The stratigraphic interval of Late Jurassic–Early Cretaceous of the Araripe Basin includes two formations: Brejo Santo, mainly pelitic rocks (below), and Missão Velha, mainly arenaceous rocks (above). The succession of the Missão Velha Formation (i) is well defined in its basal contact with the Brejo Santo Formation, (ii) the sedimentary facies is relatively well understood; (iii) detailed depositional systems are only broadly understood. However, paleogeographic and tectonic characters are not well documented for the entire unit; at the top, the contact with Abaiara Formation, and the range of the stratigraphic column of the Missão Velha Formation, there are some disagreements about its nature, type and stratigraphic and tectonic character (e.g. Assine 2007). As a way to clarify this gap, detailed stratigraphic and sedimentological studies were performed on the rocks of Missão Velha Formation. These studies were implemented through exhaustive facies analysis, architectural elements, depositional systems and paleocurrent data, and subsequentially interpreted with regional data. The interpretation of depositional systems, the recognition of stacking patterns and the characterization of the main sequential units led to the proposition of the stratigraphic evolution of Missão Velha Formation presented here.

GEOLOGICAL SETTING

The Araripe Basin is located in northeast Brazil (Text-fig. 1), in the central part of Borborema province (Almeida *et al.* 1981; Brito-Neves *et al.* 2000). It is an intracontinental basin, which belongs to the Afro-Brazilian Depression (Ponte 1994; Garcia and Wilbert 1994; Ponte and Ponte-Filho 1996; Fambrini *et al.* 2011b; Küchle *et al.* 2011; Scherer *et al.* 2014; Fambrini *et al.* 2013). Gravimetric and magnetometric data (Rand and Manso 1984; Castro and Castelo-Branco 1999) have allowed the division of the Araripe Basin into two sub-basins (western and eastern), which include some fault bounded synrift depositional troughs and the overlying post-rift successions (Text-fig. 3). The Araripe Basin presents a NE-SW to E-W structural trend, and subordinately, a NW-SE trend coincident with Precambrian basement discontinuities, re-activated for the formation of the Araripe Basin (Text-figs 2, 3). The basement of this region consists of Precambrian gneisses and migmatite terrains with plutons of granites, which were deformed along interior fold belts. This basement was affected by extensive Jurassic–Cretaceous rifting processes related to the split between Africa and South America during the break-up of Pangea (Asmus and Ponte 1973; Ponte and Asmus 1976,



Text-fig. 3. Geologic sections of the Araripe Basin based on seismic lines (modified after Ponte 1996; Ponte and Ponte-Filho 1996 a, b)

1978; Matos 1992; Mabesoone 1994; Ponte and Ponte-Filho 1996a, b). The deposition of alluvial and fluvial-lacustrine Late Jurassic to Early Cretaceous successions (Brejo Santo, Missão Velha and Abaiara formations) took place during successive pre-rift and syn-rift phases. According to Braun (1966) and Coimbra *et al.* (2002) these rocks are included in the Dom João stage, the Brazilian local equivalent of the Tithonian. Finally, after a significant erosive episode, a post-rift period with slow subsidence led to deposition of the fluvial, lacustrine and transitional marine Aptian–Albian Santana Group, which includes several formations (Barbalha, Crato, Ipubí, Romualdo and Araripina formations) (Neumann 1999; Neumann and Cabrera 1999; Assine 2007; Fambrini *et al.* 2010a, 2011b, 2013). The Cenomanian fluvial Exu Formation overlies a widespread erosive unconformity developed at the top of the Santana Group (Text-fig. 3). Several significant lacustrine depositional episodes have been recognized in the Araripe Basin (Mabesoone *et al.* 1994; Neumann *et al.* 2000; Neumann and Cabrera 2000; Fambrini *et al.* 2007, 2008, 2012a, b, 2013). A first episode took place during the Late Jurassic (Dom João Stage) and led to deposition of the fine-grained siliciclastic, shallow lacustrine successions of the Brejo Santo Formation, richly fossiliferous (ostracodes, conchostraceans, fish bones and teeth, dypnoids, Carvalho and Viana 1993; Brito *et al.* 1994; Viana *et al.* 2002; Barros *et al.* 2011; Fambrini *et al.* 2007, 2008, 2012b, 2013), which have been reported from the subsurface and from extensive outcrops. The second lacustrine episode, registered in the Abaiara Formation (Lower Cretaceous), is composed of shales and mudstones and lenticular sandstones (Fambrini *et al.* 2008, 2012a). The third lacustrine episode, late Aptian to early Albian in age (Mabesoone and Tinoco 1973), includes the upper part of the Barbalha and the Crato formations. Late Aptian (?)–early Albian lacustrine episodes took place in the evaporate dominated Ipubí Formation (Silva 1983, 1986), where thin lacustrine organic-rich deposits also occur (Neumann *et al.*

Text-fig. 4. Grota Funda, the type section of the Missão Velha Formation. A – General view of Grota Funda exposure. Black arrows indicate scale; B – Detail of the Grota Funda outcrop. Circle indicates scale

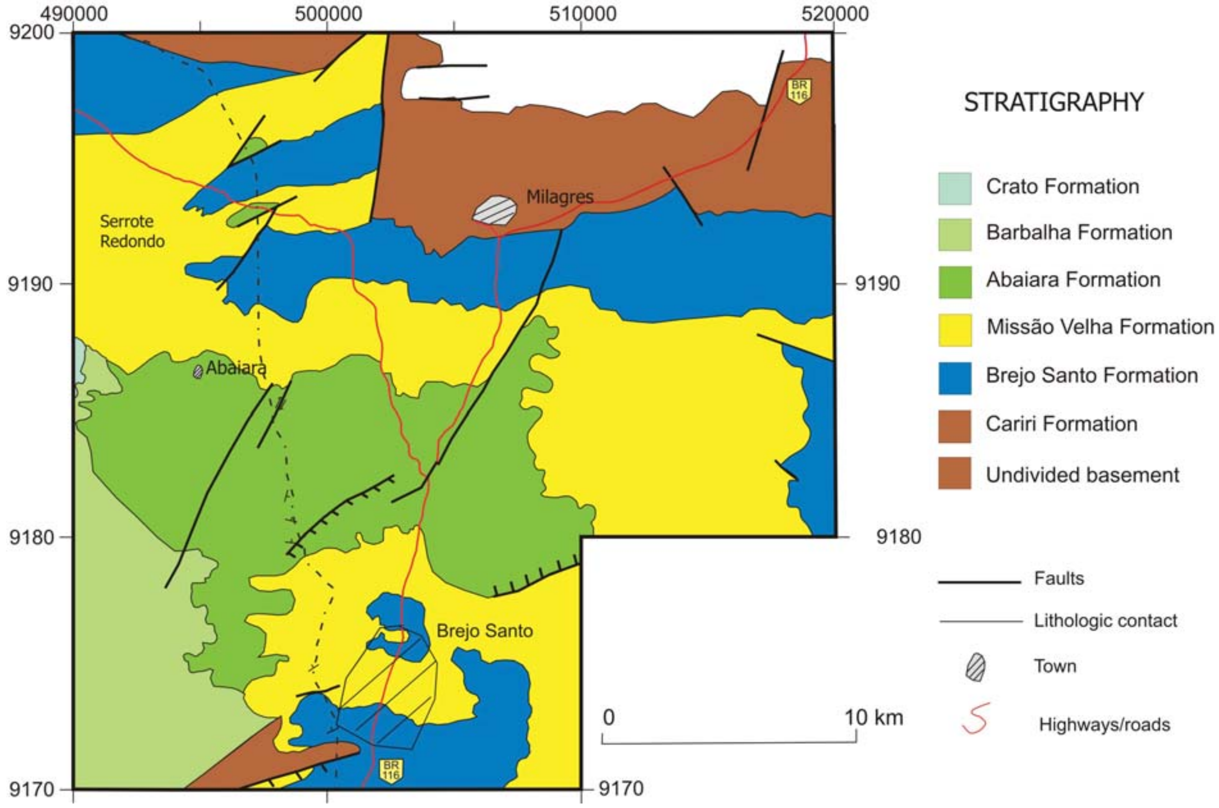
2003). The Araripe Basin includes significant intervals of fluvial sedimentation in all stratigraphic units. One of the most important alluvial intervals of the basin evolution is that of the the Brejo Santo and Missão Velha formations, which characterize the pre-rift sequence of the basin (Ponte 1994). This unit is widely known by its silicified fossil wood and trunks dispersed in fluvial coarse sandstones. The Missão Velha Formation is the main subject of this study (Text-fig. 4).

The Araripe Basin comprises four main tectonic-megasequences, as defined by Fambrini *et al.* (2010a): (i) Syneclises sequence (Paleozoic age), formed by the Cariri Formation, represented by fluvial-aeolian cross-stratified sandstones, (ii) Rift Initiation to Early Rift Climax sequence (Upper Jurassic–Lower Cretaceous), comprising the Brejo Santo Formation and the basal portion of the Missão Velha Formation; (iii) Mid to Late Rift Climax sequence, formed by the upper portion of the Missão Velha Formation and Abaiara Formation (Lower Cretaceous) which exhibit cross-stratified coarse sandstones to conglomerates and red shales intercalated with fine sandstones, respectively, and (iv) Post-Rift sequence, separated into two depositional sequences (Assine 2007), post-rift I sequence (Aptian–Albian), containing the Rio da Batateira (sandstones), Crato (mainly limestones), Ipubi (evaporites), Romualdo (red shales intercalated with fine lenticular sandstones) and Arajara (sandstones) formations; and post-rift II sequence (Cenomanian), formed by alluvial sediments of the Exu Formation. According to the proposal of Ponte and Ponte-Filho (1996), the Missão Velha Formation constitutes the main sandy unit of the so-called Afro-Brazilian Depression, a series of basins and small depressions that characterized the Upper Jurassic at the beginning of the fragmentation of the Gondwana Supercontinent resulting in an extensive sedimentary record within several northeastern Brazilian basins (Ponte 1994). According to these authors the Missão Velha Formation would represent the pre-rift stage in the development of the basin constituents of the Afro-Brazilian Depression.

METHODS

This study of the Missão Velha Formation was developed by means of geological mapping at a scale of 1:50,000, and was based on the detailed description of more than 100 outcrops in five sets of field work. Additionally the interpretation of Landsat TM5 satellite images and aerial photographs of the Brazilian Geological Survey – CPRM (scales of 1:65,000 and 1: 40,000) were incorporated, which resulted in the geological sketch of Text-fig. 5.

Geological mapping field work was accompanied by (i) detailed stratigraphic surveys, such as measurements and compilation of log sections according to the method of Selley (1987, 2000); (ii) sedimentary facies analysis, according to the precepts of Walker (1992), Walker and James (1992), Reading (1996) and James and Dalrymple (2010); (iii) establishment of sedimentary lithofacies conforming to the original proposition of Miall (1977, 1978, 1996); (iv) analyses of architectural elements on the basis of the precepts of Miall (1985, 1991, 1996, 2006) and Miall and Tyler (1991), and by alluvial and fluvial models, such as Miall (1988, 1992, 1996), Bordy and Catuneanu (2001), Jo and Chough (2001), Jones *et al.* (2001), Bordy *et al.* (2004), Opluštil *et al.* (2005), Miall (2006), McLaurin and Steel (2007), *Kędzior and* Popa (2013), Scherer *et al.* (2007), Nichols and Fisher (2007), Le Heron *et al.* (2008), Bourquin *et al.* (2009), Scherer *et al.* (2014, 2015); (v) through photographic panels (photomosaics) based on the methods



Text-fig. 5. Geological sketch of a part of Missão Velha Formation exposures in the Araripe Basin

of Sgavetti (1991) and Wisevic (1992) and, finally, (vi) collecting of paleocurrent measurements along each studied section. The interpretations of the depositional systems were based on Miall (1992, 1996), Walker and James (1992), Schanley and McCabe (1994), Reading (1996), Davies and Gibling (2003), Walker (1996) and James and Dalrymple (2010). The recognition of the sedimentary fill pattern and the characterization of the major lithostratigraphic units led to the interpretation of the depositional system according to Schanley and McCabe, 1994 and the defining of the sedimentological and stratigraphical evolution of the Missão Velha Formation.

