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Distinct styles of fluvial deposition in a Cambrian rift basin

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ABSTRACT

Process-based and facies models to account for the origin of pre-vegetation (i.e. pre-Silurian) preserved fluvial sedimentary architectures remain poorly defined in terms of their ability to account for the nature of the fluvial conditions required to accumulate and preserve architectural elements in the absence of the stabilizing influence of vegetation. In pre-vegetation fluvial successions, the repeated reworking of bars and minor channels that resulted in the generation and preservation of broad, tabular, stacked sandstone-sheets has been previously regarded as the dominant sedimentary mechanism. This situation is closely analogous to modern-day poorly vegetated systems developed in arid climatic settings. However, this study demonstrates the widespread presence of substantially more complex stratigraphic architectures. The Guarda Velha Formation of Southern Brazil is a >500 m-thick synrift fluvial succession of Cambrian age that records the deposits and sedimentary architecture of three distinct fluvial successions: (i) an early rift-stage system characterized by coarse-grained channel elements indicative of a distributive pattern with flow transverse to the basin axis; and two coeval systems from the early- to climax-rift stages that represent (ii) an axially directed, trunk fluvial system characterized by large-scale amalgamated sandy braid-bar elements, and (iii) a distributive fluvial system characterized by multi-storey, sandy braided-channel elements that flowed transverse to the basin axis. Integration of facies and architectural-element analysis with regional stratigraphic basin analysis, palaeocurrent and pebble-provenance analysis demonstrates the mechanisms responsible for preserving the varied range of fluvial architectures present in this pre-vegetation, rift-basin setting. Identified major controls that influenced pre-vegetation fluvial sedimentary style include: (i) spatial and temporal variation in discharge regime; (ii) the varying sedimentological characteristics of distinct catchment areas; (iii) the role of tectonic basin configuration and its direct role in influencing palaeoflow direction and fluvial style, whereby both the axial and transverse fluvial systems undertook a distinctive response to syn-depositional movement on basin-bounding faults. Detailed architectural analyses of these deposits reveal significant variations in geometry, with characteristics considerably more complex than that of simple, laterally extensive, stacked sandstone-sheets predicted by most existing depositional models for pre-vegetation fluvial systems. These results suggest that the sheet-braided style actually encompasses a varied number of different pre-vegetation fluvial styles. Moreover, this study demonstrates that contemporaneous axial and transverse fluvial systems with distinctive architectural expressions can be preserved in the same overall tectonic and climatic setting.

Keywords Axial fluvial systems, pre-vegetation, Camaquã Basin, Cambrian, depositional architecture, distributive fluvial systems, pre-vegetation, rift basin.

INTRODUCTION

The interpretation of fluvial successions preserved in the rock record typically relies on the analysis of depositional features that are not necessarily diagnostic of any specific depositional setting and the reconstruction of fluvial system type from preserved successions is therefore typically not straightforward. The concept of a continental rock record that is dominated by the preserved deposits of distributive fluvial systems has gained favour in recent years based largely on studies that rely on remotely sensed imagery from modern-day depositional systems (e.g. Hartley *et al.*, 2010a, b; Weissmann *et al.*, 2010), although also supported by detailed studies of ancient fluvial successions (e.g. Nichols & Fisher, 2007; Fisher *et al.*, 2008; Cain & Mountney, 2009, 2011). Considerable discussion exists in the published literature regarding the mechanisms by which predominant fluvial styles may become preferentially preserved in the rock record (Sambrook Smith *et al.*, 2010; Fielding *et al.*, 2012). However, to date little work has been undertaken to apply these concepts to pre-vegetation alluvial systems. This study describes the sedimentology and stratigraphic evolution of a Cambrian fluvial succession that was oriented transverse to the axis of an evolving rift basin; further, this study considers the style of interaction of this transverse system with a contemporaneously active, axially directed fluvial system. The two preserved fluvial successions have markedly different sedimentological expressions, despite both having developed under the influence of the same set of basin controls and experiencing similar climatic regimes.

Many pre-vegetation fluvial successions are characterized by preserved sedimentary expressions that mimic those of present-day systems developed under the influence of arid or semi-arid climatic regimes (Long, 2006). Two main depositional styles are common in pre-vegetation fluvial successions: braided fluvial architectures with compound-bar elements and fluvial architectures dominated by bedload-sheet elements. These two contrasting sedimentary styles are commonly considered to have arisen as a consequence of fluvial system development under the influence of different climatic settings, reflecting perennial and ephemeral flow, respectively (e.g. Eriksson *et al.*, 1998, 2006; Tirsgaard & Øxnevad, 1998). Existing facies models for such pre-vegetation fluvial systems (e.g. Cotter, 1978; Long, 1978, 2006, 2011; Eriksson *et al.*, 1998, 2006; Sønderholm & Tirsgaard, 1998; Tirsgaard & Øxnevad, 1998) are not necessarily effective as tools with which to account for observed palaeoenvironmental characteristics because they do not provide a generically applicable methodology with which to account for climatic signatures.

This study describes a >500 m-thick fluvial succession deposited in a continental rift-basin of Cambrian age in Southern Brazil. The research was conducted through the integration of high-resolution depositional facies and architectural-element analysis, in combination with pebble-provenance and palaeocurrent analysis, and supported by the erection of a regional tectono-stratigraphic framework. Specific objectives are as follows: (i) to study different architectural elements and their association with various types of primary fluvial forms, including channels, bars, dunes and sheets; (ii) to investigate the relations between preserved fluvial architecture, sediment provenance and palaeogeographic location within an evolving rift basin; (iii) to examine the relative roles played by autogenic and allogenic controls; (iv) to characterize depositional styles and fluvial palaeoenvironments in a pre-vegetation, synrift alluvial-plain succession; (v) to propose models with which to explain how fluvial styles can be preserved for pre-vegetation systems; and (vi) to provide a predictive facies model with which to better understand pre-Silurian (i.e. pre-vegetation) systems.

This work is significant for the following reasons: (i) it provides a specific case-study for the interpretation of depositional architecture from a pre-vegetation fluvial succession; (ii) it identifies how local environmental factors act to control the preserved architecture of such systems; (iii) it demonstrates the style of interplay between contemporaneously active axial and transverse fluvial systems; (iv) it outlines a method by which an improved understanding of the particular characteristics of such systems can be better understood.

PRE-VEGETATION FLUVIAL SYSTEMS

The absence of land plants prior to the Silurian resulted in the development of distinctive types of fluvial environments, many of which were apparently characterized by poorly stabilized channel banks and floodplains. The absence of land plants in these systems meant that rates of both chemical weathering and production of mud and soil were low, meaning that palaeosols in such successions are typically only poorly developed (Retallack, 1985; Davies & Gibling, 2010). High rates of sediment yield due to high run-off rates (Schumm, 1968) and great discharge variation occurred as a consequence of the absence of the dampening effects of vegetation cover and tended to result in bypass of fine-grained deposits to distal areas of many pre-vegetation fluvial systems (Long, 1978; Winston, 1978; Eriksson *et al.*, 1998). The absence of vegetation cover also facilitated enhanced rates of aeolian deflation (winnowing) of fine-grained sediment fractions (Fuller, 1985). Relatively rapid rates of rise to peak discharge, coupled with the presence of unstable, non-cohesive channel margins and banks tended to result in channel widening (Wolman & Brush, 1961), resulting in the preservation of channel elements with high width-to-depth ratios (Fuller, 1985). Non-vegetated river-banks would have encouraged enhanced rates of channel avulsion through rapid erosion of sandy fluvial surfaces, resulting in high rates of sediment delivery and consequent channel aggradation, a common feature of many post-vegetation dryland fluvial successions (e.g. Cain & Mountney, 2009, 2011). Moreover, as pre-vegetation fluvial channels were able to widen readily in response to increases in fluvial discharges (Wolman & Brush, 1961), rivers would have been prone to seasonal, local avulsion events within a broad belt, leaving other parts temporarily abandoned. Overall, the absence of land plants prior to the Silurian is considered to have resulted in the preservation of fluvial successions with distinctive sedimentary signatures of facies associations and depositional architectures, which in many ways resemble those of modern dryland river systems (Long, 2004).

In Neoarchean–Palaeoproterozoic cratons, fluvial braided-channel successions were more common than at present and large-scale braided perennial systems were the dominant fluvial style (Eriksson *et al.*, 2006). In basin fills of Upper Proterozoic age, occurrences of preserved architectural elements indicative of downstream accretion and the downstream migration and accumulation of trains of dune complexes, together with the preservation of well-defined channel forms in sand-prone successions, with the local occurrence of floodplains and abandoned channels, were recorded by Hjellbakk (1997). The only rare occurrence of mud-prone facies in pre-vegetation fluvial deposits is typically considered to be related to the vulnerability of non-vegetated floodplain deposits to reworking in the aftermath of channel avulsion and rapid channel migration, combined with low rates of chemical weathering that inhibited the production of clays (Long, 1978). However, Winston (1978) proposed models for the occurrence of laterally extensive, distal alluvial plains for the argillaceous rocks of the Belt Supergroup (Middle Proterozoic), which accumulated as terminal splays flowing in a basinward direction.

The significance of the role of different climatic conditions in dictating the style of preservation of pre-vegetation fluvial deposits remains an unsolved question discussed by many authors (e.g. Tirsgaard & Øxnevad, 1998; Eriksson *et al.*, 2006; Long, 2006). Pre-vegetation river systems were subject to high discharge variation, even under wet climates, and consequent significant fluctuations in run-off probably served to prevent the development of meandering fluvial channel systems because the predominance of bed-load and the non-stabilized nature of the channel banks resulted in near-constant sediment reworking as flow conditions changed repeatedly, thereby inhibiting the development of large, laterally accreting point bars. The presence of conditions considered favourable for the development of meandering channels in present-day fluvial systems, such as low gradients and only modest fluctuations in precipitation, were apparently not sufficient for pre-Silurian channels to commonly adopt such planform patterns and behaviour (Sønderholm & Tirsgaard, 1998). Despite bearing a superficial resemblance to modern-day dryland systems, Long (2006) interpreted deep-channel, perennial to semi-perennial braided systems developed under wet climatic conditions, recognizing similarities with modern-day perennial braided systems. Noting that pre-vegetation fluvial systems were relatively more sensitive to climate changes due to high run-off rates, Tirsgaard & Øxnevad (1998) identified three different fluvial styles in a 30 m-thick succession of sand-sheet deposits, each of which was considered to reflect different climatic settings; these authors interpreted preserved aeolian sets within fluvial sequences as indicative of high water table, and used it as an indicator of a wet climatic setting.

Cotter (1978) introduced the term sheet-braided (genetic units width-to-depth ratios of more than 20:1) to describe the sedimentary architecture of pre-vegetation fluvial deposits, and concluded that this style was dominant in such successions, whereas channel-braided and meandering styles became common only from the Devonian onwards. The increasing occurrence of meandering styles in post-Silurian fluvial successions has previously been considered to be directly related to the evolution of land plants (Cotter, 1978), as recorded by the progressive increase in the abundance of the lateral-accretion macroforms and thick mud-prone floodplain deposits with well-developed palaeosols, as well as well-organized, high-sinuosity channels (Davies & Gibling, 2010).

Sedimentary signatures that can demonstrably be shown to be an indicative of the occurrence of meandering fluvial architectures in pre-Silurian rocks, although recognized, are few in number and are not yet well-understood, with some lateral-accretion macroforms interpreted from pre-vegetation fluvial systems apparently related to braid-bar development (Long, 2006). Casshyap (1968), Morey (1974) and Sweet (1988) have interpreted meandering channel forms for some pre-vegetation successions, and Nußbaumer (2009) described meandering channels and point bars on Mars.

Resolution of the relative roles of both allogenic and autogenic controls in dictating fluvial style in pre-vegetation systems can only be achieved through highly detailed outcrop studies involving the mapping of the relative inclination and directional variability of foresets and higher-order bounding surfaces (Long, 2011). Only by undertaking such detailed studies can comparisons between fluvial processes in post-vegetation and pre-vegetation successions be undertaken reliably, such that distinctions can be made between the specific processes that dominated alluvial processes prior to the Silurian. This methodology is here combined with regional palaeocurrent mapping and provenance data analysis in order to understand the interplay of two distinct, coeval fluvial systems developed in the same rift basin. The comparison between the distinct fluvial architectures preserved in the same climatic and basinal settings allows the identification of other controls on the variability of pre-vegetation fluvial styles.