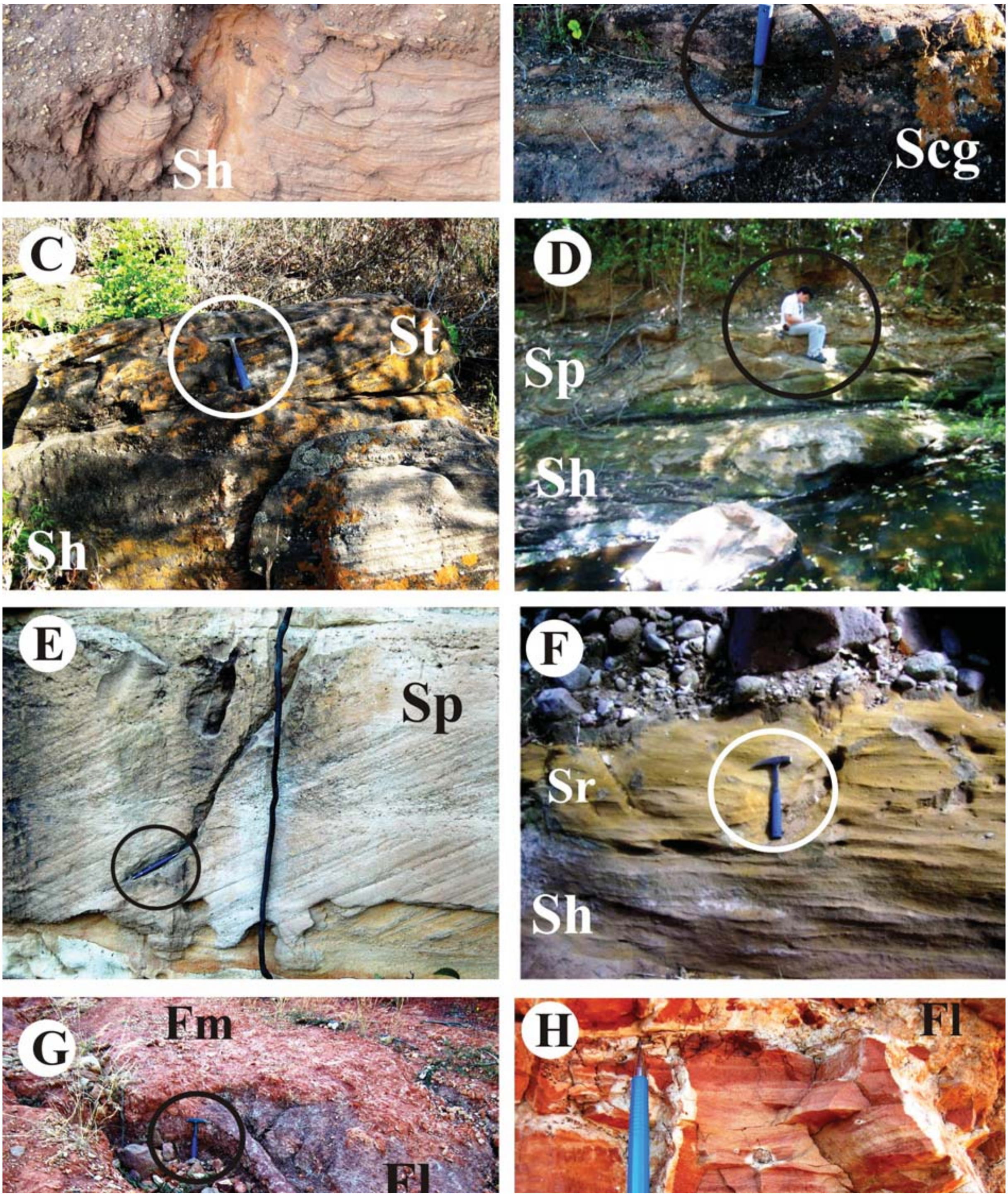
The main criteria used for defining the facies follow those of Miall (1978, 1996), which have been adopted by many authors. These criteria principally concern grain sizes and sedimentary structures, the geometry of sedimentary bodies, and presence or absence of identifiable plant remains. The codes used for facies also agree with those used by Miall (1996).

Paleocurrent analysis was based on the systematic measurements of the sedimentary structures which indicate paleoflow, mainly trough and planar cross-stratifications, according to the methods of Miall (1974, 1996, 2000) and Potter and Pettijohn (1977). When necessary, the data collected have been corrected so as to re-establish the original position of each axis or plan before the deformation and consequent overturning of the layers. In addition, axes of climbing ripples, small cross bedding and tool marks were also used as paleocurrent indicators.

Analysis of the sedimentary architectural elements generally follow the approach of Miall (1985, 1996), but outcrop-scale features are described more simply for clarity (see Bridge 1993). Architectural elements were also identified by studying outcrop photomosaics following the original concepts of Sgavetti (1991) and Wizevic (1992). The facies and structural elements are also indicated in the photomosaics with the widths and thicknesses of the architectural elements expressed as ratios.

SEDIMENTARY FACIES ANALYSIS

Fourteen lithofacies (Table 1) were recognized in the studied outcrops of the Missão Velha Formation. Most of them are sandstone- to conglomerate-domi-



Text-fig. 6. Facies of the Missão Velha Formation: (A) Gt and Gh Facies − conglomeratic to very coarse trough cross-stratified sandstones, localized trough cross-stratified pebbly-conglomerates; (B) St and Scg Facies − large-to-medium trough cross-stratified coarse-to-medium sandstones with granules and lenticular geometry; (C) Sh Facies − poorly sorted medium sandstones with sparse pebbles and horizontal stratification, and Sp Facies − poorly sorted medium sandstones with sparse pebbles and trough cross-stratifications; (D) Sp Facies − medium sandstones with sparse pebbles and trough cross-stratifications, and Sh Facies − medium-to-fine siltic sandstones with sparse granules and horizontal stratification; (E) Sp Facies − coarse-to-medium planar cross-stratified sandstones; (F) Sh and Sr Facies − fine-to-very fine siltic sandstones, tabular geometry, with horizontal stratification and cross-laminations; interlayered with (G) pelithic horizons (Fm and Fh Facies), massive or with horizontal lamination; (H) fine to very fine sandstones and siltites intercalated bearing climbing-ripples and cross-laminations (Fsm and Sr Facies)

Code	Lithofacies type	Description and sedimentary structures	Interpretation
Gh	Clast-supported, horizontal bedding conglomerates	Pebbly conglomerates ($\phi_{máx.}$= 7cm), clast-supported, organized in thinny lenticular bedding (up to 30cm) with horizontal bedding.	Deposition from plane bed or low-relief bedforms in fluvial streams.
Gt	Trough cross-stratified, matrix to clast supported conglomerates	Trough cross-stratified, matrix to clast supported conglomerates. Pebble size is between 0.5 and 4 cm, with a maximum of 20 cm. Predominant geometry is lenticular. Presence of a pebble lag a few centimeters in thickness in its base.	Deposited from traction by a unidirectional current. Gt Facies indicates deposits of migrating subaqueous dunes with sinuous crests (3D dunes and bars) under lower flow regime conditions.
Gp	Planar cross-stratified, clast-supported conglomerates	Planar cross-stratified, clast-supported conglomerates with an ordered imbricated fabric. Rip-up sandstone clasts derived from underlying sediments rarely occur at the base of the conglomerate. Spheroidal limonitic nodules are common.	Planar cross-bedding also indicates lower flow regime conditions Besides it indicates straight crested bedforms (2D dunes and bars).
Scg	Cross-stratified pebbly and conglomeratic sa	Erosionally-based channel-form bodies of fining-upward pebbly sandstones with trough cross-bedding concordant to the lower erosional surface or showing some accretion perpendicular to the elongation of the channel. These channels are typically 3 to 10 m wide and 40 to 150 cm thick, locally showing cosets of trough cross-stratification and abundant reactivation surfaces. Angular mud clasts are common, occurring as concentrated lags near the channel-bottom or scattered on the foresets.	Subaqueous sand dune deposits of lower flow regime within braided channels.
St	Coarse- to medium-grained sandstones with trough cross-stratifications, solitary or grouped	Coarse-grained feldspathic sandstones with granules, poorly sorted, lenticular geometry, with abundant silicified fossil trunks and wood organized in fining-upward cycles, with medium- to small-size trough cross-stratifications and concentration of well rounded to subangular clasts at the foresets of stratifications. Occur as homogeneous thin packages, often with conglomeratic pockets marking an erosive base.	Migration of 3D bed forms, Subaqueous sinuous-crested sand dunes deposits of lower flow regime in high energy ephemeral fluvial braided channels.
Sp	Coarse- to medium-grained sandstones with planar cross- stratifications	Coarse-grained feldspathic sandstones with sparse pebbles, poorly sorted, with medium size planar cross–stratifications structured in medium-to-small size lenticular geometry strata.	Planar-cross stratification is related to 2D subaqueous sand dunes along transverse bars under lower flow regime conditions.
Sh	Medium- to fine-grained sandstones with horizontal stratification	Medium- to fine-grained sandstones, exceptionally coarse, often micaceous and arkosic, with horizontal stratification, structured in normally tabular layers of decimetric thickness. In addition to the horizontal stratification, have frequently centimetric layers of small pebbles and granules at the base of beds that originate normal gradation.	Upper laminar flow deposits (critical flow), associated with various processes.
Sr	Current ripple, cross-laminated sandstones	Decimetric heterolithic horizons formed by intercalations of fine sandstones with parallel lamination and climbing-ripples cross-lamination, and parallel laminated pelithes.	Deposits resulted from a combination of traction and suspension of sand in flood-plain fines.
Sd	Fine sandstones with deformational structures (soft sediment deformation)	Fine silty sandstones, tabular geometry, decimetric thickness (20–60 cm), stratified, with deformational structures (mainly load structures) such as convolute and flame laminations.	Subaqueous dense current action that caused deformation in layers unconsolidated fluvial substrate.
Sla	Fine to medium sandstones with low angle cross- stratifications	Fine to medium sandstones, well-sorted by level, with low angle cross-stratification, bimodal granulometric laminations (pin stripe) and low-angle cross-laminations.	Aeolian sand sheet deposits due to reworking of fluvial sediments.
Fsm	Siltites, mudstones and laminated fine sandstones (heterolithic deposits)	Siltites, mudstones and fine to very fine sandstones, micaceous, whose main structure is the horizontal lamination. The layers typically occur in tabular and rarely lenticular, centimetric to decimetric thickness.	Deposits of subaqueous currents predominantly of lower flow regime.
Fh	Laminated mudstones	Claystones with horizontal lamination demarcated by intercalations of whiteness and brownish levels. Laminae usually tabular and rarely lenticular, centimetric thickness.	Distal floodplain deposits under subaqueous current action of lower flow regime; overbank deposits or abandoned channel.
Fm	Massive mudstones	Claystones, massive or with paleosols, bioturbation and root marks.	Backswamp or abandoned channel deposits; incipient soil, root beds.
Fp (P)	Paleosol	Paleosol staining lilac to purple, with evidence of bioturbation, root marks and pedogenic features such as nodules and filaments.	Subaerial exposure horizon with sedimentation pause; chemical precipitation.

Table 1. Lithofacies of Missão Velha Formation, Araripe Basin. Facies scheme after Miall (1978, 1996, 2006a)

nated. Mudstone-dominated facies are less common or even absent in individual outcrops.

***Lithofacies Gh: Clast-supported, horizontal bedding conglomerates*:** This facies consists of pebbly clast-supported well stratified conglomerates (maximum pebble size observed is 7 cm) arranged in lenticular thin layers (up to 30 cm wide, normally around 10–20 cm), whose clasts are rounded to subangular (Text-fig. 6A). The stratification is horizontal and highly conspicuous. Detrital fragments are composed of milky quartz, gray quartz, metamorphic rock fragments (mainly quartzites), and few silicified fossil trunks (a maximum trunk size of approximately 0.35 × 0.95 m was observed in the natural exposition known as Grota Funda (Text-fig. 7A). The matrix consists of slightly arkosic coarse sandstone, poorly sorted. Gh facies is subordinated to St and Scg facies, discussed below.

Interpretation: Deposition from plane bed or low-relief bedforms in fluvial streams. The Gh Facies is interpreted, probably, as subaqueous current deposits in longitudinal fluvial bedforms in braided rivers according to the precepts of Miall (1977, 1996, 2006).

***Lithofacies Gt: Trough cross-stratified, matrix supported conglomerates*:** These fine-to medium-grained, clast-supported conglomerates are well to moderately sorted, with subrounded pebbles (Text-fig. 6A). Coarse-grained conglomerates are less common but not rare. The latter are well sorted, clast-supported, and contain subrounded pebbles and profuse silicified fossil trunks (maximum trunk size of approximately 1.70 x 1.40 m) in the natural exposition known as Morro do Cruzeiro. The pebble size is between 0.5 and 6 cm, with a maximum of 20 cm. The conglomerate matrix is formed by medium- to coarse-grained sand and/or fine-grained gravel, occasionally with some amount of compressed plant material. Sandstone rip-up clasts derived from [the] underlying strata rarely occur close to the conglomerate base. Spheroidal limonitic nodules are common. The most common sedimentary structures are trough and tabular cross-bedding with an imbricated fabric. Fining upwards into coarse-grained sandstone is occasionally observed. The sediments of these facies form erosionally based bodies, with a relief between 0.5 and 1.2 m. The base is characterized by a pebble lag a few centimeters in thickness. The predominant geometry is lenticular. These facies alternate with the cross-bedded sandstone facies.

Interpretation: *Gt Facies* indicates deposits of migrating subaqueous dunes with sinuous crests. The conglomerates of these facies were deposited from traction by a unidirectional current. Trough cross-bedding indicates lower flow regime conditions, *i.e.* low ratio of inertial to viscous resistance for a flowing fluid. It also indicates sinuous crested bedforms (3D dunes and bars).

***Lithofacies Gp: Planar cross-stratified, clast supported conglomerates*:** This coarse-grained conglomerate is well sorted, clast supported, and contains subrounded pebbles. Sedimentary structures include planar cross-bedding, with an ordered imbricated fabric. Fining upwards into coarse-grained sandstone was observed in one case. Its conglomeratic matrix is composed of coarse-grained sand and/or fine-grained gravel, occasionally with a small amount of clay fragments. Rip-up sandstone clasts derived from underlying sediments occur rarely at the base of the conglomerate. Spheroidal limonitic nodules are also common. The conglomerate's base is sharp and erosional, with up to 0.5 m deep cuts into the underlying deposits. This facies is underlain by coarse-grained sandstone in most cases, and rarely by fine-grained sandstone and/or fine-and medium-grained gravel. The overlying deposits consist of coarse-grained sandstone, fine- and medium-grained gravel, and rarely of fine-grained sandstone.

Interpretation: The conglomerates of Gp Facies were deposited from traction by a unidirectional current. Planar cross-bedding also indicates lower flow regime conditions (Boggs Jr. 2006), *i.e.* low ratio of inertial resistance to viscous resistance for a flowing fluid, not necessary high discharge or depositional energy. Besides it indicates straight crested bedforms (2D dunes and bars) (Boggs Jr. 2006). The coarse grain size reflects a higher discharge and higher energy of the depositional current compared to that of the Gh and Gt facies.

***Lithofacies Scg: Cross-stratified pebbly and conglomeratic sandstones*:** The cross-bedded pebbly sandstones facies (Scg Facies) is best exposed in the study area of the Missão Velha Formation, where the St Facies, defined below, is also well exposed. This facies (Scg) is composed of erosionally-based channel-form bodies of pebbly coarse to very coarse sandstones, locally conglomeratic, with granules and pebbles, quartzose, with abundant silicified fossil trunks, forming fining upward cycles (Text-fig. 6B). The silicified fossil trunks, allocated to the genus *Dadoxilum benderii,* are up to 1.50 m long (Braun 1966; Brito 1987). The geometry of the sandstone bodies is predominantly lenticular where sandy packets are amalgamated. Notable sedimentary structures occur, such as various small trough cross-beddings (0.2–1.0 m) concordant with the lower erosional surface or showing some accretion perpendicular to the elongation of the channel. These channels are typically 1 to 5 m wide and 20 to 100 cm thick, locally showing cosets of trough cross-stratification. Other significant features include cut and fill structures and an abundance of well-rounded to subangular clasts in foresets of strata. The presence of lenticular pebble lags at the base of the layers or the cross-bedding is common (pebble lags on basal scours). Angular mud clasts are also common, occurring as concentrated lags near the channel-bottom or scattered on the foresets. Occasionally these facies also occur as homogeneous thin packages, often with conglomeratic pockets marking [an] erosive base.

Interpretation: This facies represents subaqueous dunes deposits of lower flow regime in braided fluvial channels, according to Miall (1977, 1981, 1996, 2006).

***Lithofacies St: Trough cross-stratified sandstones*:** Along with the Scg and Sp Facies, the Trough cross-stratified sandstones (St Facies) is also very well exposed in the study area of the Missão Velha Formation. This facies comprises coarse to medium sandstones, with sporadic granules and pebbles. It is locally conglomeratic (framework < 50 %), poorly sorted, with a lenticular geometry. The conglomerate matrix is formed by medium- to coarse-grained sand and/or fine-grained gravel, occasionally arkosic and/or kaolinic. Sedimentary structures include medium to large trough cross-stratified units (> 50 cm), solitary or grouped, highlighted by an abundance of clasts disposed in the foresets of stratifications (Text-figs 6B, C), rarely with an ordered imbricated fabric. There are many silicified fossil trunks, sometimes constituting anomalous concentrations as in the big exposure of Grota Funda (Text-fig. 7A, B). The sedimentary succession forms fining upward cycles into coarse-grained sandstones (Text-fig. 6B) with a predominantly tabular geometry that persists laterally (> 30 m). Locally small trough cross-bedding can occur (< 30 cm). Subrounded to subangular mud clasts are common, occurring as concentrated lags near the channel-bottom or scattered on the foresets.

Interpretation: Trough cross-stratified sandstone is routinely interpreted as the product of three-dimensional winding crested bedforms (3D dunes and bars) migrating in channels under the conditions of the upper part of the lower flow regime (Miall 1977, 1981, 1996; Hjellbakk 1997). High pebble contents indicate the high energy of the depositional current. This facies is associated with the migration of 3D subaqueous dunes under a lower flow regime. The relatively high frequency of St Facies is probably due to the low energy and relatively low discharge of the channels. The character of the streams is a consequence of ephemeral braided fluvial channels.

***Lithofacies Sp: Planar cross-stratified sandstones*:** This facies is composed of medium- to coarse-grained, cross-stratified, arkosic sandstones (Text-fig. 6E). Geometry is generally tabular with great lateral persistence (> 50 m). It may occur as planar cross-stratified cosets in multistoreyed sandstone bodies (see Text-fig. 13). Its base is sharp and displays up to 1.2 m deep scours. A pebble lag a few centimeters thick can be present at the base. These facies are usually underlain by fine- or coarse-grained gravel, and are rarely underlain by fine-grained sandstone or medium-grained gravel. Overlying deposits consist of fine- or coarse-grained sandstone. Sandstone Sp is moderate to poorly sorted with subrounded grains. In most cases this sandstone has a pebbly admixture (maximum pebble size observed is 10 cm). Quartz pebbles are usually better rounded than quartzite, proterozoic schist, and siltstone pebbles, which can even be angular. Coalified stems may be present. Rare silt interbeds, silt intraclasts, and pebbles are present either as scattered deposits or as layers within the sandstone bed. Pebble size is usually between 0.5 and 3 cm, and up to 5 cm in diameter. Sedimentary structures include planar cross-stratification, sometimes demarcated by concentrations of clasts disposed in the foresets of stratifications (Text-figs 6B, C), with rare ordered imbricated fabric. Current ripple bedding is very rare. The presence of silicified fossil trunks is very common within the strata. Sedimentary structures have been locally destroyed by soft sediment deformation, water escape structures, and bed slumping of Sd facies, discussed below.

Interpretation: Sandstone Sp was deposited from traction by a unidirectional current. Planar-cross stratification is related to 2D subaqueous sand dunes along transverse rather than longitudinal bars. Secondly, tongue bars can present planar cross-stratification. Planar cross-bedding also indicates lower flow regime conditions (Boggs Jr. 2006). It also indicates migration of large-scale straight crested bedforms (2D dunes and bars) (Boggs Jr. 2006). High pebble contents indicate the high energy of the depositional current. Pebble lags preserved on the base of the sandstones suggests the cessation of a rolling gravel bed load, which could mean a fall in the initial energy of

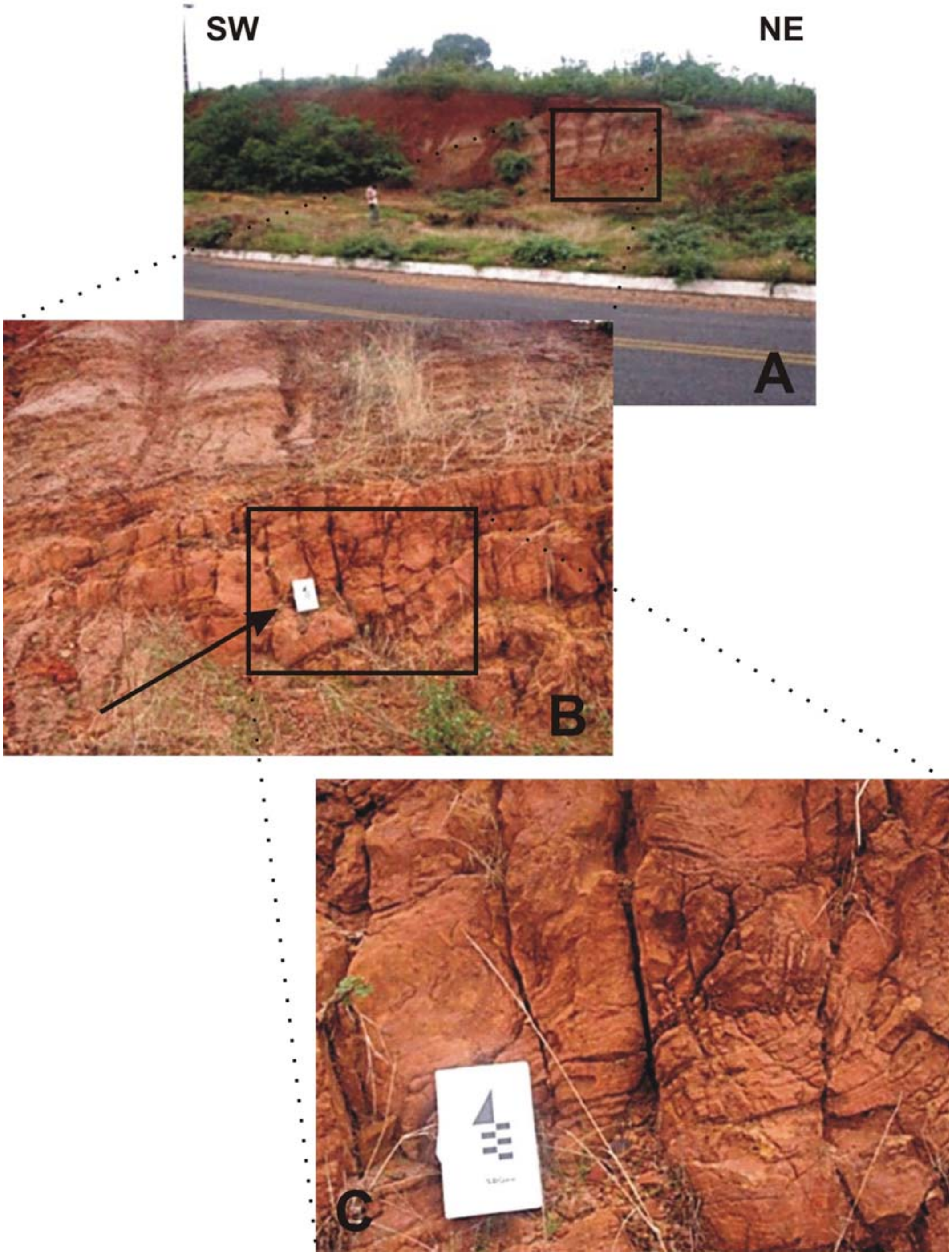
Text-fig. 7. Fossil trunks of the Missão Velha Formation related to the coniferous species *Dadoxilon benderi* (Braun 1966; Brito 1987; Freitas *et al*. 2008). A – trunk fossil detail, very common feature in Grota Funda; B – Profuse fossil trunks showing marks of insect activity (according to Pires and Guerra-Sommer 2009)

the depositional current. Abundant large-scale planar cross-stratified cosets in multistoreyed sandstone sequences may be attributed to downcurrent migration of sand dunes, sand waves, and transverse bars in shallow-water stream channels. Sp Facies may record the migration of channel bedforms in fluvial transverse bars of braided rivers (Miall 1996). This interpretation is further supported by the fining upwards of several beds terminated locally by current-ripple-bedded sandstone. Soft sediment deformation and slumping reflect channel bank instability.

***Lithofacies Sh: Horizontally stratified sandstones*:** Medium- to fine-grained sandstones form bodies that are up to 0.95 m thick (normally 30–75cm), with sharp bases underlain by the fine- and/or coarse-grained gravel of Gp and Gt facies, and overlain by coarse- to medium-grained sandstones (facies Sp, St) and fine- and/or coarse-grained gravel (Gp, Gt facies) (Text-fig. 6D). The fine-grained sandstones are well sorted with subrounded grains; occasionally sparse pebbles may occur. Sedimentary structures include horizontal stratification and lamination and the presence of subangular mud fragments (rip-up clasts), occurring as concentrated lags near the base of strata/laminations or scattered throughout. The geometry of the bodies is often tabular with great lateral extension (more than 20 m). The sandstones often contain fossil trunk remains and are rarely interlayered with siltstone.

Interpretation: The sandstone Sh facies represents upper flow regime bedding (critical flow) formed by reduction in water depth during the last stages of flood events. It may occur in transverse or tongue bars of braided fluvial streams.

***Lithofacies Sr: current ripple, cross-laminated sandstones*:** This facies comprises recurring thin



Text-fig. 8. Deformational structures in the Missão Velha Formation. A – General view of the deformed sandstones of Sd facies; B, C – Close-up photos of the internal structures of the deformed sandstones showing contorted lamination, load structures and disrupted and deformed beds caused by strong fluvial currents caused deformation of non-consolidate sediments. Outcrop at the BR-116 Federal Road in the vicinity of the town of Brejo Santo

beds of well stratified fine to very fine-grained sandstones that form bodies that are up to 0.55 m thick (normally 15–30 cm), with sharp bases underlain by coarse- to medium-grained sandstone (Sp, St facies), and overlain by heterolithic pelithes (Fsm, Fh and Fm facies). The fine-grained sandstone is well sorted with rounded to subrounded grains. Sedimentary structures include climbing-ripples, cross-lamination and current ripple lamination (Text-fig. 6H).

Interpretation: The deposits were the result of a combination of traction and suspension of sand in flood-plains. This facies is formed by migration of current ripples with deposition both from traction and suspension. Current ripple lamination and silt interbeds indicate changes in velocity and sediment load within the channel.