GEOLOGICAL SETTING

At the end of the Ediacaran, after the complete cessation of the main orogenic events related to the Neoproterozoic assembly of West Gondwana, a large system of rift-basins formed in eastern South America, from southern Uruguay to south-eastern Brazil (Fragoso-Cesar, 2008; Almeida *et al.*, 2010). The Camaquã Basin is the main preserved basin of the system, preserving a >10 000 m-thick succession of siliciclastic and volcanogenic deposits of Ediacaran to Cambrian age (Fragoso-Cesar *et al.*, 2003; Janikian *et al.*, 2008; Almeida *et al.*, 2012a). Its deposits are controlled structurally by NNE trends (Almeida *et al.*, 2012b) and located on a *ca* 50 km-wide and >150 km long basin (Almeida *et al.*, 2009). The Guaritas Group (Fig. 1) overlies in angular unconformity a >10 km-thick sedimentary and volcanic succession of Ediacaran age (Janikian *et al.*, 2008). The Rodeio Velho Intrusive Suite presents many syn-sedimentary intrusive features, such as shallow sills and dykes that caused fluidization (i.e. soft-sediment deformation) of the host sediments of the Guaritas Group: the crystallization age of this intrusive suite is thus considered to have occurred penecontemporaneously with the sedimentation of the Guaritas Group. Ar–Ar whole-rock dating revealed a 535·2 ± 1·1 Ma age (Almeida, 2005), whereas U–Pb zircon dating revealed a 547 ± 6·3 Ma age for the Rodeio Velho Suite (Almeida *et al.*, 2012a). Several previous works have discussed distinct aspects of the sedimentation of this group, including Ribeiro & Lichtenberg (1978), Fragoso-Cesar (1991), Paim (1995), Paim *et al.* (2000), Paim & Scherer (2003), Scherer *et al.* (2003), Marconato *et al.* (2009) and Santos *et al.* (2012). Geological mapping and correlation between stratigraphic sections led Almeida *et al.* (2009) to confirm previous interpretations (Fragoso-Cesar *et al.*, 1984, 2000; Paim, 1995; Paim *et al.*, 2000; Paim & Scherer, 2007) that the Guaritas Group accumulated as the remnant fill of a rift basin that was characterized by a variety of depositional environments preserved in a >1500 m-thick succession.

The Guarda Velha Formation is the basal unit of the Guaritas Group, preserving a >500 m succession of fluvial strata; the lowermost succession of the Guarda Velha Formation is restricted to fills of localized depressions directly above the basal unconformity and is markedly coarser grained than the overlying deposits, being characterized by conglomerate bars forming assemblages of strata that apparently accumulated in unconnected depocentres during the rift-initiation stage (Almeida *et al.*, 2009). Paim (1994, 1995) highlighted two major sub-environments

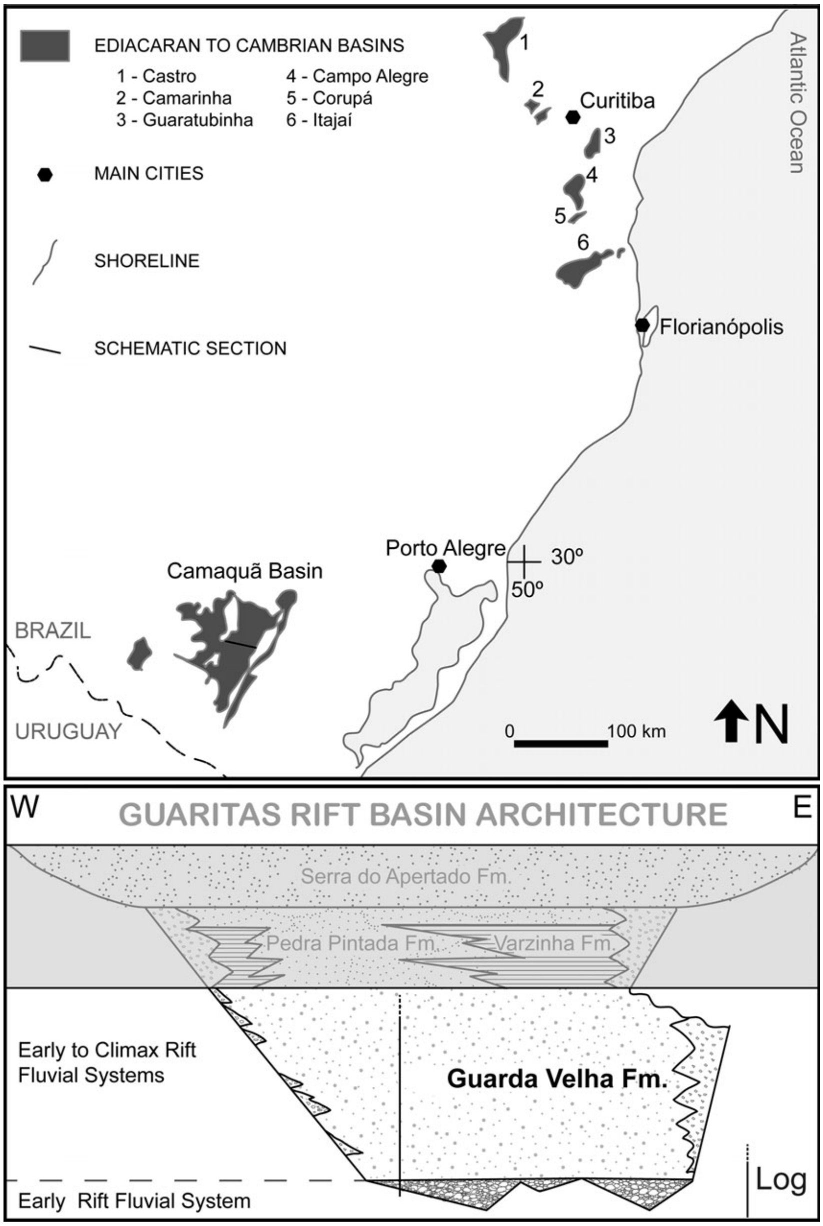


Fig. 1. Regional map with the Ediacaran to Cambrian basins in southern Brazil (simplified from Almeida *et al.*, 2010) and schematic cross-section of the Guaritas Group (youngest unit of the Camaquã basin) basin architecture (below, simplified from Almeida *et al.*, 2009). The log presented in the lower figure indicates the location of the >500 m long core described further on this work.

(Fig. 2) for the alluvial succession of the Guaritas depositional sequence (equivalent to the Varzinha Alloformation of Paim *et al.*, 2000): alluvial fan sub-environments recording palaeocurrents aligned perpendicular to the basin-bordering trends (eastern border alluvial fan deposits and western border alluvial fan deposits), and a trunk braided river sub-environment recording palaeocurrents aligned parallel to the basin axis (western border trunk river deposits). The alluvial fan systems were interpreted as having formed tributary systems to the main axial trunk system. For the alluvial fan sub-environment from the eastern part of the basin, Paim (1995) described a basinward grain-size decrease and high palaeocurrent-vector dispersion, characterizing two distinct fan lobes. Through analysis of palaeocurrent and pebble provenance data, Almeida *et al.* (2009) suggested that an axial fluvial system (the trunk river system of Paim, 1995) was fed by a broad catchment area north of the basin, which acted as the source area for a great volume of arenaceous sediment but only a modest supply of fine-grained, argillaceous sediment. The presence of multiple alluvial fan-lobe deposits that apparently originated at both basin borders and that are characterized by (i) a basinward grain-size decrease from NNE-striking

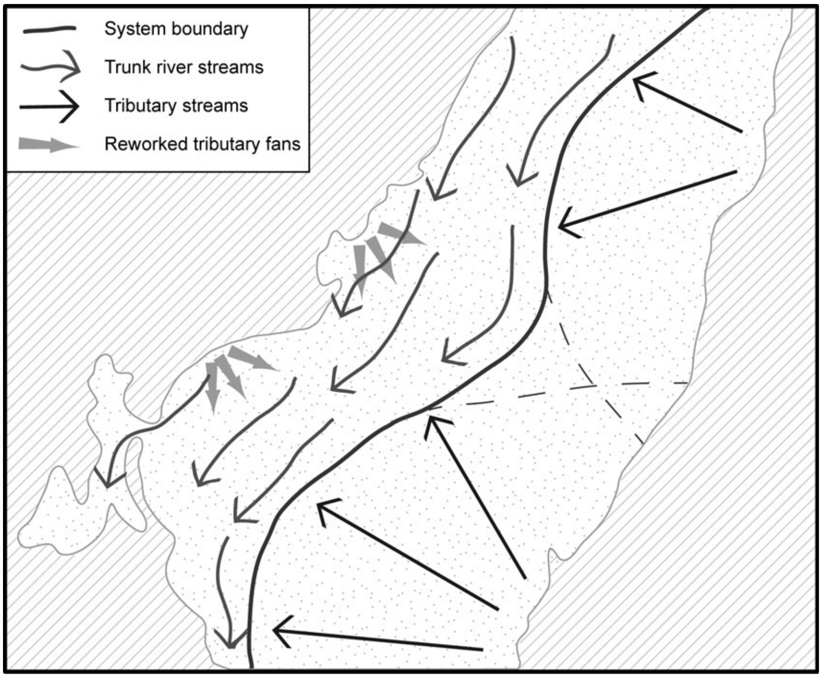


Fig. 2. Palaeogeographic reconstruction of the alluvial facies of the Guaritas Group (simplified from Paim, 1995) showing the two major dispersal trends of palaeocurrent: contributary streams showing main sedimentary transport to the west and trunk river streams showing main transport to the south. Reworked alluvial fans are present to the west of these deposits.

regional faults (Paim, 1995); and (ii) preserved vertical successions that are each several hundred metres thick, has been interpreted previously to indicate the syn-sedimentary development of an escarpment at the basin margins (Almeida *et al.*, 2009), which probably acted as a local sediment source. Alluvial-fan deposits on the western border are preserved in isolated occurrences (Paim, 1995) which are characterized by debris-flow related breccias and conglomerates composed of sub-angular pebbles and cobbles (Almeida *et al.*, 2009); these fans were intensely reworked by the trunk river system (Paim, 1995). Evidence of syn-sedimentary tectonic activity in the western basin margin is also recorded by rhythmically repeated occurrences of seismically induced liquidization features throughout the vertical profile of the western deposits of the Guarda Velha Formation (Santos *et al.*, 2012). The presence of these well-defined syn-sedimentary faults defines a tract of laterally equivalent units ascribed to the mid- to late-rift climax episodes by Almeida *et al.* (2009).

METHODOLOGY

An integrated study was conducted through regional stratigraphic mapping, provenance and palaeocurrent analyses, in combination with high-resolution outcrop logging and mapping to describe the spatial and temporal evolution of a distinctive succession of preserved fluvial deposits that accumulated in a range of sub-environments in a pre-vegetation alluvial plain rift-basin setting. Depositional architectures have been interpreted based on an analysis of lithofacies and their association with one another to classify architectural elements according to their external and internal geometry and orientation, together with analysis of palaeocurrent data and interpretation of the sedimentary significance of different types of bounding surfaces. A series of two-dimensional measured architectural and photographic panels have been used to characterize depositional architectures from cliff faces aligned in a variety of orientations. These panels form the basis for reconstruction and interpretation of the three-dimensional geometry of fluvial elements. Detailed palaeocurrent and lithofacies data were located on panels representing studied sections, and this involved the measurement of depositional surfaces (for example, foresets and trough forms exposed on well-exposed bedding surfaces), parting lineation, clast imbrication and erosional bounding surfaces (for example, channel margins) in order to determine the relation between various types of fluvial elements and primary bedding. Sediment provenance investigation was undertaken to identify likely sediment-source areas and to establish regional palaeoflow trends of the fluvial systems within the basin. This was achieved via a combined analysis of 17 spatially distributed locations where pebble type was examined to establish provenance; 599 palaeocurrent measurements were made and 139 depositional bounding surfaces were recorded. At each site examined for provenance, at least 300 pebbles were examined, recording lithology, roundness, and the orientation and lengths of the two principal axes, with a total of 5440 pebbles examined across all 17 sites. Statistical analysis was undertaken to account for the variance found in the data set, enabling a correlation between provenance data and depositional system type to be made. Potential source areas for the pebbly clastic detritus were identified based on comparisons between clast-lithology type in the fluvial deposits of the Guarda Velha Formation and known regional bedrock lithologies. Basin structural setting was determined by Almeida *et al.* (2012b); tectonic tilting is minimal (regional tilt <5º). The stratigraphic position of the studied deposits, as well as the location of the inferred source areas, was determined by (i) regional field mapping supported by information available in previously published papers; and (ii) by additional mapping based on remote sensing. Results were integrated to generate a series of palaeogeographic reconstructions (models), both in three-dimensions (two spatial dimensions plus time) and four-dimensions (three spatial dimensions plus time).