***Lithofacies Sd: Soft sediment deformation sandstones*:** This facies is more subordinate and contains laminated silty fine sandstones disposed in thin layers (20–60 cm), with load deformational structures. Normally the geometry of the bodies is tabular. Sd Facies is frequently intercalated with coarse- to medium-grained sandstones (Scg, Sp and St facies) and fine-and/or coarse-grained gravel (Gp, Gt and Gh facies). Deformational structures comprise soft sediment deformation, water escape and load structures, and features related to slumping such as contorted laminations and slumps, respectively (Text-fig. 8).

Interpretation: This facies is interpreted as having resulted from near bed drag caused by strong fluvial currents causing deformation of non-consolidate[d] sediments. Soft sediment deformation and slumping reflect channel bank instability.

***Lithofacies Sla: Low-angle cross-stratified sandstones*:** This facies is composed [of] fine to medium sandstones with low-angle cross-stratifications of medium size, well-sorted by level and bi-modal granulometric laminations (pin stripe lamination).

Interpretation: The well-sorted, bi-modal nature of the facies suggests aeolian processes.

***Lithofacies Fsm: Heterolithic deposits*:** This facies consists of interlaminations of mud, silt, and very fine-grained sand. It includes (i) fine- to very fine-grained laminated muddy sandstones, occasionally silty, (ii) whitish gray to ochre laminated siltites, and (iii) decimetric reddish brown to purplish stained laminated muddy horizons (Text-fig. 6F). The thickness of particular sharp-based bodies varies from 0.1m to more than 1 m (normally 25–60 cm). Fsm Facies often rests on an erosional surface; sometimes it occurs on medium- to coarse grained sandstones that pass upwards into fine-grained, ripple bedded sandstone; at the top it can be overlain by medium-to coarse-grained sandstone. Lamination can be prominent. Plant remains are locally present either as detritus or identifiable plant remains. Root marks are occasional but are most frequently observed at the Grota Funda locality (Fp Facies, described below).

Interpretation: Sediments of this facies were deposited mostly out of suspension, but also by low velocity unidirectional currents under a lower flow regime. They can represent flood plain fines, or overbank fines. Another interpretation is that they point to an abandoned channel fill, as indicated by the erosional surface at the base or by the presence of medium- to coarse-grained sandstone.

***Lithofacies Fh: Laminated Mudstones*:** The Fh Facies consists of horizontally laminated reddish to brown mudstones. The horizontal lamination (5–25 mm) is demarcated by colourless and browner intercalated tabular mud layers (Text-fig. 6G). Occasionally these layers are lenticular in form.

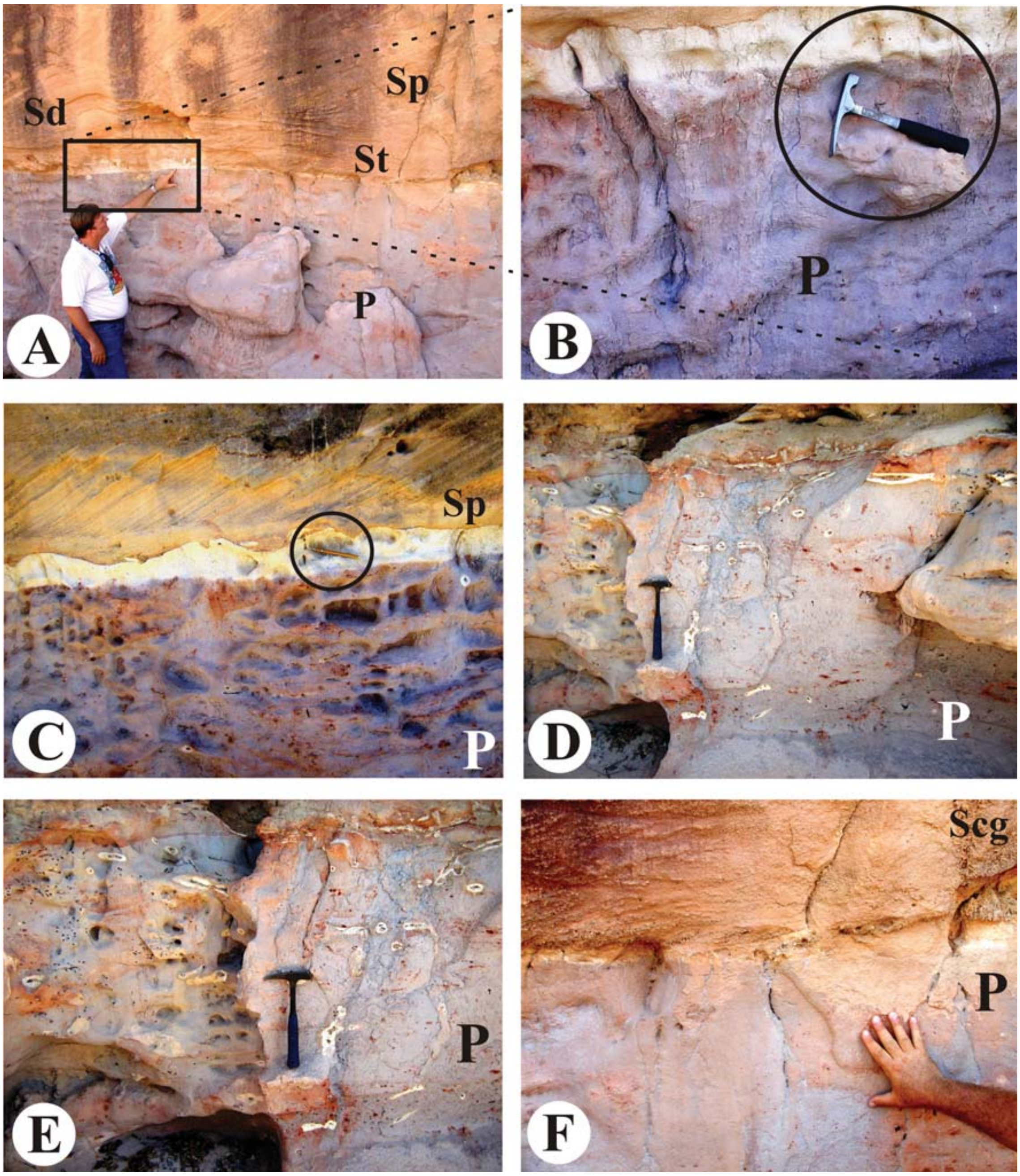
Interpretation: The Fh Facies can be interpreted as mud settling from weak, subaqueous currents. It constitutes the distal deposits of a floodplain caused by underwater current action in a predominantly lower flow regime.

***Lithofacies Fm: Massive Mudstones*:** The Fm Facies consists of massive reddish-purple mudstones, with various bioturbation features and root marks (Text-fig. 6G). Millimeter to a few centimeters thick and few meters wide concave-up lenses of desiccation-cracked and curled mudstones may also occur. Desiccation cracks form polygonal patterns in plan view. The cracks are filled by fine to medium-grained sand of similar texture to the overlying sandstone bed.

Interpretation: The interpretation of Fm facies is restricted to mud settling within calm, shallow and later desiccated subaqueous environments. In a broad sense, it belongs to the more distal deposits of a floodplain in a fluvial settling. The settling of fine-grained particles in depressions between bedforms took place after flood events on alluvial plains. It can be interpreted as backswamp or abandoned channel deposits.

Lithofacies Fp (Paleosol): Pedogenic: The Fp Facies consists of a thick lilac to purple coloured muddy paleosol horizon (up to 2.3 m see Text-fig. 9A), with various bioturbation and pedogenic features and root marks (Text-fig. 9B). Intense alteration of the protolith is seen compared with preserved portions of the original rock, and there are intense variation of colour and hue, and the presence of nodules and filaments. This facies is frequently observed at the Grota Funda locality, type-section of the Missão Velha Formation.

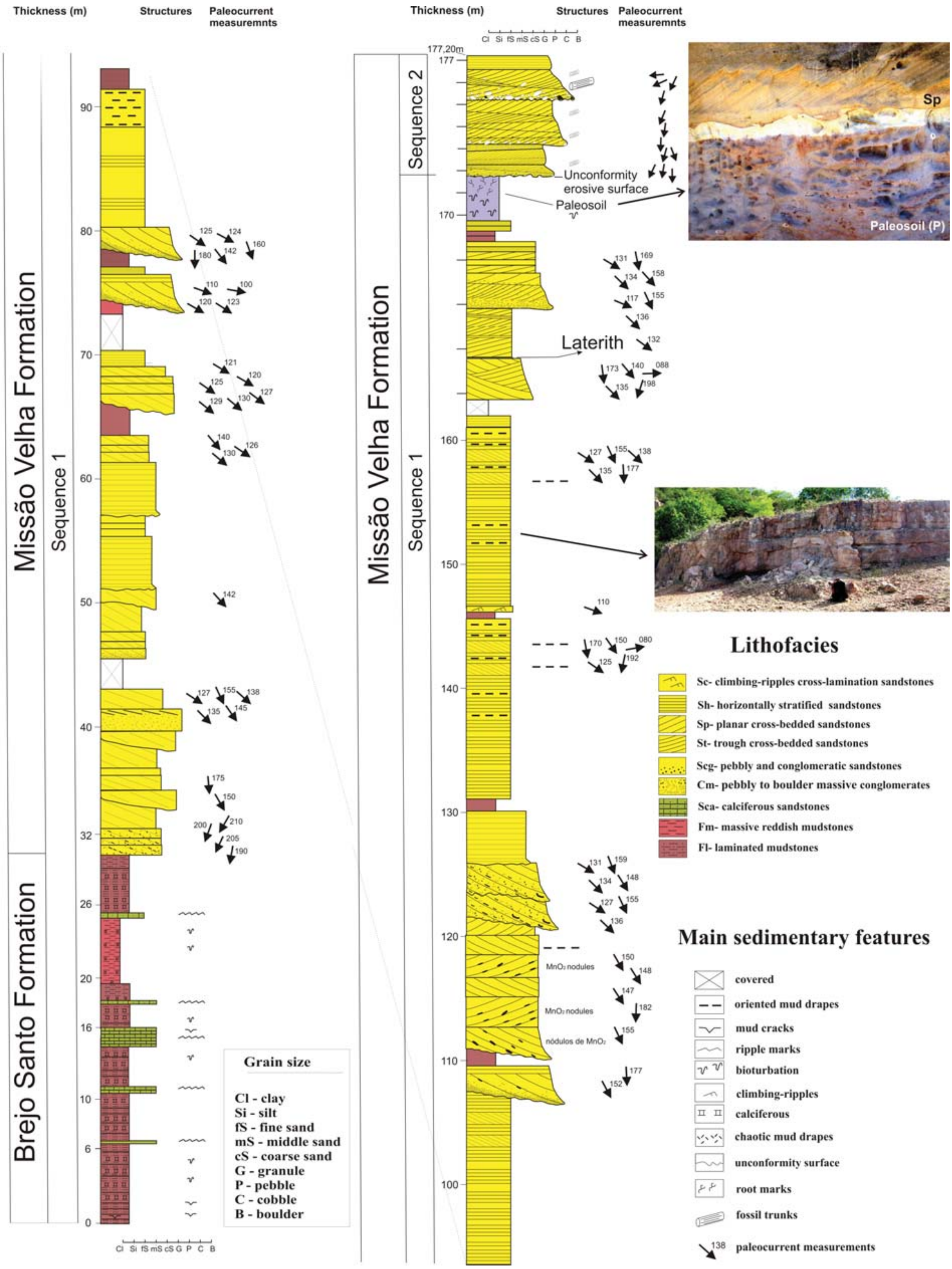
Interpretation: This facies experienced subaerial exposure and a pause in the process of sedimentation.



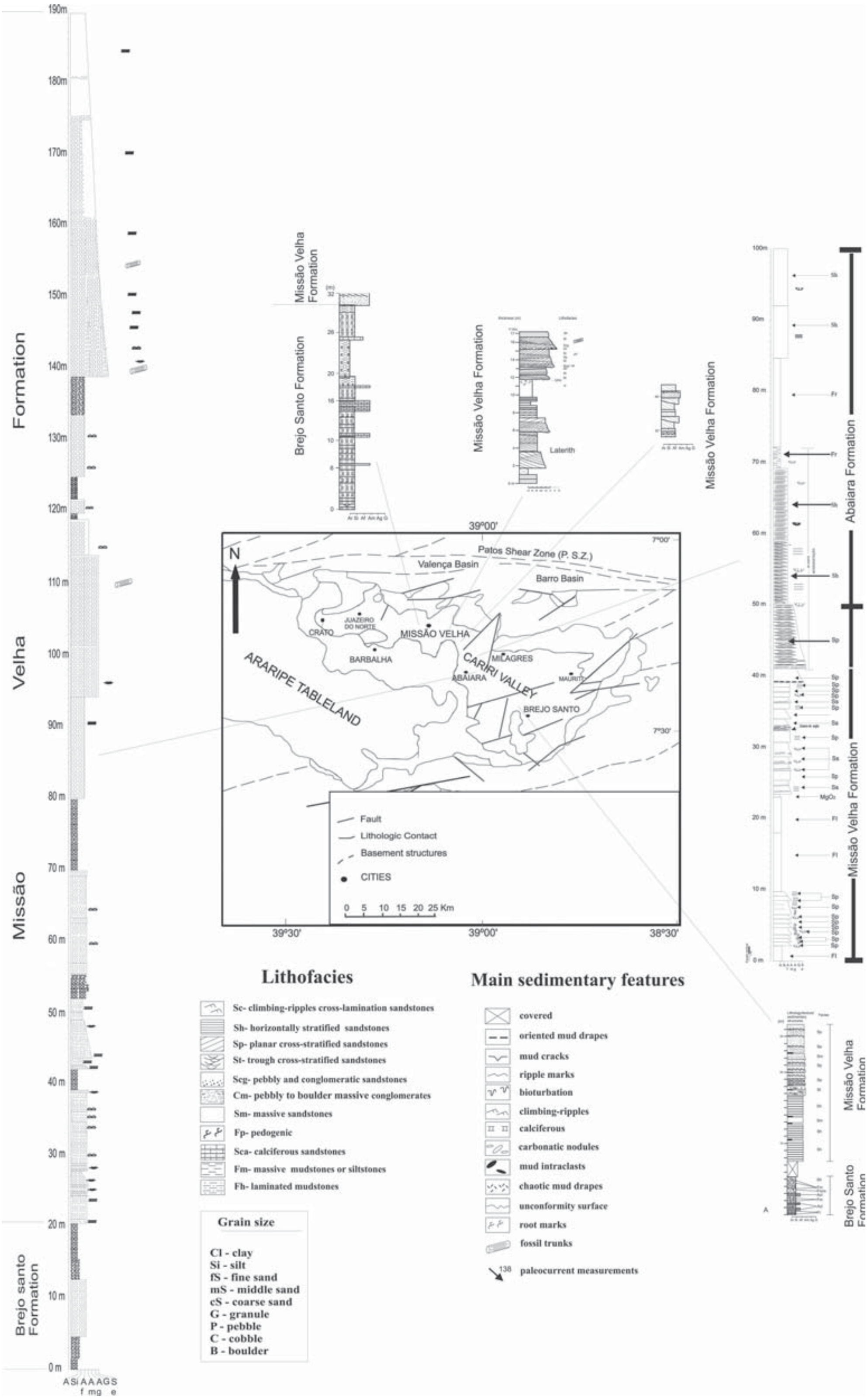
Text-fig. 9. Mud paleosol horizon (Fr Facies) in fluvial system of the Missão Velha Formation at Grota Funda. A – General view of Paleosol (P); B – Bioturbation and pedogenic features and root marks in P horizon; C – Erosional contact with Sp facies (above) and presence of root marks and pedogenic features; D, E – Intense bioturbation, root marks and pedogenic features; F – Erosional contact of P horizon with Scg facies (above) and pedogenic features in P horizon

VERTICAL STACKING SUCCESSION OF THE MISSÃO VELHA FORMATION

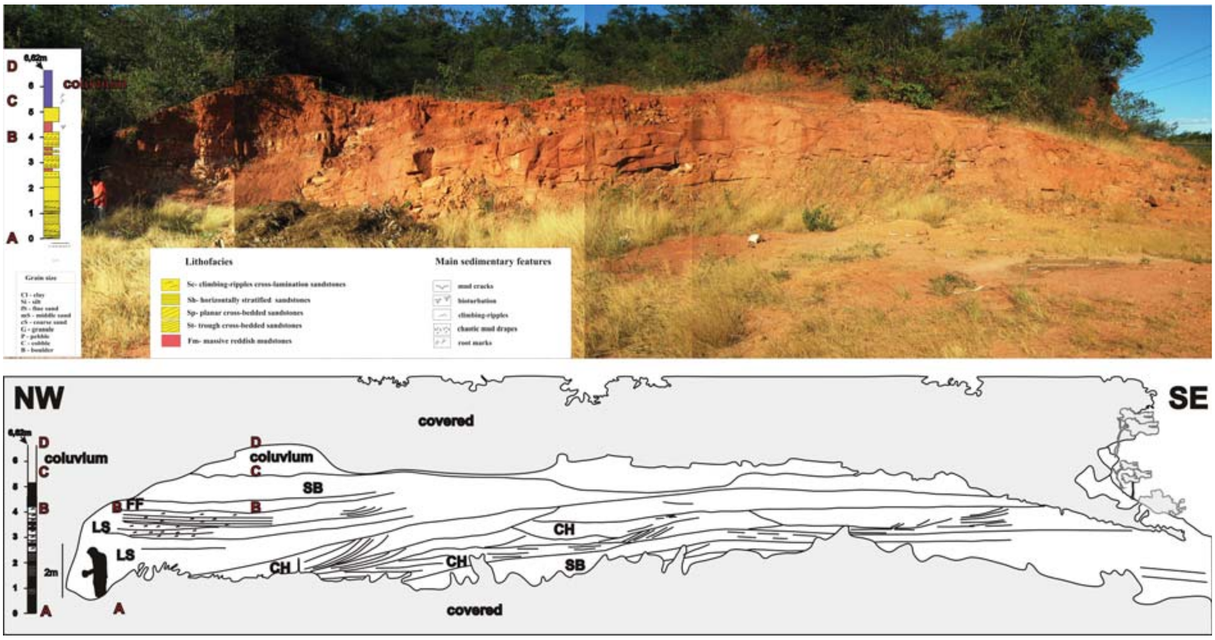
The Missão Velha Formation stacking patterns show a predominately fining-upward cyclic repetition composed of sandstones intercalated with thin beds of pelites in the lower portion (Text-fig. 10). This stacking pattern can be related to the Sequence 1. Towards the top there is an increase in the of amount of sandstone bodies parallel to an increase in the grain size and thickness of beds suggesting a coarsening-upward megacycle (Text-figs 10, 11). In addition, the



Text-fig. 10. Composite log of the Missão Velha (entire) and top of the Brejo Santo Formations. Outcrops used to logging shown at Text-fig. 11



Text-fig. 11. Map showing the location of logs used for this study. Note the fining-upward, coarsening-upward or uniform trends of the cycles. Some logs represent the basal contact with the Brejo Santo Formation; others show the upper contact with the Abaiara Formation. Log-sections are at same scale



Text-fig. 12. Lower portion of the Missão Velha Formation showing stratified fine sandstones intercalated with some mudstones. Observed are also CH, SB, LS and FF architectural elements. Outcrop at CE-293 road near Grota Funda. See Table 2 for element codes

upper part of the unit shows an erosive unconformity distinguished by the presence of conglomeratic sandstones and conglomerates rich in clasts of medium to fine sandstones derived from the rocks directly below of the surface, related to Sequence 1 (Text-figs 10, 11, 13–15), as discussed later. This group of rocks can be allocated to Sequence 2.

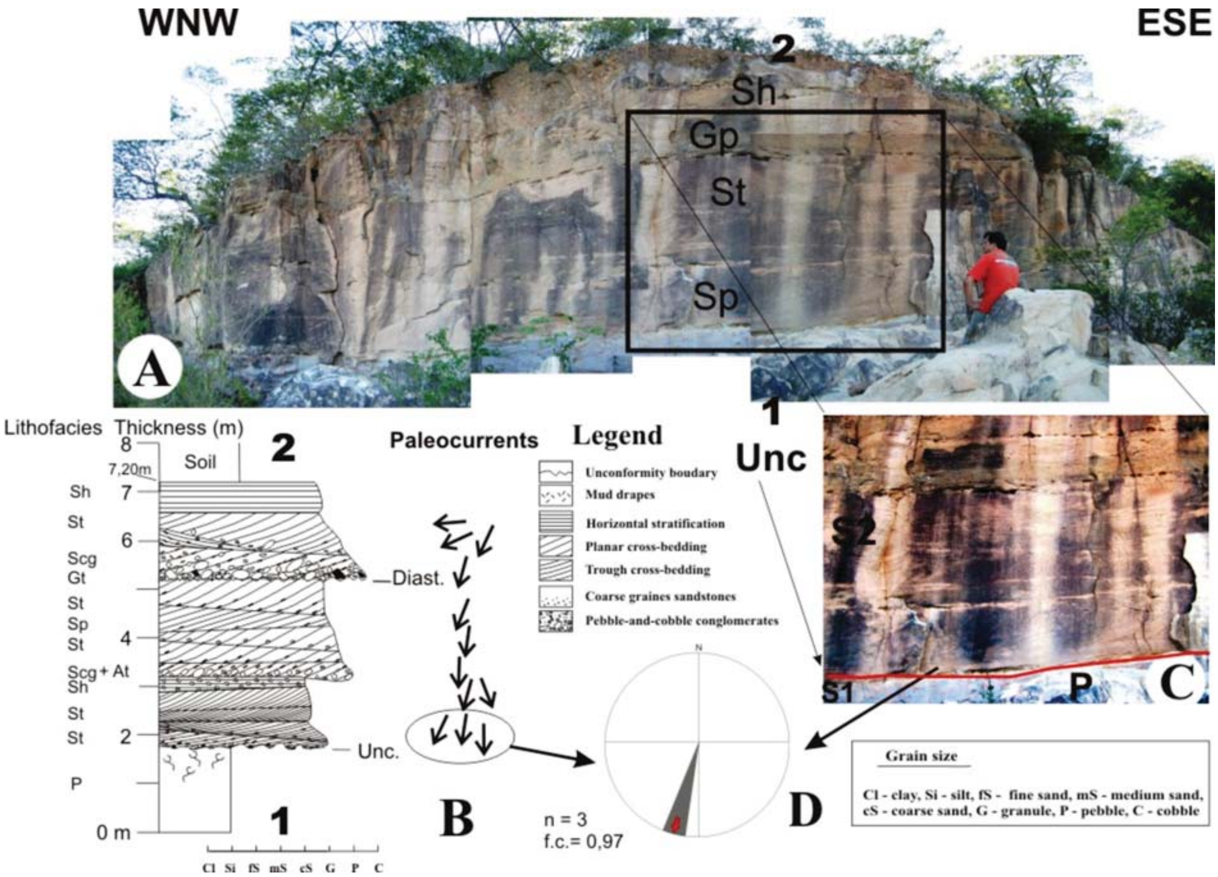
In the lower portion (Text-fig. 12) of the Missão Velha Formation (Sequence 1, also including the upper part of the Brejo Santo Formation) there is a marked presence of medium- to fine-grained sandstones, sometimes coarse, as represented in all detailed sections (Text-figs 10, 11, 13–15). The paleocurrent measurements have a consistent dispersion pattern to S, SE and SW (Text-figs 10, 11, 13–15).

The upper portion of the Missão Velha Formation (Sequence 2) presents coarser lithofacies (Text-fig. 13), described as coarse-grained feldspathic conglomeratic sandstones, localized pebbly stratified conglomerates, with abundant silicified fossil trunks, organized in fining-upward cycles and several large-to-medium trough cross-stratifications with predominantly lenticular geometry (Text-fig. 14). Aside from the cyclic repetition of small fining-upward cycles, the whole stacking pattern of this sequence shows an increase of thickness of beds and grain size suggesting a coarsening-upward megacycle (Text-figs 10, 11). At this level in the beds of conglomeratic sandstones and localized pebbly conglomerates, abundant silicified fossil wood and trunks occur An important feature is the presence of sandstone clasts derived from the rocks of Sequence 1 below (Text-fig. 15). The paleocurrent measurements showed a more variable dispersion pattern, in addition to the measured directions of S, SE and SW, also for E, NE and N (Text-figs 10, 16, 20). See discussion forward.

ARCHITECTURAL ELEMENTS AND FACIES ASSOCIATIONS. DISCUSSION ON DEPOSITIONAL SYSTEMS AND STACKING PATTERNS

Architectural Elements

The facies associations and related architectural elements found in the Missão Velha Formation in the type area are detailed below (see Table 2). Nine architectural elements were recognized: CH: Channels, GB: Gravel bars and bedforms, SB: Sand bars and bedforms, SB (p): sand bedform with planar cross-stratification, DA: Downstream accretion macroforms, LA: Lateral accretion macroforms, LS: Laminated sheet sand, FF: Floodplain fines and OF: Overbank fine deposits. Not all of these features were observed at each outcrop. The elements, defined by their geometries and bounding surfaces, form the



Text-fig. 13. Grota Funda, the type section of the Missão Velha Formation, upper portion. A – Photomosaic of Grota Funda showing detailed lithofacies and log location (1–2); B – Detailed log of the outcrop with lithofacies types and paleocurrent measurements; C – Close-up of photo A (cross-stratified sandstones) with an unconformity (Unc.) separating sequences 1 and 2, where paleocurrents were collected (D) in trough and planar cross-strata rose diagram

basis for interpreting their respective depositional environments.

Architectural elements
CH – channel
GB – gravel bars
SB – sand bed form
SB (p) – sand bed form with planar cross-stratification
DA – Downstream accretion
LA – lateral accretion
LS – Laminated sand sheets
FF – Floodplain fines
OF – Overbank flow deposits

Table 2. Main architectural elements found in the Missão Velha Formation in the type area, Araripe Basin

***CH: Channels (Text-figs 12, 13, 14 and 17)*:** Channel deposits comprise lithofacies Gm, Gh, Gt, Gp, Scg, St, Sp and Sd that combine the facies associations of laminated and amalgamated sandstones. Occasionally abandoned channels in the study area are filled with Fsm and Sh lithofacies. Most of the exposures are almost transverse to the channel elongation, such as at the Grota Funda and Transnordestina railway localities. Channel deposits have sharp erosional bases with a relief of approximately 4m at the Grota Funda locality. They often erode sand bedforms and other channels. Their channel geometry is concave-up in shape, occasionally forming a multistorey channel geometry, with each story bounded by an erosional surface, as in the architectural model of Miall (1985, 1996, 2006). Channel thicknesses are up to 1 m in most cases, but usually between 0.3 and 0.5 m, and rarely up to 2 m. Channel widths vary between 0.5 m and 3 m. The average width/thickness ratio is 2.5 within the whole study area.