THE GUARDA VELHA FORMATION

The Guarda Velha Formation comprises a >500 m-thick succession of feldspathic-arenite (arkosic) composition preserving mainly coarse-grained sandstone and conglomerate, with minor occurrences of finer-grained sandstone, siltstone and mudstone. Predominant primary structures include trough and planar cross-stratification, horizontal to low-angle-inclined stratification, and localized occurrences of ripple forms on bedding surfaces. Three distinct assemblages of fluvial deposits of the Guarda Velha Formation have been identified and studied through analysis of depositional architecture, facies associations, palaeocurrents and pebble provenance analysis: (i) a basal conglomerate succession that unconformably overlies rocks of the Santa Bárbara Group, and which crops out in isolated areas of the basin (early-to-climax rift stage deposits); (ii) a conglomeratic sandstone succession that overlies the basal conglomerate and crops out in the eastern part of the study area (early to climax rift-stage deposits); and (iii) a conglomeratic sandstone succession that also overlies the basal conglomerate but crops out in the western part of the study area (early-to-climax rift stage deposits). The characteristics of distinct lithofacies and architectural elements of the Guarda Velha Formation are presented in Tables 1 and 2, respectively. Palaeocurrent data (Figs 3 and 4) reveal two main dispersal patterns: one transverse to the basin axis (from both basin borders) and the other parallel to the basin axis (from north to south). Results of statistical analyses of pebble provenance data (Fig. 5) indicate three clusters of distinct clast types; main source areas are Precambrian igneous and metamorphic rocks of the basement located to the north and east of the basin, with a minor contribution from the west. Overall, the entire succession records a general fining-upward trend and this is summarized in a graphic sedimentary log from a core (CPRM-CQP-01) that records 518 m of stratigraphy from the study interval of the Guarda Velha Formation (Fig. 6).

The examined fluvial deposits have been classified and interpreted to represent three distinct fluvial system types, based on the occurrence of distinct styles of depositional architecture, facies associations, palaeocurrents and pebble provenance. The three identified fluvial systems include one from the basalmost part of the succession (early rift-stage deposits) and two from the uppermost and thicker part of the succession (early-to-climax rift stage deposits) that represent a transverse and an axial system, each characterized by distinct palaeocurrent trends, source areas and depositional architecture.

Early-Rift Fluvial System

Description

The lowermost strata of the Guarda Velha Formation lie in angular unconformity over the Santa Bárbara Group and are characterized by a distinctive coarse-grained succession (Table 1). The basement is characterized by folded and faulted, older sedimentary rocks from the Camaquã Basin (Almeida *et al.*, 2012b). A vertical log representing the typical facies assemblages of this system is presented in Fig. 7A. This lower part of the succession is characterized by crudely stratified conglomerates, typically of rounded, imbricated pebbles to boulders of polymictic composition (Fig. 8A), alternating with sets of medium-grained sandstone with

Table 1. Summary lithofacies description and interpretation for the Guarda Velha Formation.

Facies association	Facies	Description	Interpretation
Early-rift fluvial system	F1 – Stratified conglomerates	Imbricated, clast-supported, incipiently low-angle cross-stratified conglomerates, typically in 0·8 to 2·0 m thick and 10 to 20 m wide sets. Basal contacts are usually erosional, while the upper ones may be erosional or gradational to F2. Grain sizes vary from granules to boulders, typically rounded and presenting polymictic composition	Gravel bars in braided streams
	F2 – Planar-stratified sandstones	Medium-grained sandstones with plane-parallel to low-angle cross-stratification commonly presenting parting lineation. Sets are commonly 10 cm to 1·5 m thick and more than 20 m wide	Deposits generated during the last stages of flood events, as planar beds or low relief sand waves (e.g. Best & Bridge, 1992) under supercritical flow or near to critical velocity
	F3 – Channelized pebbly sandstones	Medium to pebbly-trough cross-stratified sandstones presenting multi-storey channel bodies in several scales. Trough cross-strata range from 0·3 to 1·0 m thick. Pebbles are sparse or concentrated on the foreset	Channelized stream-flow under lower-stage flow regime. Three-dimensional dune migration
Axial fluvial system	F2 – Planar-stratified sandstones	Medium-grained sandstones with plane-parallel to low-angle cross-stratification commonly presenting parting lineation. Sets are commonly 10 to 60 cm thick and more than 5 m wide	Deposits generated during the last stages of flood events, as planar beds or low relief sand waves under supercritical flow or near to critical velocity
	F3 – Channelized pebbly sandstones	Medium to pebbly-trough cross-stratified sandstones presenting multi-storey cut relations of many scales. Trough cross-strata range from 0·3 to 1·0 m thick, pebbles are sparse or concentrated on the foreset	Channelized stream-flow under lower flow regime. Three-dimensional dune migration
	F4 – Planar cross-stratified sandstones	Pebbly sandstones presenting planar cross-stratification of low to medium angle sets are 0·3 to 1·5 m thick and 5 to 20 m wide. Intraformational mud clasts are often found. Sets commonly pinch-out both up and down current direction	Accretion bar increment during maximum flood events. Related to elements DA and LA
Transverse fluvial system	F2 – Planar-stratified sandstones	Medium grained sandstones with plane-parallel to low-angle cross-stratification commonly presenting parting lineation. Sets are commonly 10 to 60 cm thick and more than 5 m wide	Deposits generated during the last stages of flood events, as planar beds or low relief sand waves under supercritical flow or near to critical velocity
	F3 – Channelized pebbly sandstones	Medium to pebbly trough cross-stratified sandstones presenting multi-storey cut relations of many scales. Trough cross-strata range from 0·3 to 1·0 m thick, pebbles are sparse or concentrated on the foreset	Channelized stream-flow under lower flow regime. Three-dimensional dune migration

(continued)

Table. 1 (continued)

Facies association	Facies	Description	Interpretation
	F4 – Planar cross-stratified sandstones	Pebbly sandstones presenting planar cross-stratification of low to medium-angle-inclined, sets are 0·3 to 1·5 m thick and 5 to 20 m wide. Intra-formational mud clasts are often found. Sets commonly pinch out both up-current and down-current direction	Accretion bar increment during maximum flood events. Related to elements DA and LA
	F5 – Scour-filling trough cross-stratified pebbly sandstones	Trough cross-stratified, coarse to pebbly-sandstones commonly presenting intra-formational mud clasts of up to 15 cm. Infilling scours of 5 to 15 m wide and 0·3 to 1·2 m thick. Cross-stratification is usually concordant to the erosional base surface	Events of rapid deposition of poorly selected material transported by subcritical tractive currents after erosion peak discharge
	F6 – Cracked mudstones	Mudstone lenses presenting desiccation mud cracks on the upper limit. Thickness ranges from 0·15 to 0·60 m; widths are 15 to 20 m	Events of flow stagnation followed by decantation, sub-aerial exposure and desiccation. Erosive bodies of pebbly sandstones can occur infilling inter-crack spaces
	F7 – Fine-grained sandstones with climbing ripples	Centimetric layers of fine-grained to medium-grained sandstones presenting climbing-ripple cross-lamination. Always associated with facies F8	Loss of current velocity during waning stages of flood events under upper-flow regime
	F8 – Laminated mudstones	Lenses of greenish-grey to red-brown laminated mudstones, 0·05 to 0·90 m thick and 3 to 15 m wide. Commonly occur as mud drapes infilling abandoned channels. Occur also as small lateral floodplains associated with minor channels	Small ponds and floodplain deposits of decanted-fines
	F9 – Convolute medium to pebbly sandstones	Trough cross-stratified, plane-parallel laminated and planar low-angle cross-stratified sandstones presenting local or set-confined deformation. Grain size varies from medium to pebbly sandstones. Presents non-harmonic folding, overturned cross-strata and dewatering pipes	Soft-sediment deformation due to liquidization right after and/or during deposition. Flow shear deformation mechanism appears abundantly
	F10 – Sigmoidal-stratified sandstones	Medium-grained to coarse-grained sandstones presenting sigmoidal cross-bedding due to the preservation of the topset	Humpback dunes generated during periods of changing flow regime. Similar to those described by Fielding (2006)
	F11 – Coarse to pebbly sandstones with graded foresets	Coarse to pebbly-sandstones with normally graded foresets presenting centimetric planar to tangential cross-bedding. Sets are usually 20 to 30 cm thick	Formed by avalanching on the foresets of conglomeratic unit bars. Similar to those described by McConnico & Bassett (2007)

plane-parallel to low-angle-inclined cross-stratification – exposed bedding surfaces of which commonly preserve parting lineation (Fig. 8B) – and 0·2 to 0·9 m-thick lens-like bodies of low-angle-inclined, planar-stratified medium sandstone (Fig. 8A and B), and trough cross-bedded medium- to coarse-sandstone (Fig. 8C). No mudstone clasts or lenses are preserved in this part of the succession. Pebbles are imbricated with their long axes aligned transverse to the inferred direction of palaeoflow to the west.

The preserved depositional architecture of this system (Table 2) is dominated by gravel bedforms, which commonly alternate with laminated sand sheets and sandy bedforms (Fig. 9). Sandy bedforms occur nested within channel-like bodies, which are each 1 to 3 m thick and principally composed of trough cross-stratified, pebbly sandstone and conglomerate (Fig. 8C). These sandy bedforms typically grade laterally to laminated sand sheets characterized by plane-bedded sandstones with parting lineation. Crude cross-stratification is observed locally in conglomerate sets, examples of which are commonly overlain by lens-shaped sets of laminated, horizontally bedded, medium-grained to coarse-grained sandstone.

Analyses of the bounding surfaces of forms show a mean dip direction towards an azimuth of 215° ($n = 7$), whereas cross-strata preserve a mean flow direction to 274° ($n = 57$). Pebble imbrication data indicate a mean flow direction to 269° ($n = 51$), similar to the mean palaeocurrent direction obtained from cross-beds and to the trend of parting lineations (Fig. 8B). Provenance analysis reveals potential sediment sources of granitic and metamorphic composition to the east of the studied locations in an area related to the eastern margin of the basin, which is thought to have become uplifted during subsidence of the basin (Almeida *et al.*, 2009).

Interpretation

Conglomerate sets preserving crude cross-stratification that are truncated by lenses of flat bedded to low-angle-inclined cross-stratified conglomerate are interpreted, respectively, as bar and bar-top deposits, the latter recording waning-stage flow (Smith, 1990; Best & Bridge, 1992). Isolated lenses of trough cross-bedded sandstone are interpreted as 3D dune deposits in braided channels that developed at low-flow stage (Bristow, 1993). Provenance analysis reveals a polymictic composition, with sources to the east of the basin; this is supported by palaeocurrent analysis (mean vector of 268°). The coarse grain size of this system is indicative of a proximal position within the fluvial system in relation to the eastern border of the basin.

Overall, this fluvial system is interpreted to represent the deposits of an alluvial apron (bajada), representing the accumulation of clastic detritus in areas close to the eastern basin margin that accumulated in a depositional environment related to rift-initiation that was characterized by gravel-dominated braided fluvial systems, with shallow braided channels developed between large conglomerate bars. The source of this system is located to the east of the basin – as interpreted through palaeocurrent and provenance analysis – indicating that this system flowed transverse to the basin axis with a radial pattern of palaeocurrents (Figs 3 and 4). Collectively, these interpretations suggest that this system was a distributive fluvial system (a fluvial fan) that originated close to the eastern margin of the basin and which probably represents the fluvial-dominated part of alluvial fans that flowed from the eastern basin border in the direction of the main basin depocentre.

Early- to Climax-Rift Stage Fluvial Systems

The younger and thicker (>400 m) succession of the studied fluvial systems is characterized by sandstone and pebbly sandstone deposits with distinct facies associations (Table 1). Depositional architectural analysis (Table 2) reveals the occurrence of sandy bedform elements that alternate with elements of laminated sand sheets, fine-grained units (overbank deposits) and abandoned channels in the easternmost part of the study area, whereas larger scale fluvial forms of amalgamated bars, which are indicative of both lateral and downstream accretion, occur to the west. Provenance analysis (Fig. 5) reveals two major sediment sources, one related to basement rocks associated with the northern part of the basin and the other related to the eastern basin margin; this is supported by palaeocurrent analysis, which also reveals two preferential flow directions in the preserved fluvial successions of the upper part of the basin fill (Figs 3 and 4). This analysis has led to the recognition of two distinct, coeval fluvial successions: one fluvial succession crops out in the western part of the study region, and is indicative of a fluvial system that

Table 2. Summary description and interpretation of architectural elements of the Guarda Velha Formation.