Interpretation: CH element comprising lithofacies Gm, Gh, Gt, Gp, Scg, St, Sp and Sd records channel

Text-fig. 14. Coarse-grained trough cross-stratified sandstones (St Facies) of the top of the Missão Velha Formation at Morro do Cruzeiro near the village of Abaiara. The paleoflow trends S and SW

deposition. The presence of coarse-grained conglomerates may indicate a sudden increase in the velocity of the depositional current. High lateral migration of channels is typical evidenced by successive superposition of fluvial bars (Scg, St and Sp Facies) (Text-figs 14, 17). Most channels have a multi-storey and multi-lateral nature. Single channels with a simple fill were found rarely (i.e. in the upper part of the section cropping out in the Morro do Cruzeiro). Sandstone clasts indicate autophagic processes due to tectonic activity and the unconformity bounded surface within the Missão Velha Formation (Text-fig. 15).

The channel geometry probably represents channels with nearly N-S paleocurrent directions; the NNE-SSW orientations of most of exposures display the channels in transverse cross sections (i.e. almost at a right angle to the direction of paleoflow).

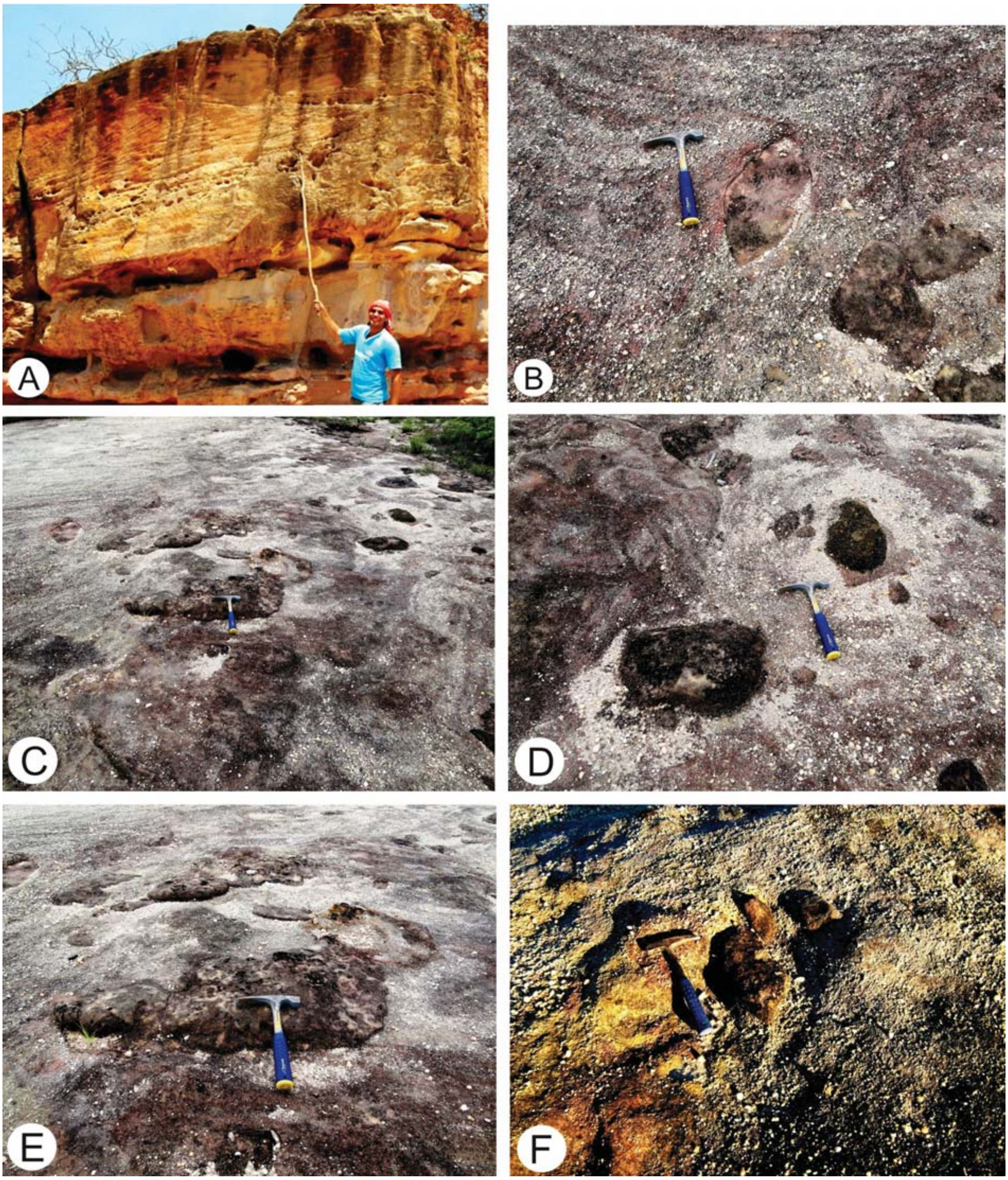
***GB: Gravel bars and bedforms (Text-figs 17, 18 and 19)*:** Gravel bar and bed deposits include lithofacies Gh, Gt and Gp. They have sharp erosional bases and often erode sand bedforms and channels. Their geometry is lobate or sheet-like. These gravel mesoforms are often amalgamated into macroforms, or bars. Element GB forms multistorey sheets tens of meters thick. The average width/thickness ratio of the gravel bar and bedforms is 10.6 cm within the study area. The thicknesses of the gravel bar and bedforms are up to 2 m in most cases, and rarely up to 4 m. Gravel bar and bedforms widths are up to 6 m along the Transnordestina Railroad outcrops (Text-fig. 18). A flat based gravel bar could be observed only in the Transnordestina Railroad outcrops. This sheet-like body with a sharp flat base is overlain by sand bedforms and channels. The recurrent alternation laterally of Gp facies with Gh and sandstone lithofacies may represent the variations in gravel sheet growth (Miall 1996).

Interpretation: Gravel bar and bedform deposits, comprising facies Gt and Gp, record intra-channel deposition. These gravel bar and bedform deposits can be divided into two groups based on their width/thickness ratios: (i) with ratios up to 1.5, and (ii) with ratios higher than 2.0. Gravel bedforms with width/thickness ratios up to 1.5 display an erosional relief of between 1.5 to 4 m. They consist of fine-to coarse-grained conglomerates of the Gh, Gp and Gt facies. Gravel bedforms record either migrating channel bed loads when comprised of coarse-grained conglomerates (Gh and Gp facies), or migrating channel bedforms when comprised of Gt facies. Gravel bedforms with width/thickness ratios higher than 2.0 record fluvial bar deposition when they are comprised of coarse-grained conglomerate facies and have erosional relief of 0.5 m, or the migration of large channel bedforms when comprised of Gt and Gp facies.

If a gravel bedform a few centimeters thick is present within the channel just above the erosional base, it is assumed that gravel bar erosion and subsequent deposition within the channel occurred. This indicates a sudden increase in the velocity of the depositional current.

***SB: Sand bars and bedforms; Element SB (p): sand bedform with planar cross-stratification (Text-figs 12, 15 and 17)*:** [Deposits of s]heet-like bodies of sand comprise mainly lithofacies Sh, St and Sp, but lithofacies Gs and Sr also occur. These lithofacies constitute facies association of sandstones in amalgamated sand sheets. They have sharp bases and are often eroded by channels. The erosional relief of the sand bedforms can be up to 2 m, although at Serra da Mãozinha Cliff it is only between 0.1 and 0.6 m. Sand bedforms are usually about 1.5 m thick, but occasionally reach thicknesses up to 3 m. Their widths vary between 20 m and 40 m in most cases, whereas at the Serra da Mãozinha locality it is only between 10 m and 15 m in most cases. The average width/thickness ratio is 19.3 within the study area.

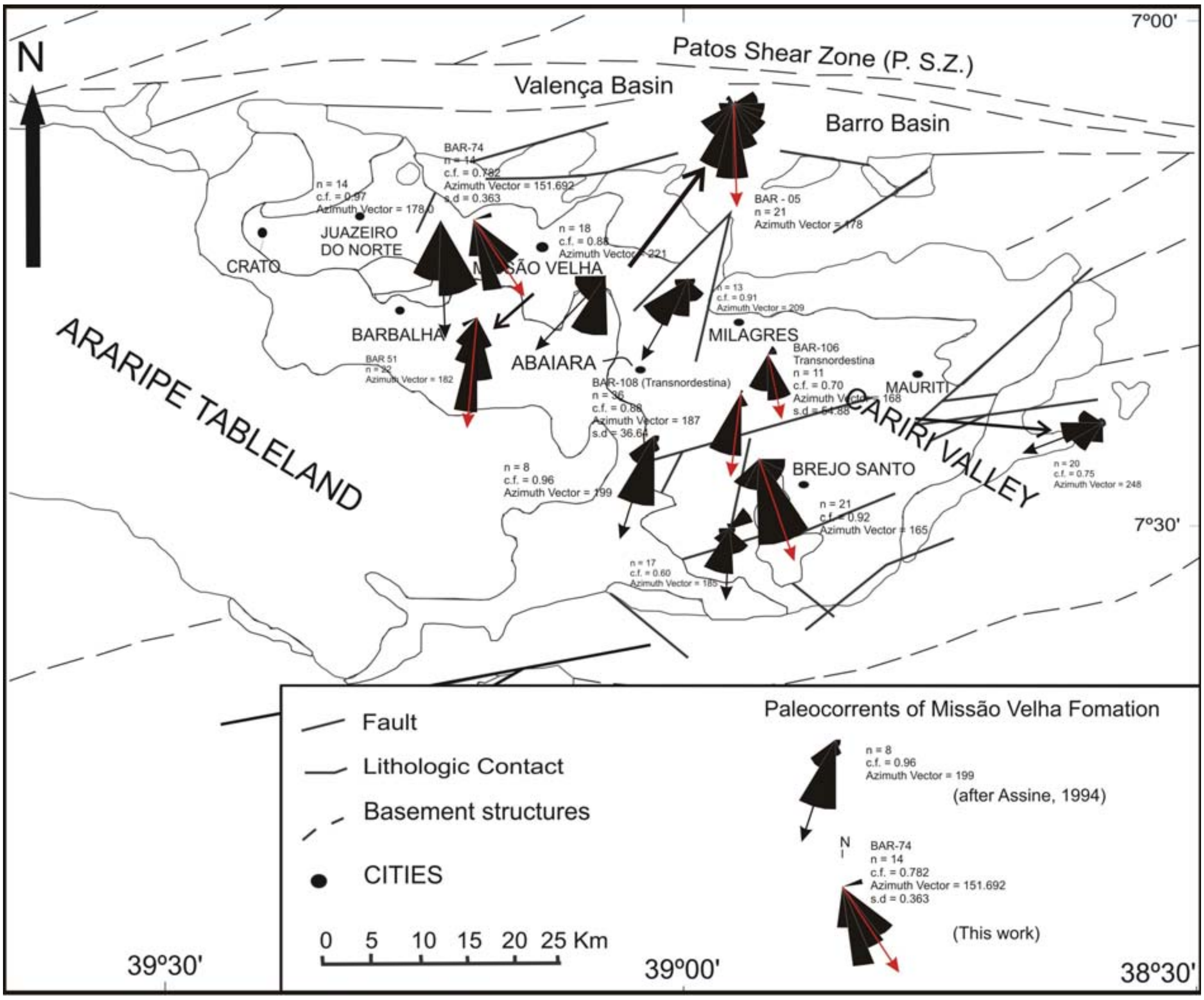
Interpretation: Sand bedforms record intra-channel deposition. They were probably produced by migrating dunes within the channel. This is supported by paleocurrent measurements, which show paleoflow directions to the SSE and SW. Because of the NNE-SSW orientations of almost all exposures, where channel geometry is displayed close to the longitudinal cross section (subparallel to paleoflow



Text-fig. 15. Coarse-grained sandstones (Gt, St, Sp and Scg Facies) of the top of the Missão Velha Formation at Morro do Cruzeiro, near the village of Abaiara (A). Clasts are composed mainly of sandstones of under rocks of Sequence 1, showing an unconformity within the Missão Velha Formation B, C, D, E and F

direction), the channel geometry appears sheet-like. Sand bedforms were probably deposited by migrating dunes within the channel.

DA: Downstream-accretion macroforms (Figs. 17 and 18)**:** Downstream-accretion macroforms (element DA) are represented mainly by lithofacies Sp,

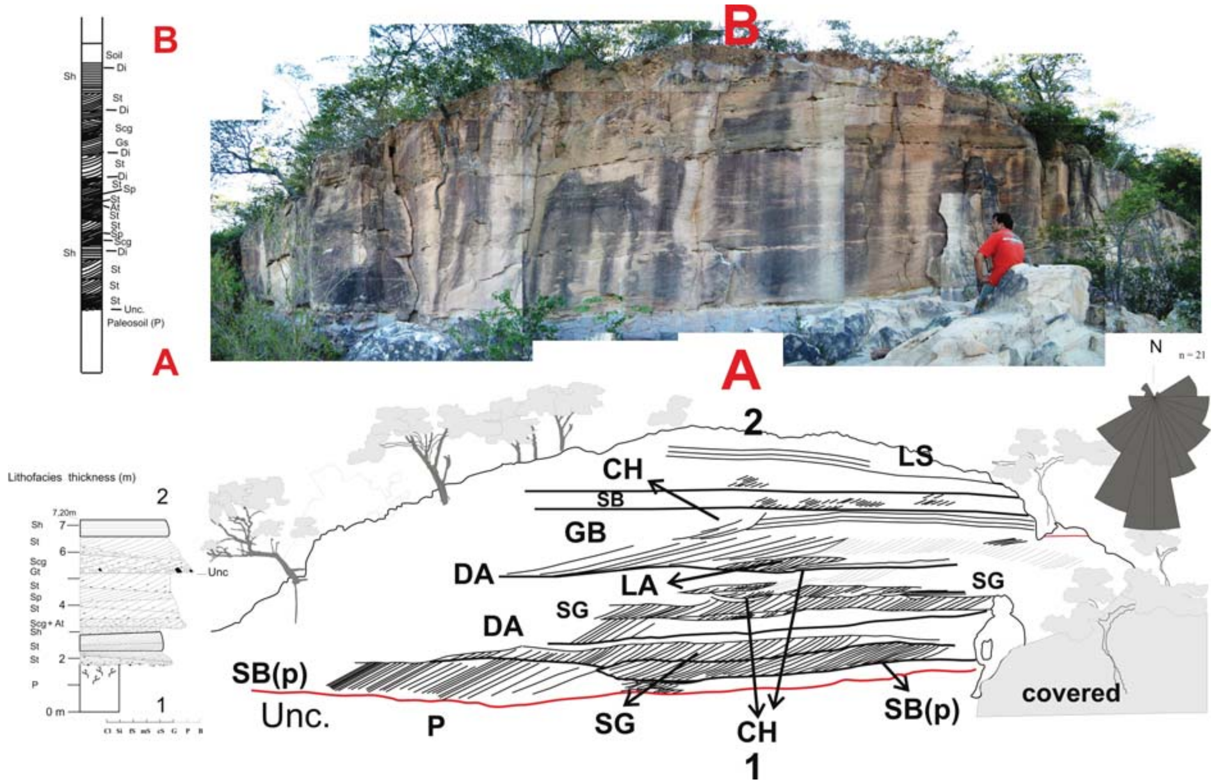


Text-fig. 16. Paleocurrent measurements of Sequence 1 of the Missão Velha Formation. Data collected for this study (red arrows) and after Assine (1994) (in black)

St, Scg, Sr, and sometimes by lithofacies Gp, and Gt (sand and gravel bedform deposits). Their geometry is sheet-like. Element DA consists of several cosets of downstream-oriented flow-regime bedforms dynamically related to each other by a hierarchy of internal downstream-dipping bounding surfaces (Text-fig. 17). Element DA is one of the most well exposed in the study area. However, downstream accretion macroforms were not recognized within the Serra da Mãozinha region. Downstream accretion macroform thicknesses are up to 4.5 m, and widths vary between 10 m and 40 m. Their average width/thickness ratio is of 13.8 within the study area.

They are internally characterized by frequently displaying beds of cross-strata, which are distinguished by the presence of multiple cross-sets separated by gently sloping surfaces oriented in the direction of the stream, as in the models of Miall (1988), Bristow (1993), Miall (1996, 2006). They represent bars or bar complexes of mid channel (middle or braided bars).

Interpretation: Downstream accretion macroforms (DA element) record channel deposition. They were most likely formed due to the migration of large sandy to gravel bars on the river main channel (Bristow 1993; Miall 1996, 2006a), representing bars or bar complexes of mid channel (middle or braided bars). The generation of these macroforms is associated with high-energy fluxes that allowed large dune foresets, which migrated for tens of meters (Text-fig. 17). Sometimes, downstream accretion macroforms can contain a lateral accretion component, so displaying the lateral gradient of the element DA to LA, as shown in Text-fig. 17. The generation of these



Text-fig. 17. Architectural elements of the Missão Velha Formation at Grota Funda, the type section of the unit. Note paleocurrent dispersion pattern. See Table 2 for element code description

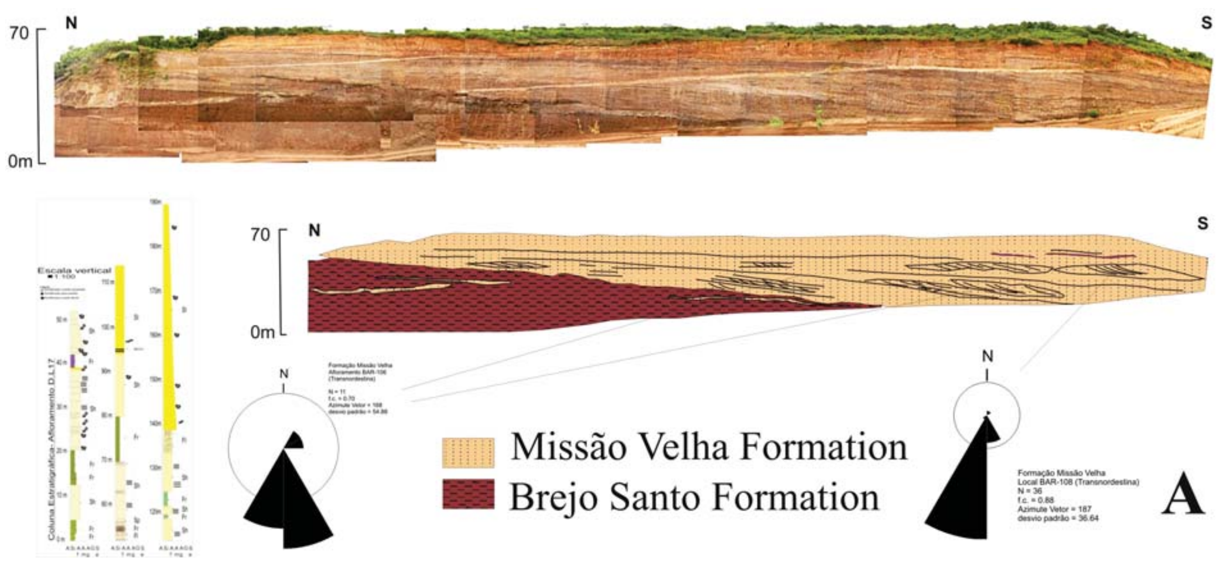
macroforms is associated with high-energy fluxes that allow large sandy dune foresets, which migrate by dozens of meters in asymptotic form (tangential or planar base) (Text-fig. 18). Following Miall (1996, 2006) DA and LA elements are very common in braided sheet sandstones. They are also indicative of a relatively low energy/sinuosity braided rivers.

***LA: Lateral accretion macroforms*:** As mentioned above, element LA is characterized by low-angle cross-strata compounds downlapped onto the channel floor, forming gently sloping surfaces. LA is present in Sp, St and Sr Facies. It represent bars or bars complexes of mid channel (middle or braided bars).

***LS: Laminated sand sheet deposits (Figs. 12, 17 and 19)*:** The LS architectural element, constituted by the Sh and Sr facies, is represented by the facies association of stacked tabular sandstones. The LS architectural element represents extra-channel deposits generated during periods of flooding. They are composed of laminated sand flanks that may be associated with overbank deposits (OF element) originating in flood plains or in abandoned channels by sporadic flows. In torrential river flood deposits this element is related to the SG element (gravel bedforms) in accordance to precepts of Miall (1985, 1988, 1996).

Interpretation: The LS architectural element, constituted by the Sh and Sr facies, represents extra-channel deposits generated during periods of flooding. Laminated sand sheets have been interpreted as the product of flash floods depositing sand under upper flow-regime plane bed conditions (Miall 1977, 1996, 2006). The facies association of stacked tabular sandstones involves the Laminated sand sheet architectural element (LS element), which denotes unconfined deposits formed by an upper flow regime through rapid flooding of a sandy alluvial plain, but also with much more variable hydraulic conditions such as lower flow regime (Sp, Sr) to almost stagnant water conditions (Fl). The sediments of Sla Facies were deposited as aeolian sand sheet deposits due to reworking of fluvial sediments when bars formed by sheet sandstones were exposed in periods of prolonged droughts.

***FF: Floodplain fines*:** Floodplain fine deposits consist of lithofacies Fsm, Fh and Fm, and occasionally Sr. They often form tabular 1mm to several centime-



Text-fig. 18. Architectural elements of the Missão Velha Formation at the Transnordestina Railway outcrop, near the village of Abaiara. See Table 2 for element code description

Text-fig. 19. GB (gravel bars) and LS (laminated sand) architectural elements of the Missão Velha Formation at Morro do Cruzeiro, near the village of Abaiara. See Table 2 for element code description

ters thick mudstones with desiccation cracks (cracked mudstones of Fm Facies). Sometimes they can occur as sheet-like beds or lenses.

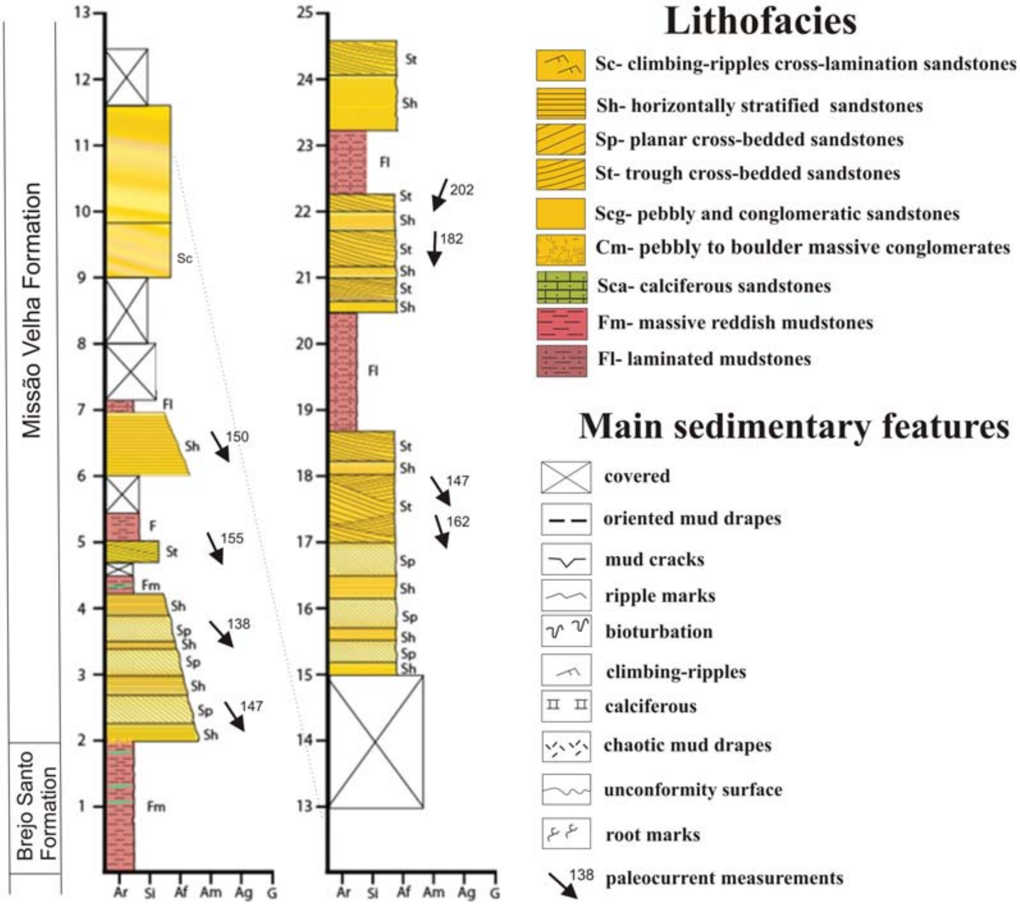
Interpretation: Floodplain fine deposits are formed in separate increments representing individual flood events followed by seasonal or long-term drying-out of the floodplain (Miall, 1996, 2006a).

***Of: Overbank flow deposits*:** Overflow fine deposits (architectural element Of with Facies Fm, Fsm and Fh) represent floodplain deposits [upon] an alluvial plain, with temporary lakes and wetland areas, probably occurring in more humid climatic conditions (Miall 2006a).

DISCUSSION

The predominant lithology of the Missão Velha Formation consists of coarse to medium sandstones, sometimes conglomeratic, but conglomerates can appear, while there are clay levels (shales and mudstones) and fine sandstones intercalated, especially in the lower portion of the unit. The interfingering between bodies of shales and sandstones can be interpreted as [showing the occurrence of] small flood plains in the midst of the braided river system (Text-fig. 20).