Element	Lithotype	Geometry	Early-rift system	Axial system	Transverse system
Sandy bedforms	F3, F2, F9, F4	*Description*: Laterally continuous sheets and lenses presenting planar- to smoothly convex-bases, 0·6 to 1·8 m thick and 2 to 15+ m wide *Interpretation*: Deposits of small channels subaqueous dunes and low amplitude bars	X	X	X
Gravel bedforms	F1, F2, F3	*Description*: Tabular bodies with incipient stratification, 0·3 to 1·8 m thick and 4 to 15+ m wide *Interpretation*: Conglomerate bedform migration during peak flood discharge. Bar-top preservation indicates preservation of form	X		
Laminated sand sheets	F2	*Description*: Tabular sheets 0·6 to 2·1 m thick presenting planar, erosive basal surface *Interpretation*: Deposits of unconfined and low-depth flow of main flood waning stages	X	X	X
Downstream accretion	F2, F3, F4	*Description*: Lenses of 0·3 to 1·6 m thick and 5 to 15 m wide. May pinch out downstream. Basal surface dips on the same direction as the cross-sets but at much smaller angles. May be undulated *Interpretation*: Bar accretion during peak flood events		X	X
Scour fill	F5, F3	*Description*: 0·3 to 1·2 m thick and 0·4 to 2 m wide incised channels cutting erosively elements SB or FF *Interpretation*: Peak discharge floods deposits under subcritical flow		X	X
Abandoned scour	F8, F7, F3	*Description*: 0·15 to 0·7 m thick and 4 to 14 m wide channel-shaped lenses with erosional basal surface filled by mud drape *Interpretation*: Ephemeral channel filled by mud			X
Overbank fines	F8, F7	*Description*: 0·05 to 0·7 m-thick and 4 to 20 m-wide lenses with planar basal and upper surfaces *Interpretation*: Areas next to main channels flooded during peak discharge and posteriorly deactivated and eroded on top by superposed SB			X
Lateral accretion	F2, F3, F4	*Description*: Lenses of 0·6 to 1·6 m thick and 10 to >15 m wide. May pinch out downstream. Basal surface dips perpendicular to the cross-sets but at a smaller dip angle. May be undulated *Interpretation*: Bar accretion with lateral component during peak flood events		X	

flowed southward in an orientation parallel to the main basin axis (the Axial Fluvial System); the second fluvial succession crops out in the eastern part of the study region and is representative of a fluvial system that evolved from the early-rift fluvial system and that flowed in a transverse direction relative to the basin axis (the Transverse Fluvial System).

Axial Fluvial System

Description: This fluvial system is represented by deposits located in the western part of the study region, close to the main basin-bounding, syn-depositional fault. A typical vertical log of this system is presented in Fig. 7B. Main facies associations are presented in Table 1, and are characterized by medium- to pebbly-sandstone with trough (Fig. 10A) and planar cross-stratification (Fig. 10B), preserved as decimetre-scale sets bounded by low-angle-inclined, down-current-dipping surfaces, and associated with minor scour-filling bodies.

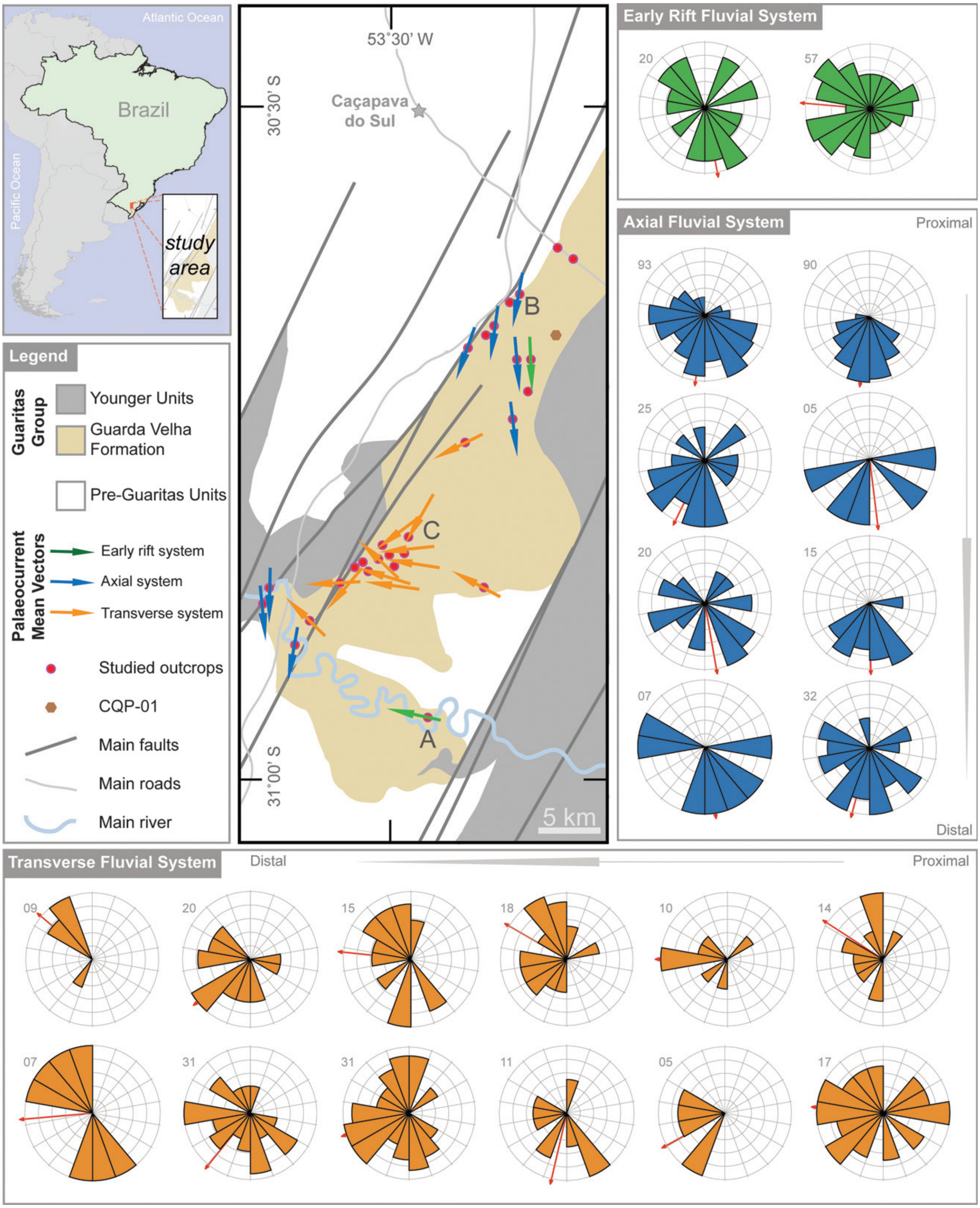
The preserved depositional architecture of this system (Table 2) is characterized by the alternation between laterally extensive, amalgamated bars indicative of both lateral and downstream accretion (Fig. 11), with minor occurrences of sandy bedforms and scour-fill forms. The outcrop depicted in Fig. 11A records evidence for upstream deposition on the upper part of a unit bar in the form of sets overlying preserved bar forms (cf. Reesink & Bridge, 2009). The outcrops depicted both in Fig. 11A and B show evidence of an upward transition from lateral to downstream accretion where the latter truncates the former. Figure. 11B reveals the stacking of elements indicative of both downstream accretion and lateral accretion, as indicated by the relation between the orientation of both foresets and bounding surfaces. Intraformational mud-clast occurrences are rare; no mudstone lenses or drapes are preserved. Scour-and-fill structures in Fig. 11 are rare and those that are present are laterally extensive for less than 4 m, occurring solely in the uppermost parts of the bar form elements. Localized occurrences of lobate diamictites presenting angular clasts of western provenance and palaeocurrents directed to the east inter-finger with these deposits and record the activity of debris-flow-dominated alluvial fans in the western part of the basin.

Figure 11A reveals a widely dispersed distribution of palaeocurrents with the mean vector direction of cross-strata towards 186° ($n = 93$). Set bounding surfaces indicate a mean vector direction of maximum dip towards 155° ($n = 80$). Provenance analysis of this system (Fig. 5) indicates a source area mainly to the north of the study region, with a secondary minor contribution from the eastern and western border-fault scarps. Regional palaeocurrent analysis reveals a southward-directed flow. Figure 11B reveals a consistent pattern of palaeocurrents, with evidence for modest lateral accretion of channels demonstrated by the orientation of cross-bedding foresets in relation to set-bounding surfaces. Preserved mean set thickness obtained from 46 non-scoured cross-bedded sandstone sets is 0·57 m. Figure 12 shows a laterally extensive fifth-order surface at the base of fluvial forms deposited over older sediments which were subject to considerable erosion prior to the deposition of these forms.

Interpretation: These deposits are interpreted to record an axial river system that flowed parallel to the main basin axis, in a NNE to SSW direction. The obtained preserved mean set thickness, coupled with the large horizontal-scale of cross-beds is indicative of deep flow and possibly large channels (Bridge, 2003). Evidence for rela-

Fig. 3. Location map (upper left) and present-day outlines of the Guaritas Group (centre), with the synthesis of palaeocurrent data and studied outcrops. Provenance data obtained in many of the studied outcrops are presented in Fig. 2. Points ‘A’ to ‘C’ show the location of the columnar sections presented in Fig. 7. Arrows represent the vector means of palaeocurrent data presented in the corresponding rose diagrams. Rose diagrams are organized from proximal to distal (see grey arrows) as follows: Axial Fluvial Systems (from top to bottom); Transverse Fluvial System (from right to left). Note the predominance of southward-trending palaeocurrents of the Axial Fluvial System (blue), and the predominance of a radial pattern of east-trending palaeocurrents of the Transverse Fluvial System (orange), as well of the Early-Rift Fluvial System (green). Rose diagram frequency is expressed in number per cent; red arrow in each rose diagram represents vector mean direction. Numbers at the top-left of each rose diagram indicate the number of measured readings. The Guaritas Group comprises the Guarda Velha Formation, and younger units (including the Rodeio Velho Suite). Older Units comprise unconformable underlying older groups from the Camaquã Basin (Santa Bárbara Group, Bom Jardim Group and Maricá Group) and its basement.

tively continuous deposition includes the absence of small-scale bedding and mudstone bodies (mud chips are rare), observations typical of relatively constant flow characteristics and indicative of a fluvial system that experienced perennial or at least semi-perennial (intermittent) flow (cf. Miall, 1996; Long, 2006). The accumulation of this large river system, with a markedly



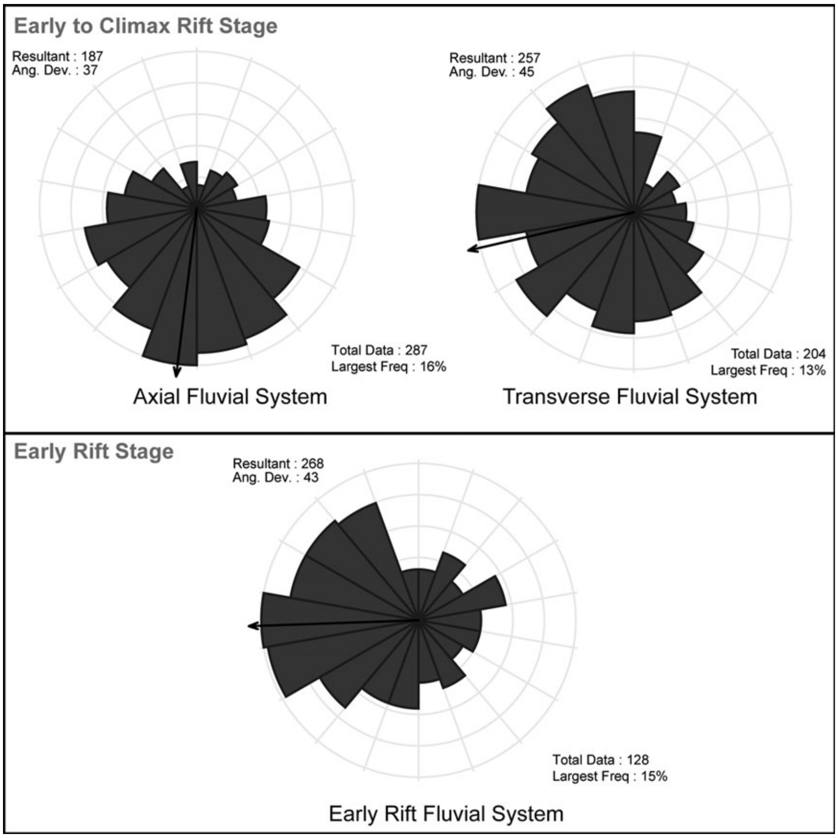


Fig. 4. Palaeocurrent data recorded by this study for the three studied fluvial systems: Early-Rift Fluvial System; Early to Climax-Rift Fluvial System (Axial system); and Early to Climax-Rift Fluvial System (Transverse system).

different palaeocurrent flow direction from that of the underlying rift-initiation deposits, probably reflects the capture of an existing river system that flowed outside the confines of the basin during the early-rift stage (cf. Gawthorpe & Leeder, 2000). The mechanism for this capture might have arisen as a consequence of ongoing subsidence leading to an increase of gradient in a direction towards the main basin depocentre, with this fluvial system constantly migrating or avulsing towards the maximum-subsidence areas (e.g. Leeder & Gawthorpe, 1987; Peakall, 1998).

Fluvial forms record a tendency of bars to develop upwardly from lateral- to downstream-accretion, a pattern described elsewhere by Bridge (2003), and which would be expected in longitudinal sections wherever a braid-bar shows both downstream accretion and some degree of lateral expansion. Smaller-scale bedforms, such as minor-scours, which are characterized by relatively widely dispersed palaeocurrent distributions, probably reflect the presence of bar-chute and bar-top channels (Bristow, 1993). By contrast, larger-scale forms are characterized by relatively uniform and unimodal trends of palaeocurrent data. Analyses integrating the complete set of palaeocurrent data, together with bounding-surface data, reveal a predominantly downstream pattern of bedform migration, showing vector mean dip direction towards 158° for bounding surfaces (n = 122) and 187° for cross-strata (n = 183).

The combined interpretation of outcrops shows mean palaeocurrent vectors with similar trends, but a contrasting dispersion of palaeocurrent directional data. For example, the presence of scour and fill structures (Fig. 11A), as well as the occurrence of small-scale sets of trough cross-stratification, corroborates the idea of a more complex arrangement of bar-top channels for this succession in relation to that of the panel depicted in Fig. 11B. This difference may be due to variation in the preservation of the upper part of the bars due to different flow regimes as a consequence of variations in fluvial discharge related to different rates of precipitation. The presence of concave-up fifth-order surfaces (for example, Fig. 12) suggests considerable channelization, probably induced by the confined palaeogeographic setting of this system determined by the basin margin to the west and the transverse fluvial system (see below) to the east.

It seems that the fluvial-fan system located close to the eastern margin of the basin (related to the Early-Rift Fluvial System described previously and the Transverse Fluvial System described below) was directly eroded by the large-scale, axial fluvial system. It is likely that the erosion of this fan system inhibited the development of more extensive and more complex fan-systems emanating from the eastern part of the basin, principally because the rate of water discharge and sediment supply from the northerly source was sufficiently great to overwhelm sediment being delivered by the system flowing from the east.

Transverse Fluvial System

Description: A typical vertical succession showing the style of stacking of lithofacies present in deposits of the eastern part of the study region is illustrated in Fig. 7C. This system preserves a more varied occurrence of facies associations than that of the previously described axial system. Not only do sets and cosets of trough cross-stratified, medium to pebbly sandstone

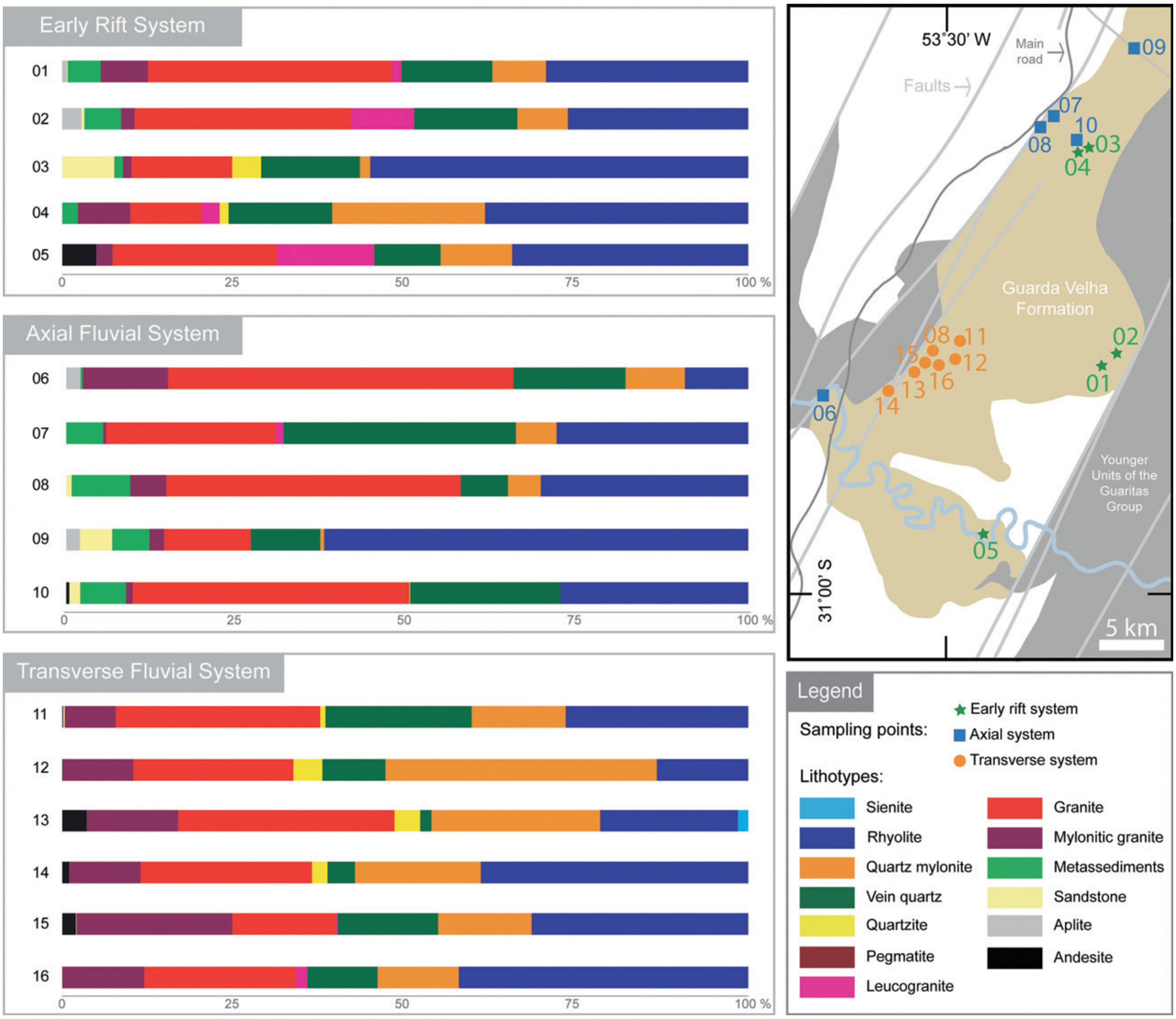


Fig. 5. Pebble count data from the Guarda Velha Formation. For each counting site, all clasts bigger than 50 mm were analysed in one or more rectangular areas containing in total at least 300 clasts. Clast percentage is based in magnitude of area which was obtained through the measurement of the bigger and minor axes, and through the assigning of form parameters.

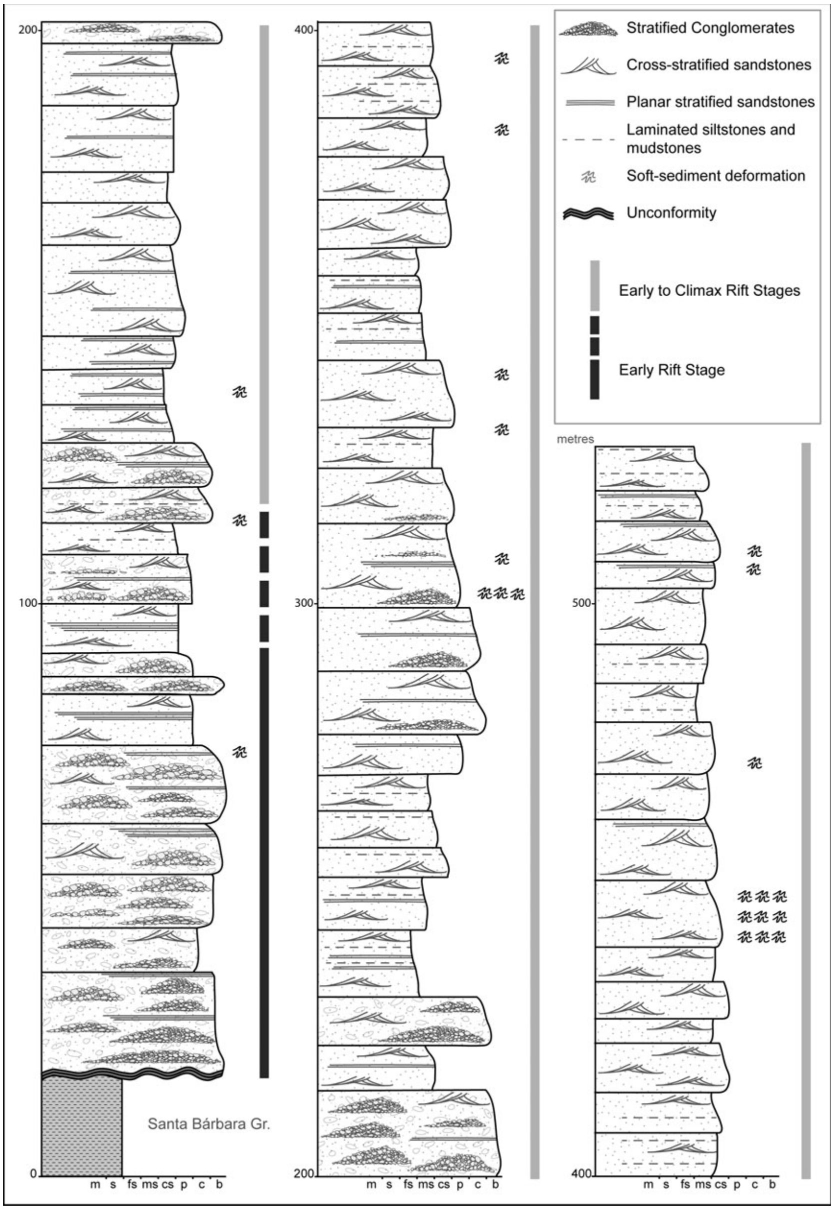


Fig. 6. Sedimentary analysis of a >500 m long core showing the basal coarse-grained deposits of the early-rift fluvial system, and the overall fining-upward trend of the Guarda Velha Formation. Occurrences of soft-sediment deformation (from Santos *et al.*, 2012) are represented, showing a gradual increase in its occurrence in the upper part of the succession. Vertical scale is in metres. Grain size: m (mud), s (silt), fs (fine sand), ms (medium sand), cs (coarse sand), p (pebble), c (cobble) and b (boulder).

alternate with horizontally laminated medium to coarse sandstone or planar cross-stratified sandstone but mud drapes and mud lenses are also present (Fig. 10C), outcropping examples of which are always eroded at their top by erosionally based overlying sandy-bedform elements typically formed of coarse pebbly sandstone. Deposits of this system are characterized by abundant occurrences of soft-sediment deformation structures (Fig. 10D), which occur at multiple scales, and which are present in different types of fluvial bedforms and elements. Mudcracks up to 0·15 m deep occur locally, as do intraformational mud chips up to 0·1 m long, which are always associated with scour-fill elements (Fig. 10E). Many small-scale features, including ripple-marks and sets of ripple cross-lamination (Fig. 10F) are intimately associated with draping mud lenses. Laterally extensive major erosional bounding surfaces commonly cut through a series of different fluvial forms (Fig. 10G) and are typical of this succession. The preserved mean set thickness is 0·4 m, which was obtained through the analysis of 70 cross-sets.