The Missão Velha Formation, as proposed in this paper, comprises several facies of lenticular sandy and gravelly sediments, amalgamated, or subordinately interfingered with mudstones and siltstones, and with abundant silicified fossil trunks, many in a position parallel to the bedding of sandstones. This is found through detailed study of the outcrops of the Missão Velha region, the type area of the unit, and also other sites of exposition. It is worth mentioning that the paleocurrents found show a consistent pattern towards the SE, S and SW (Text-figs 10, 16) in accor-

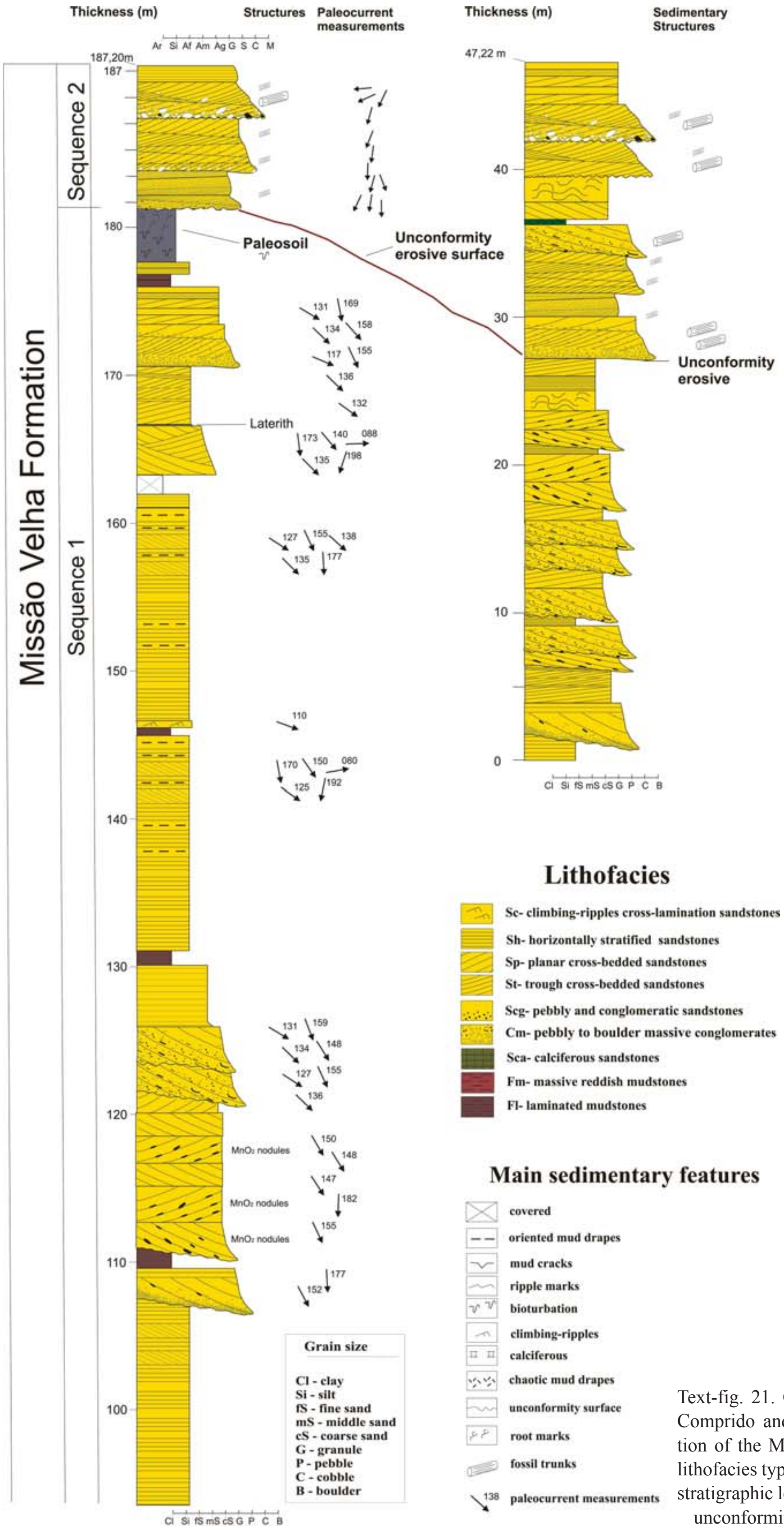


Text-fig. 20. Interfingering between bodies of shales and sandstones interpreted as small flood plains in the midst of the braided river system of the Missão Velha Formation. Note the sharp contact between the Brejo Santo and Missão Velha formations

dance with previous work (e.g. Assine 1994; Freitas *et al*. 2008). However, this observation is valid only for the lower part of the Missão Velha Formation. In the upper portion, it was demonstrated here that the paleocurrent pattern, as well as the sedimentary filling, change towards the W, S and SW (Text-fig. 21). This pattern of paleocurrent data in relation to the position of the Missão Velha Formation was also found by Fambrini *et al*. (2011b), Küchle *et al*. (2011) and Scherer *et al*. (2014).

The conjugate analysis of lithofacies, architectural elements, paleocurrent data and depositional systems has provided the development of a stratigraphic framework for the sedimentary package of the Missão Velha Formation. In this understanding, the unit features an internal erosional unconformity separating it into two fluvial sequences: sequence 1 and sequence 2. Sequence 1 (S1) show a predominance of medium to fine sandstones and fines (lithofacies St, Sh, Sm, Fh, Fm), while in Sequence 2 (S2) coarse to very coarse sandstones predominate, sometimes conglomeratic, with subordinate conglomerates, and with abundant silicified fossil trunks and woods. Sequence 1 regionally comprises also the muddy rocks of the Brejo Santo Formation (lacustrine system). In this sequence some aeolian sediments also occur, normally as river bars reworked by wind in prolonged drought periods.

Sequences 1 and 2 are separated by an unconformity, traceable throughout the study area, showing a period of stratigraphic base-level fall. This surface marks a change in depositional style, from the fluviatile-aeolian-lacustrine system of Sequence 1, to the eminently fluvial sedimentation of Sequence 2. This change in depositional style is accompanied by an increase in grain size and by a change in direction of the paleocurrent pattern of fluvial systems (southeast in Sequence 1, and southeast, southwest and northwest in Sequence 2), suggesting a restructuring in the drainage system, probably associated with tectonic



Text-fig. 21. Composite log of the Olho D'água do Comprido and Grota Funda outcrops, the type section of the Missão Velha Formation. Shown are the lithofacies types, paleocurrent measurements per each stratigraphic level, sedimentary structures and erosive unconformity that separates sequences S1 and S2 movements in the basin. In addition to the restructuring of the drainage basin, a change has occurred in the characteristics of the fluvial system, towards a discharge associated with probably more humid climatic conditions. The fluvial deposition of Sequence 1 is associated with ephemeral systems, while the architecture of the fluvial facies of Sequence 2 (macroforms, domain of lower flow regime bedforms) indicates a perennial braided fluvial system, albeit with variations in the sedimentary discharge.

Sequence 1 represents sedimentation formed by a lacustrine system with a fluvial contribution (Brejo Santo Formation), an ephemeral fluvial system with wind reworking and a perennial braided fluvial system (the latter related to the Missão Velha Formation).

In Sequence 1 (basal portion of the Missão Velha Formation) the paleocurrent measurements have a consistent dispersion pattern to SE and S, and subordinately, towards the SW, suggesting a lower dispersion than would be normal for a river system. The measurements indicate source areas located towards the NW, N and NE, i.e., the northern Araripe Basin along the Patos Shear Zone, where the strong-relief lands of Borborema Province lie, due to the action of shear zone faults (Arai 2006). In Sequence 2 the paleocurrent dispersion pattern suggests there were many source areas for the sediments in the Rift Climax Stage. This is a typical situation for a tectonic rift system.

The sedimentary accumulation of Sequence 2 is associated with a new rise of the base level of the basin. This succession is characterized by a wide alluvial plain, with braided belt channels which, according to paleocurrent data, flowed to SW, W and NW directions from structural highs located E and SE. Sequence 2 has no variations in the depositional architecture of its fluvial system, indicating the maintenance of the rates of creation of accommodation space throughout the stratigraphic interval (Miall 1996). The dominance of the sandy bodies of the fluvial channel belts in comparison to the thin strata of the floodplain is evidence for the situation of the low creation rate of accommodation space. According to different authors (e.g. Schanley and McCabe 1994; Richard 1996; Miall 1996) in the contexts of low creation rate of accommodation space, the vertical accumulation of deposits of the floodplain is small, forming thin packages that are constantly reworked due to lateral displacement of channel belts. This depositional dynamic results in a stratigraphic architecture characterized by sheet amalgamated sandstone bodies, multiepisodic and multilateral, while the preservation potential of the fine deposits of the floodplain is quite rare.

The internal unconformity of the Missão Velha Formation is related to the short time interval of compressional style tectonics, which acted to organize fluvial successions over lacustrine successions in sequences 1 and 2. This tectonic and stratigraphic pattern is most evident in Sequence 2. In the sequential model of Prosser (1993) this phase was defined as the initial stage of rift sequences (Rift Initiation phase) in which there is little accommodation space for sediments, favoring the installation of river systems. In the sequential stratigraphic model of Martins-Neto and Catuneanu (2010) the installation of river systems begins at the end of the lacustrine sequence (overfilled phase), where in a similar manner to Prosser (1993), the sedimentation rate exceeds the rate of generation of accommodation space of sediments. Flooding surfaces are eminently related to the extensional tectonic style, with a large time span, which generated accumulation and accommodation space for sediments and, consequently, formed recurrent lacustrine systems. For this phase Prosser (1993) assigned the term Rift Climax. In the model of Martins-Neto and Catuneanu (2010) these authors put the sequence boundary directly in this horizon, and again analogous to Prosser (1993), they relate the installation of lacustrine systems (underfilled phase) to a rate of generation of accommodation space of sediments greater than sedimentation rates.

At last, the changes in sediment supply, paleocurrent patterns and stratigraphic package of the stratigraphic interval of the Missão Velha Formation are linked to the great transformations provided by the breakup of the Gondwanaland Supercontinent in the Jurassic–Cretaceous and the origin and opening of the South Atlantic, as pointed out previously by Da Rosa and Garcia (2000). These changes were the initial stages of the tectonic rupture inside the Borborema Province that causes the development of a narrow, long and shallow basin named the African-Brazilian Depression (ABD) (Asmus and Ponte 1973; Ponte and Ponte Filho 1996b; Da Rosa and Garcia 2000; Fambrini *et al.* 2011; Küchle *et al.* 2011), well exposed in Sequence 1 which includes also the Brejo Santo Formation. Part of the sequence composed of units ABD is just the lower portion of the Missão Velha Formation, and other correlative units, such as the Serraria Formation in the Sergipe-Alagoas Basin (Garcia and Wilbert 1994; Da Rosa and Garcia 2000; Küchle *et al.* 2011) and the Sergi Formation in the Recôncavo-Tucano-Jatobá basins (Magnavita *et al.* 1994, 2012; Scherer *et al.* 2007; Assine 2007; Küchle *et al.* 2011; Scherer *et al.* 2014). Sequence 1 marks the initial stages of the rifting of the South Atlantic.

CONCLUSIONS

The Missão Velha Formation comprises various facies of sandy rocks of great lateral continuity, amalgamated, or interfingering with some thin shale strata, bearing abundant silicified fossil trunks and wood, many in position parallel to the stratification of sandstone. As discussed above, the Missão Velha Formation possesses an important intraformational unconformity, probably created between the Rift Initiation to the Early Rift Climax stages of the development of the Araripe Basin. Fifteen main fluvial and aeolian lithofacies have been recognized. The main facies recognized can be summarized as: (i) coarse-grained arkosic conglomeratic sandstones, locally pebbly conglomerates, with abundant silicified fossil trunks, organized in fining-upward cycles and with several large-to-medium trough cross-stratifications and predominantly lenticular geometry; (ii) lenticular coarse-to-medium arkosic sandstones with some granules, locally pebbly conglomerates, with abundant silicified fossil wood and trunks, arranged in fining-upward cycles; the main sedimentary structures are large-to-medium trough cross-stratifications, cut-and fill and mud drapes on the foresets of cross-strata, (iii) poorly sorted medium-grained sandstones with sparse pebbles and with horizontal stratification, (iv) fine to very fine silty sandstone, stratified and laminated, interlayered with (v) decimetric pelithic layers with horizontal stratification and climbing-ripple cross-lamination. The paleocurrent measurements show a dispersion pattern to S, SE and SW. The facies described here were interpreted as being generated by alluvial systems represented by (i) a high energy perennial braided river system and (ii) ephemeral river systems indicated by the presence of floodplain deposits (claystones and other fine deposits) and wind reworking. Aeolian sand dunes and sand sheets generated by the reworking of the alluvial deposits may also occur. This study demonstrates the presence of an intraformational unconformity within the Missão Velha Formation where trough and planar cross-stratified pebbly-conglomerates lie directly with erosional contact on medium to fine stratified sandstones. These conglomerates pass laterally and vertically into amalgamated coarse to conglomeratic sandstones with medium scale trough and planar cross stratification, and contain abundant silicified fossil wood and trunks of a coniferous genus up to 1.50 m long at the top of the Missão Velha Formation. Paleocurrent data show a broad and wide dispersion pattern. These data indicate that Missão Velha Formation contains an important unconformity interpreted as the start of the Rift Climax stage.

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