Four distinctive facies occur in this fluvial succession: (i) sigmoidal stratification, which preserves part of the topset of bedforms; (ii) pebbly sandstones with normally graded normally-graded foresets preserved as sets up to 0·3 m

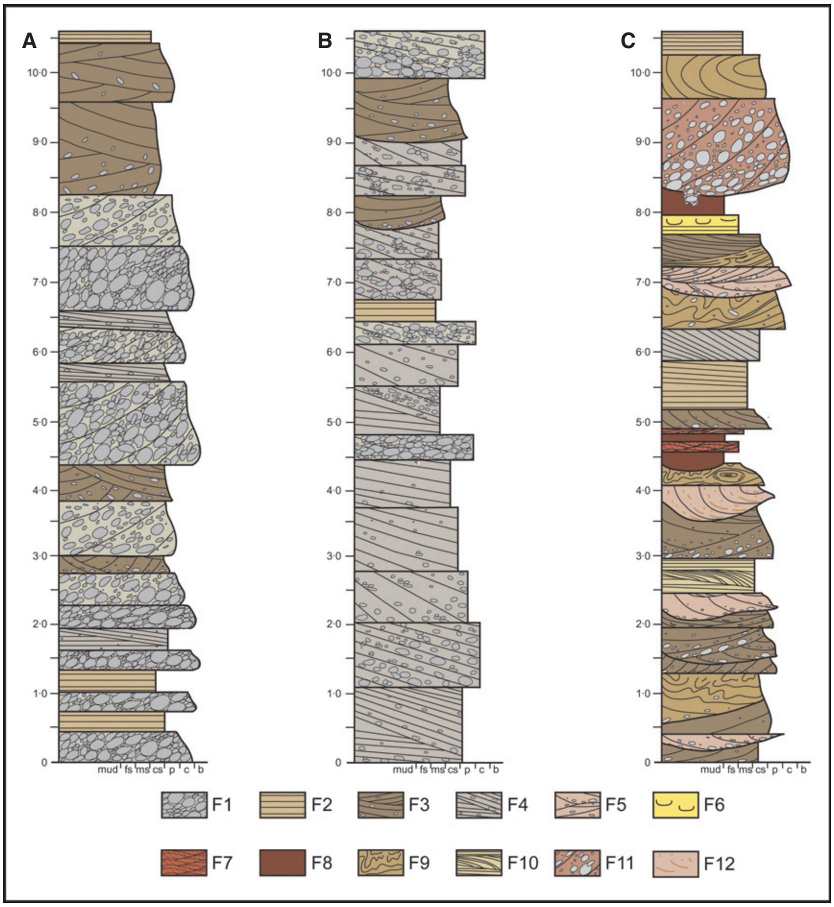


Fig. 7. Typical columnar sections of the Guarda Velha Formation: (A) Early-rift fluvial system; (B) Axial fluvial system; (C) Transverse fluvial system. Legend: F1, stratified conglomerate; F2, planar-stratified sandstone; F3, channelized, trough cross-stratified pebbly sandstone; F4, planar cross-stratified sandstones; F5, scour-filling trough cross-stratified pebbly sandstones; F6, cracked mudstones; F7, fine-grained sandstones with climbing-ripple cross-lamination; F8, laminated mudstones; F9, liquidized medium to pebbly sandstones; F10, sigmoidal-stratified sandstones; F11, coarse to pebbly sandstones with graded foresets; F12, cross-stratified pebbly sandstone with mud flakes. Distances are in metres.

thick; (iii) small-scale structures, such as climbing ripples, that only occur rarely and which are laterally related to fine-grained floodplain and overbank deposits; and (iv) soft-sediment deformed structures, which occur in multiple horizons and which are abundant particularly in the distal parts of the succession (i.e. near the main syn-depositional fault).

Deformation structures indicative of syn-depositional liquidization processes (Allen, 1984) in the Guarda Velha Formation are present in fine-sandstone or pebbly-sandstone facies but such features do not occur in mudstone facies. Such structures include water-escape cusps, recumbent-folded cross-stratification, synclines, anticlines, disharmonic folds, eye-shaped folds and dewatering pipes. None of these structures are apparently related to any particular bedform type or fluvial form. There is no evidence of slumps or deformation related to heterolithic features. The size of liquefaction features ranges from centimetre-scale (open folds restricted to individual sets and with associated water-escape structures) to metre-scale (overturned cross-stratification always bounded sharply by non-deformed, overlying erosional surfaces). Some examples of laterally extensive deformation affecting a series of several cross-bedded sets are also observed, but are rare. Although erosional set-bounding surfaces are typically non-deformed, some examples of deformed surfaces are also present, especially where deformation is pervasive through a series of sets. Importantly, there is a near-rhythmic alternation between trough cross-stratified sets presenting overturned cross-stratification and non-deformed foresets.

Details of the varied range of depositional architectures present in this system are provided in Table 2, and include the presence of elements indicative of the development of scour-fill, the accumulation of fine-grained overbank deposits, abandoned channels, downstream accretion and the common alternation between sandy bedforms and laminated sand sheets. Depositional architecture is characterized by the dominance of sandy bedforms, alternating with laminated sand sheets (Fig. 13), abandoned-scours (Fig. 13), overbank-

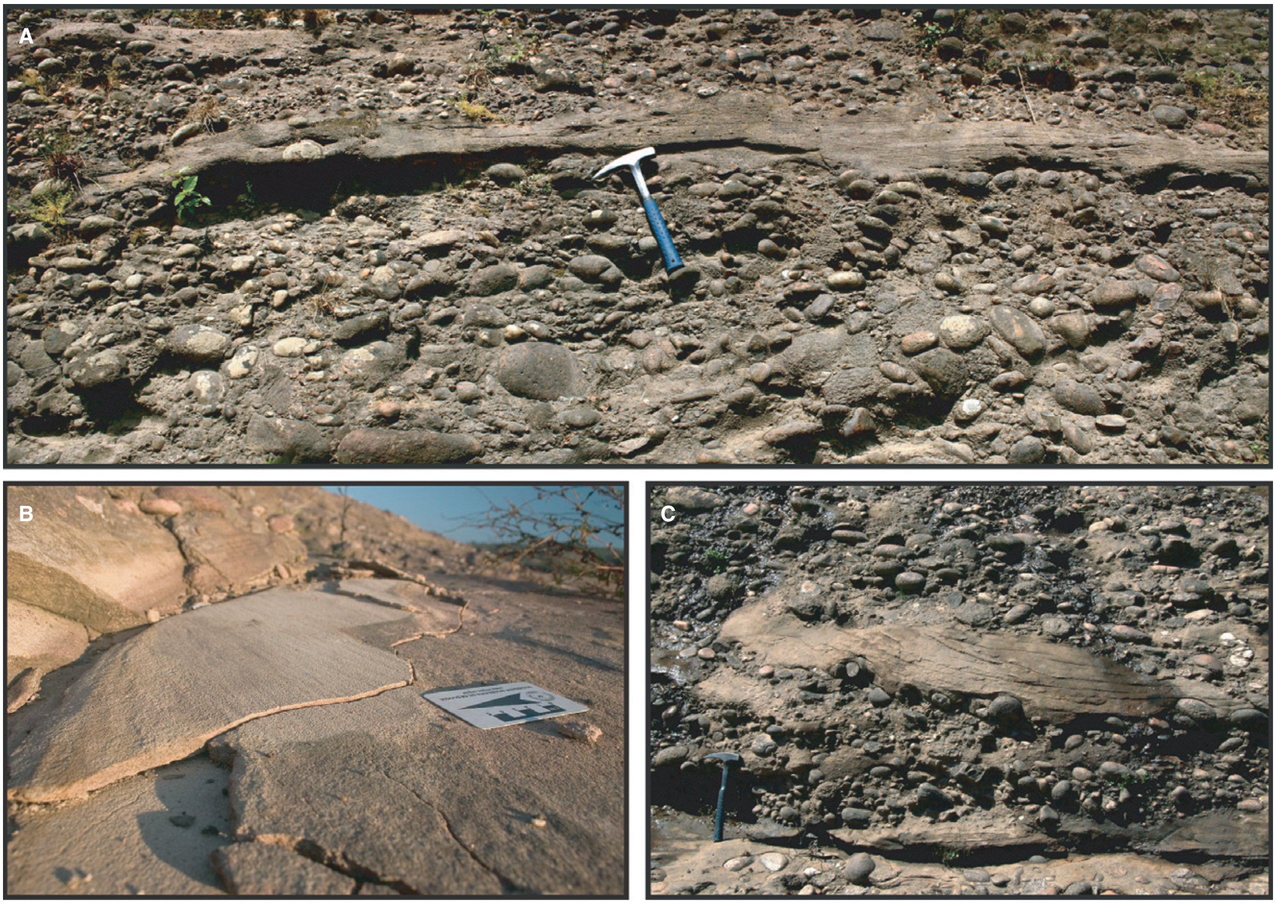


Fig. 8. Principal facies and facies associations of the early-rift fluvial system: (A) stratified conglomerate in Gravel Bedform element, with lens of bar-top planar-stratified sandstones; (B) detail of planar-stratified sandstone presenting parting lineation (scale has 10 mm markings; arrow points north); (C) channelized pebbly sandstone facies. Hammer for scale is 330 mm long.

fines (Fig. 14), downstream accretion and scour filling (Fig. 15). Fine-grained overbank elements and abandoned-scours are rare but those observed are exclusive to this system. Concave-up, erosional bounding surfaces of higher-order (inferred fifth-order; see Fig. 16) cut a series of laterally extensive, 1 to 5 m thick sandy bedform elements themselves composed of multi-storey cosets of trough and planar cross-stratified pebbly sandstone; some examples of such erosional surfaces are incised up to 6·5 m into the underlying elements. Sandy bedform elements are commonly truncated and immediately overlain by laminated sand-sheet elements, which are themselves laterally extensive for 10 to 30 m (Fig. 10G). Palaeocurrent analysis demonstrates a mean flow direction towards 257° (n = 189) with a considerable dispersion of palaeoflow direction, recording a radial pattern with direction trends varying from 015° to 140°, and an overall direction transverse to the basin axis and perpendicular to the interpreted flow of the previously described axial system.

Interpretation: Analysis of data collected from the eastern part of the study region reveals the deposits of a fluvial system originated from a basin-border region with a radial pattern of palaeocurrents recording flow that was transverse to the elongate axis of the basin and towards the main depocentre, similar to those interpreted in the literature as distributive fluvial systems (e.g. Hartley *et al.* 2010a, Weissmann *et al.*, 2010). Provenance analysis demonstrates a sediment source area related to the bedrock lithologies currently present at the eastern margin of the basin, revealing no relative lateral displacement of the basin during or following accumulation. Tectonic uplift of the eastern-margin fault scarp, as demonstrated by accumulation of a continu-

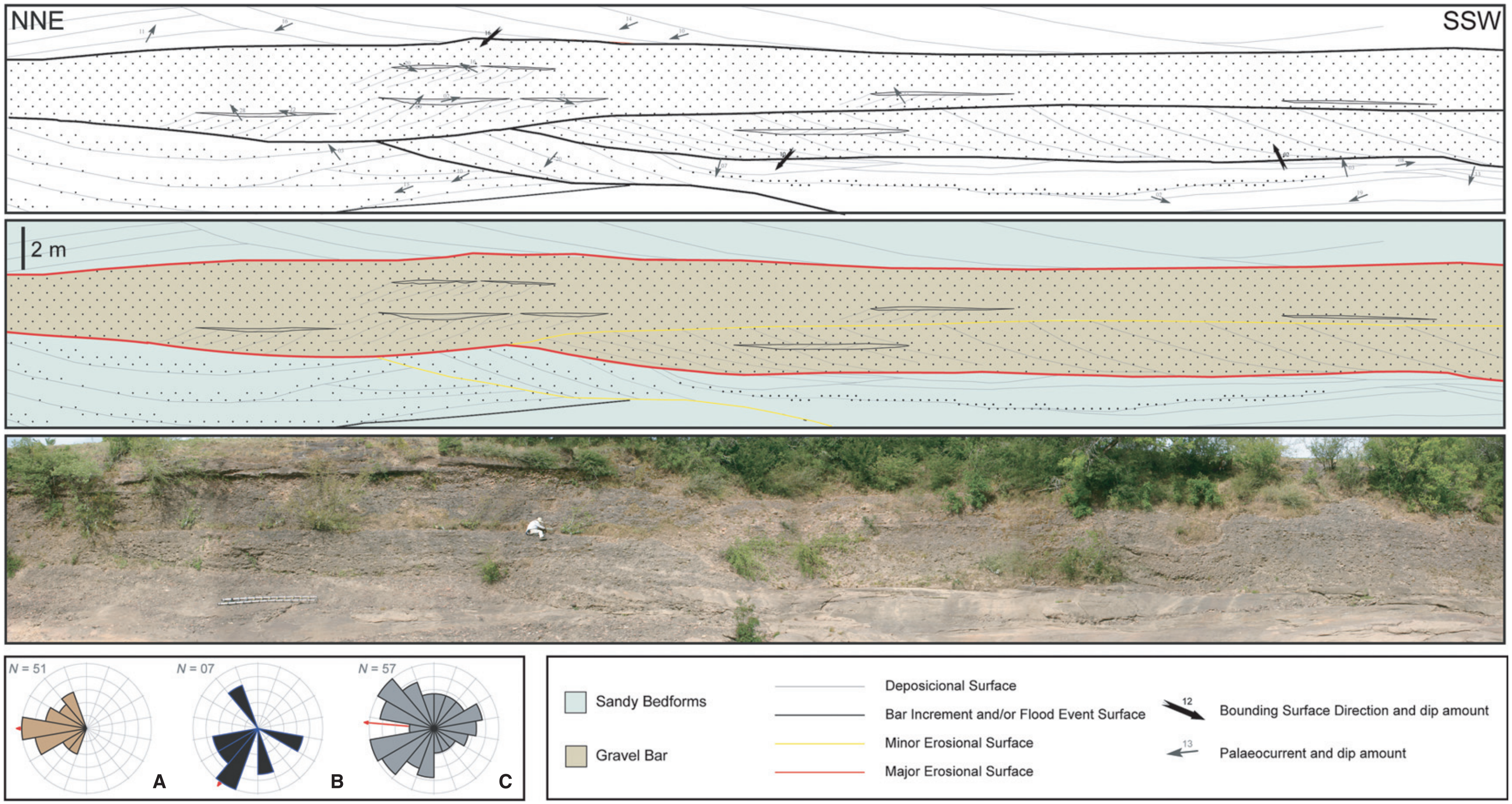


Fig. 9. Interpretation of architectural elements of the early-rift fluvial system. Thick arrows indicate the dip direction of bounding surfaces that separate sets; thin arrows indicate the dip direction of foresets used to determine palaeocurrent directions. Rose diagrams: (A) palaeoflow direction indicated by clast imbrication (n = 51); (B) bounding surfaces (n = 7); (C) palaeocurrents (n = 57).

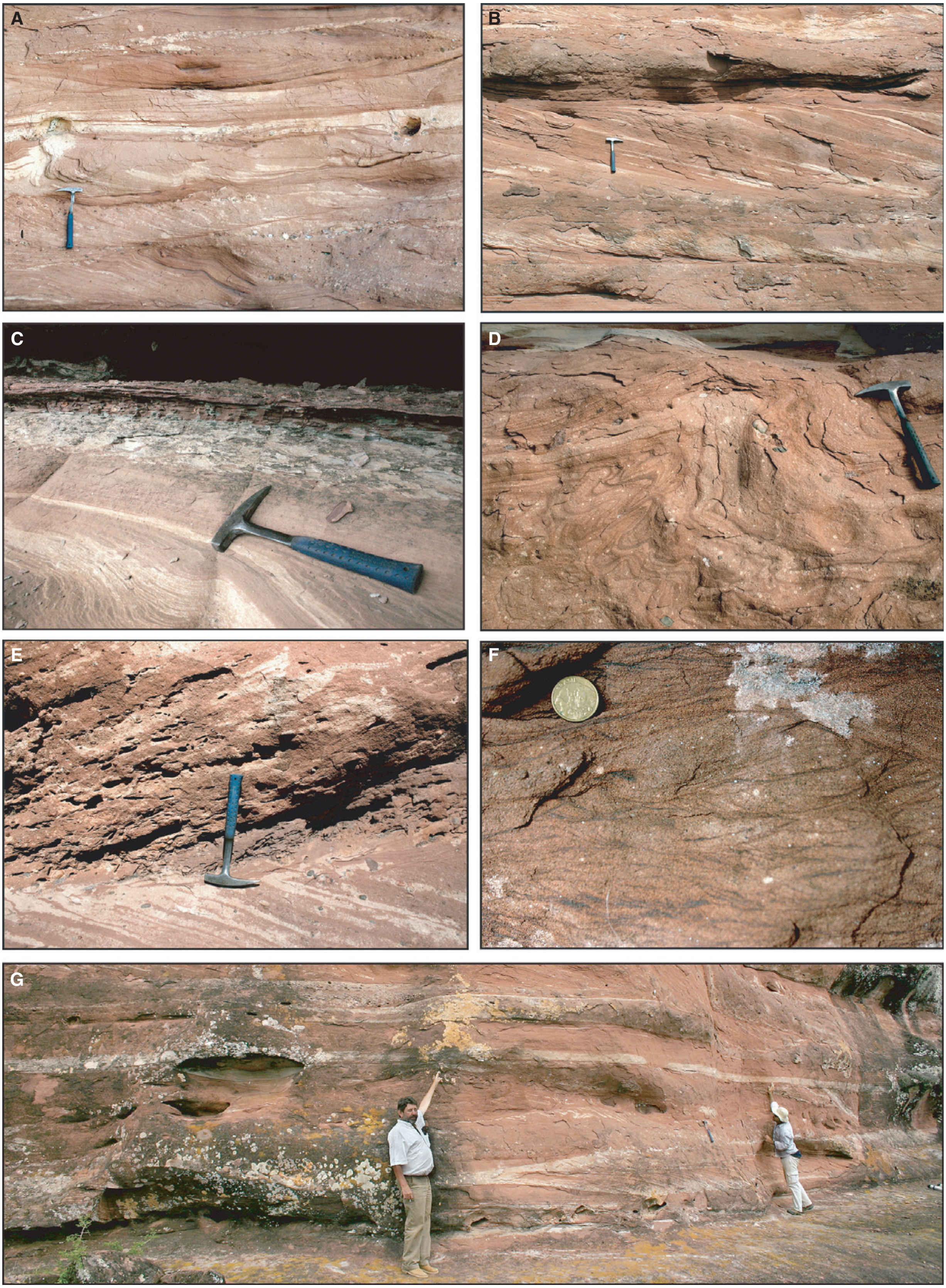

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Fig. 10. Principal facies and facies associations of the Early to Climax-rift fluvial systems (Axial and Transverse Fluvial Systems): (A) pebbly trough cross-stratified sandstone; (B) medium-grained to coarse-grained sandstone arranged into planar cross-stratified sets; (C) mudstone lens; (D) soft-sediment deformed pebbly sandstone with liquefaction features; (E) scour-filling trough cross-stratified pebbly sandstone with intraformational mud chips; (F) fine-grained sandstone with climbing-ripple cross-lamination (coin for scale is *ca* 20 mm); (G) example of laterally extensive, planar erosional surface related to toe-cut erosion (Prof. Fragoso-Cesar for scale at the front of the picture is 1·72 m tall). Hammer for scale is 330 mm long.

ous belt of debris-flow-dominated alluvial-fan deposits with basinward-directed palaeocurrents originating from a NNE-striking fault region (Paim, 1994, 1995; Almeida *et al.*, 2009), probably resulted in the development of a fluvial-fan system, of which the distributive fluvial system studied here is interpreted to represent the distal part. Importantly, such fluvial fans reworked sediments delivered by the debris-flow-dominated fans. Moreover, the transverse orientation of the mean palaeocurrent direction relative to that of the axial fluvial system denotes a contributory character for this particular sub-system that enables it to be distinguished from the axial fluvial system, implying that the transverse river system drained into the axial trunk river. This situation, together with the basinward grain-size fining described by Paim (1995), suggests a basin-wide overall downslope gradient towards the western part of the basin. Provenance analysis indicates that metamorphic and granitic basement regions with limited areal extent lying adjacent to the eastern margin of the basin acted as source areas to these sediments, similar to the previously described early-rift fluvial system; sediment source repeatedly varied through time from distal to proximal.

Accumulation and preservation of sigmoidal-stratified sets occurs under conditions transitional between the dune and plane-bed stability fields (Fielding, 2006). Pebbly sandstones with normally graded foresets are interpreted as conglomeratic unit bars with angle-of-repose formed by the avalanching of particles previously sorted in superposed bedforms (McConnico & Bassett, 2007). Preserved mean set thickness suggests that water depth for this fluvial system was shallower than that of the axial fluvial system, as would be expected for a contributory system; the ability of this system to avulse coupled with its relatively unconfined setting (in comparison with that of the axial system) would also have facilitated channel widening allowing the fluvial system to occupy broader areas.

The cyclic intercalation between bodies of trough and planar cross-bedded sets of varied thickness that are commonly eroded in their upper part by sets of plane-parallel-laminated sandstone is interpreted to reflect high variation in discharge (Miall, 1984). The presence of varied facies associations, including mud lenses and rippled sandstone also supports the interpretation of a fluvial system subject to considerable discharge variation. The local occurrence of mud flakes implies that mud deposits were dried and then eroded, and in this way such features are indicative of sub-aerial exposure soon-after succeeded by flow characterized by traction currents (cf. Tirsgaard & Øxnevad, 1998). Mud lenses, minor-scale bedforms and mudcracks are interpreted in Fig. 17. Some laterally extensive laminated sand-sheet elements characterized by planar erosional surfaces cutting a series of fluvial forms (Fig. 10G) might record floods from the axial system that occurred at a time when the distal alluvial plain of the contributory (transverse) system acted as the floodplain to the main axial system, resulting in toe-cutting erosion processes (cf. Leeder & Mack, 2001), or alternatively floods originating in the uplands to the east, with reworking and erosion of the un-vegetated river-banks. This type of erosion therefore could record the lateral erosion of bajada-forming alluvial systems by river channels directed along the main basin axis. The style of preservation of a transverse river system draining into an axial trunk river system demonstrates not only the evolution of the fluvial system on the hangingwall of a half-graben but also the evolution of the early-rift system (rift-initiation stage) into a mature through-going basin (through-going-rift) with a well-developed bajada system along its eastern margin (cf. Gawthorpe & Leeder, 2000).

The common occurrence of scour-fill elements (Fig. 15), together with large sandy-bedform elements preserving concave-up lower surfaces, is indicative of a system in which channels were widely developed. The actual size of the main channel elements is not clearly recognizable because they are laterally more extensive than the studied outcrops; however, examination of the more extensive outcrops reveals numerous major erosional surfaces incising a series of older deposits (Fig. 16). Channel incisions are probably related to proximal parts of fluvial systems, leading to the amalgamation of channel forms (cf. Nichols & Fisher, 2007; Cain & Mountney, 2009). The transverse-system deposits preserve highly amalgamated channel forms, which are interpreted to have accumulated as the result of high rates of channel avulsion, a situation probably enhanced by the non-cohesive (and non-vegetated) nature of the channel banks. This probably resulted in the generation and preservation of laterally extensive sandbodies, which are many tens to hundreds of metres wide, indicating the likely occurrence of preserved channel elements with high width-to-thickness ratios (Gibling, 2006). Inferred fifth-order bounding surfaces (Miall, 1985; Fig. 16) confirm that channel forms were indeed laterally extensive; preserved channel elements are 10 to 20 m thick and >200 m wide. According to the methodology proposed by Gibling (2006), the data presented herein are indicative of medium-width channels characterized by narrow to broad sheets, demonstrating that this system was characteristically poorly confined.

Facies analysis of soft-sediment deformed strata reveals no relation between liquefaction structures and bedform type, set thickness or grain size; thus, the deformation features occur in an apparently random distribution. This situation, combined with the similarity of the studied structures with laboratory features which were triggered by seismic-shaking (Owen, 1996; Moretti *et al.*, 1999), suggests that these structures are likely to have been triggered by seismic activity (Santos & Almeida, 2010; Santos *et al.*, 2012). This would be expected in a tectonically active basin, particularly during the climax rift stage, during which tectonic activity would have been heightened (Prosser, 1993). For an autokinetic (process-based) mechanism to have served as the trigger for liquidization, a direct relation between facies and architectural elements and deformation structures would be expected (Leeder, 1987). Overturned cross-stratification reveals liquefaction events that occurred simultaneous to current shear-drag (Allen & Banks, 1972), revealing a relation between river-flow activity and liquidization. The near-rhythmic alternation between sets preserving overturned cross-stratification and non-deformed sets suggests constant flow because the coincidence of river-flow activity and seismic-events is very unlikely to have been repeatedly recorded had the fluvial system not experienced perennial flow (Santos *et al.*, 2012).

Interpretation of the Early- to Climax-Rift-Stage Fluvial Systems

The Guarda Velha Formation records the development of a complex arrangement of fluvial deposits that collectively demonstrate the coeval development of an alluvial plain comprising two laterally interacting fluvial systems: an axial river characterized by a channel belt indicative of a braided fluvial system that flowed from north to south and a transverse, contributory distributive fluvial system that flowed from east to west. A large catchment area north of the basin is interpreted from the scale of the preserved bedforms, together with palaeocurrent and pebble provenance analysis. The main difference between eastern and northern sources is the presence of a belt of quartz mylonites and mylonitic granites next to the eastern basin border and trending parallel to the basin. Granites and rhyolites occur in all areas surrounding the basin. Given the restricted occurrence of these mylonites to the first few kilometres to the east of the basin, the abundance of such clast types in the transverse system (always more than 25%) suggests a greater contribution of local sources than is observed in the axial system, which is richer in reworked vein quartz. Since the transverse system was contributory to the

Fig. 11. Architectural elements of the Axial Fluvial System: (A) amalgamated braid-bars exhibiting a markedly dispersed pattern of palaeocurrent, combined with scour features, suggesting preservation of bar-chute and bar-top channels (I. bounding surfaces of fluvial forms, $n = 80$; II. palaeocurrent diagram of cross-strata dip directions, $n = 93$); (B) prograding bars presenting both lateral and downstream accretion (I. palaeocurrent diagram of bounding surfaces of fluvial forms, $n = 42$; II. palaeocurrent diagram of cross-strata dip directions, $n = 90$). Note the variation in the direction of dip of the bounding surfaces (thick arrows) and the palaeocurrents measured from foreset attitudes (thin arrows). Overall flow direction was from left to right (the outcrop is aligned parallel to mean flow direction). Arrow directions are presented with north pointing upwards.

axial one, mylonites are also found in the latter, and are notably more abundant downstream of the area of the inferred confluence of the two systems. Apart from this marked difference in proportion of clasts from an identifiable source, some clast types found in the axial system seem to be absent from the transverse one: notably, sandstones from older units of the Camaquã Basin are composed, in part, of detrital minerals and clasts of aplite, and low-grade metasediment, sources of which crop out in the area west of the basin, suggesting transport to the axial system via debris-flow related alluvial fans identified in the western border area.

The area of occurrence of the Guarda Velha Formation supports the interpretation of a basin-wide intra-rift fluvial plain that, according to the variation and spatial distribution of facies associations, accommodated a complex fluvial system in which the two recognized fluvial-system types were characterized by contrasting patterns of channels and hydraulic regimes. These were due, in part, to their different catchment areas (identified through provenance analysis – Fig. 5 – which revealed different sediment sources), their different settings within the evolving rift basin (rift axis versus hangingwall rift-basin margin) and their style of lateral inter-fingering. The basinal-scale development of the hangingwall fluvial and alluvial fans to the east apparently forced the axial river system to the footwall side of the basin, a situation typical of asymmetrical rifts (e.g. Leeder & Gawthorpe, 1987; Peakall, 1998; Gawthorpe & Leeder, 2000). Indeed, the deposits of the eastern basin margin were able to develop fluvial-dominated streams, whereas the deposits of the western basin margin were fed by proximal sources, and were rapidly reworked by the major, southerly flowing axial system. This situation is similar to those described by Gawthorpe & Leeder (2000), where hangingwall-sourced alluvial fans typically present larger dimensions than footwall-sourced fans. These results collectively suggest that, although both basin borders were active, the western fault represents the main syn-sedimentary basin border fault that gave rise to a basin asymmetry with the western part of the basin experiencing higher subsidence rates.

There exists an overall upward-decrease in grain size throughout the Guarda Velha Formation, from the early-rift fluvial system with its conglomeratic bars, passing upward through the relatively finer-grained succession characterized by the inter-fingering of the axial river system, in the west, and the transverse river system in the east of the rift. There is clear evidence, particularly in the transverse system, to demonstrate the increased proportion of mud lenses in higher parts of the succession. This style of preservation may have arisen as a result of climatic controls leading to distinct temporal changes in fluvial discharge regime, or subsidence rates, or to a combination of both.

DISCUSSION

The study of the early-rift succession documents a coarse-grained fluvial system that flowed transverse to the elongate basin axis towards an inferred depocentre that developed in response to progressive movement on a main basin-bounding fault. The radial pattern of this system supports its interpretation as a fluvial fan (i.e. a distributive fluvial system) that originated close to the eastern margin of the basin and flowed towards the main depocentre in the west. The succession probably records the distal (fluvial-dominated) part of one or a series of alluvial fans, which originated close to the eastern border of the evolving basin. This system is interpreted to have evolved into the younger transverse system, and the finer-grained characteristic of this younger system might indicate that the basin was widening in an orientation perpendicular to its axis (Fig. 18).

Geological mapping of depositional units of the early- to climax-rift stage confirms that the axial fluvial succession represents a major trunk river system and that the transverse/contributory system developed contemporaneously to this, as demonstrated by the lateral inter-fingering relation of these successions. The contributory system not only supplied the axial fluvial system with additional sediment supply, but also confined it to the western region of the basin. Moreover, the western margin debris-flow-dominated alluvial fans also forced the axial system basinward, but probably exerted a minor influence compared to that of the eastern-margin fans. This situation resulted in the axial fluvial system being confined by debris-flow-dominated alluvial fans to the west and fluvial-dominated fans to the east. This relation may have been characterized by lateral erosion due to toe-cutting (cf. Leeder & Mack, 2001) which could be

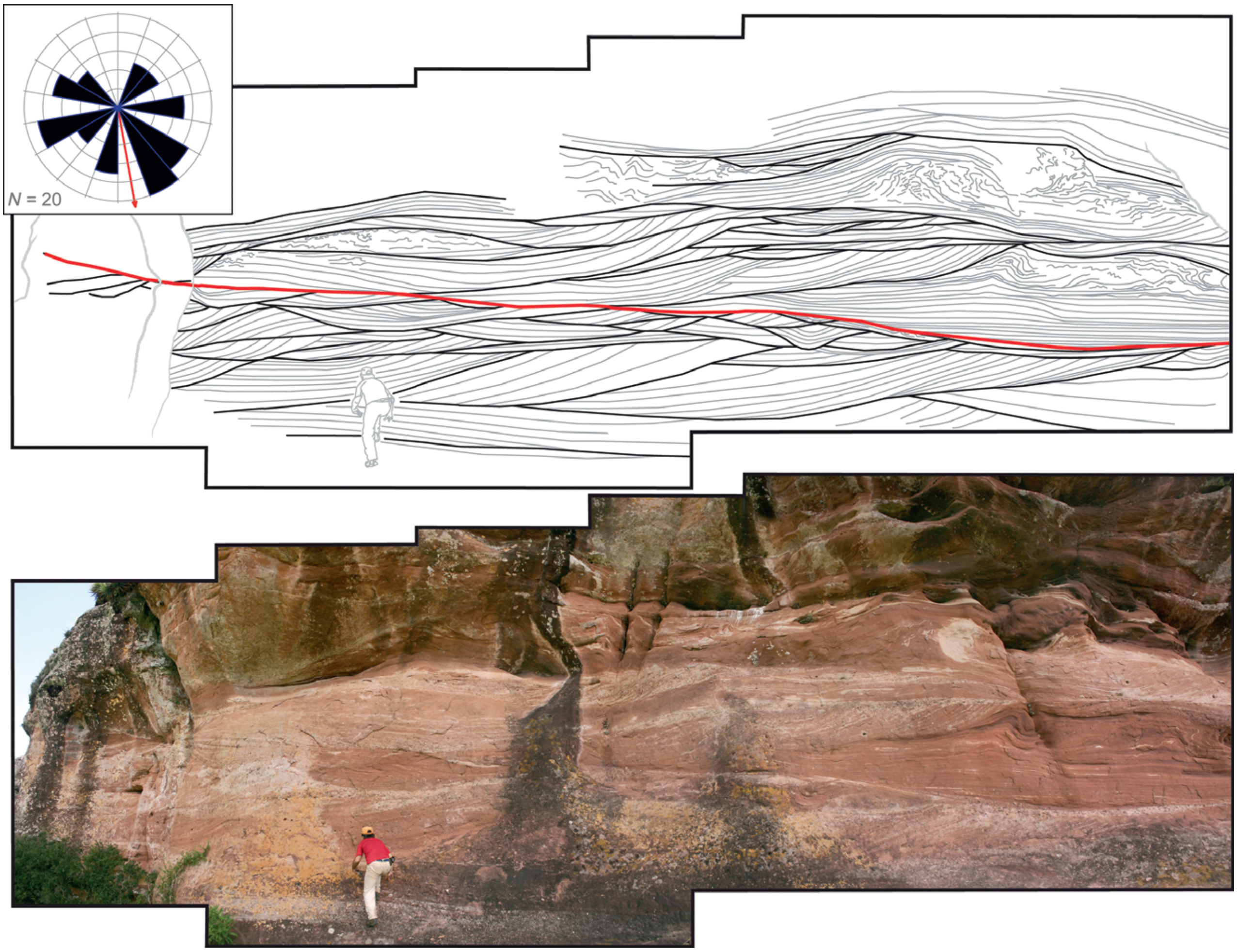

Fig. 12. Example of channelized incised form in the Axial Fluvial System. The red line represents a fifth-order bounding surface; black lines represent set and coset boundaries; grey lines represent depositional surfaces. Outcrop is perpendicular to mean palaeoflow direction. Notice the abundant soft-sediment deformation in different types of bedforms. Upper right: rose diagram with palaeocurrents (n = 20). Person for scale is 1·80 m tall.

controlled by a combination of tectonic or climatic factors.

The main sedimentological differences between these two coeval systems most probably arose as a function of the different geomorphological and basin settings that they occupied, which resulted in the adoption of different drainage patterns in the same regional basin setting (Fig. 19). Discharge was apparently greater and more consistent in the main axial trunk river, as demonstrated by the preserved depositional architecture and set and coset dimensions. This is also supported by the preservation of compound bars, built by successive flood events, each promoting the accretion of additional sediment in the same macroforms (Allen, 1983). Accommodation space also played an important role in controlling the preserved sedimentary architecture: the axial system, which was located close to the main basin-bounding fault, probably experienced greater rates of accommodation creation due to higher rates of subsidence. By contrast, accumulation of the transverse system, which developed on the hangingwall and originated at the eastern basin margin, was probably limited by a relatively slow rate of generation of accommodation, meaning that the transverse fluvial system was more probably to undertake progradation and to adopt a distributive form (Nichols & Fisher, 2007). This alone could potentially account for the difference in preserved fluvial style.

Downstream and lateral accretion in the axial system occurred as a result of incremental bar growth during episodes of high-stage flow, a diagnostic indicator for continuous and

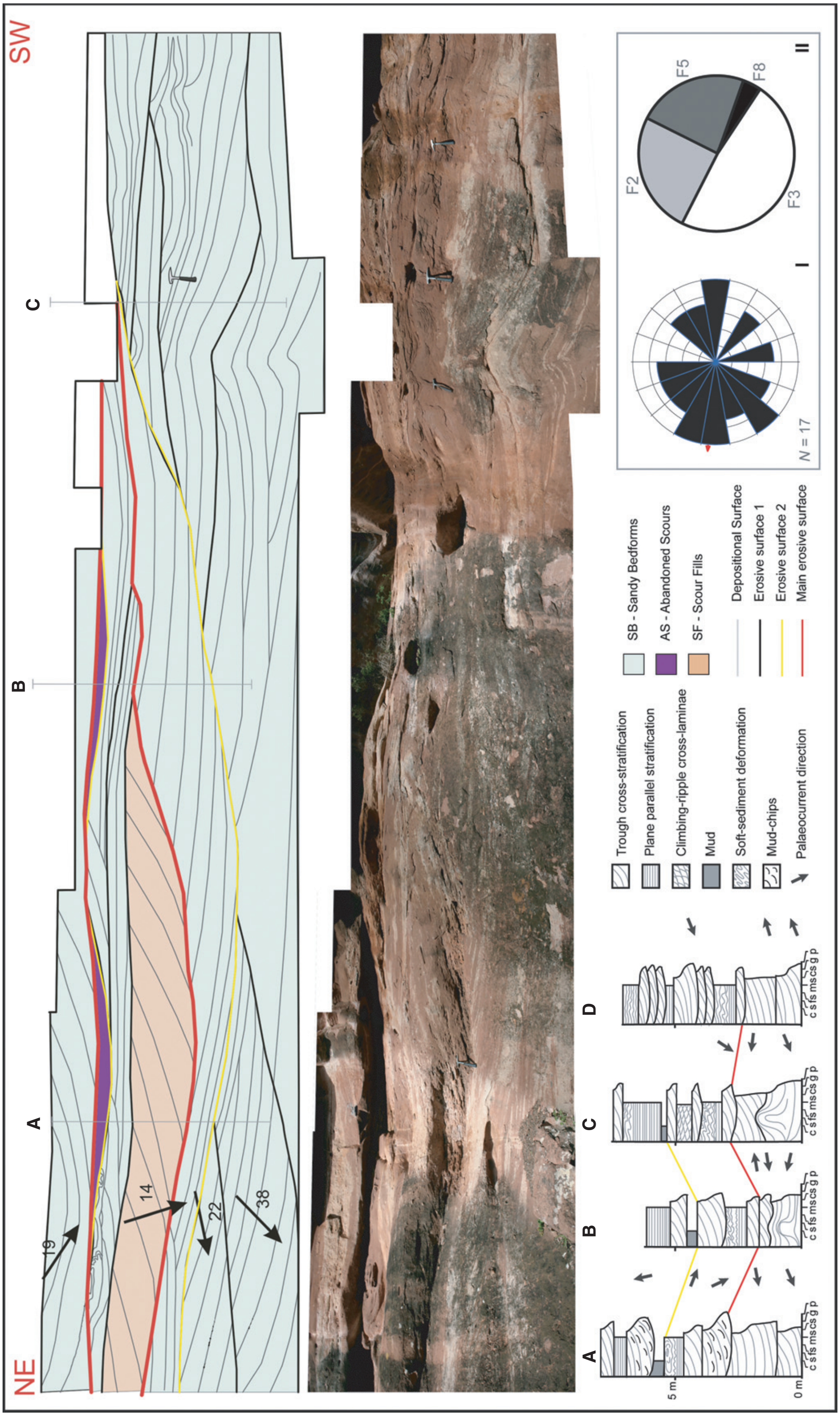

Fig. 13. Architectural elements of the Transverse Fluvial System. Note the presence of two abandoned-scours overlying a soft-sediment deformed horizon. Hammer for scale is 330 mm long. Lines 'A', 'B', and 'C' on the upper panel show the location of vertical logs depicted below the figure. Lower right: I. palaeocurrent data based on measurements of foreset attitude (n = 17); II. facies proportions.

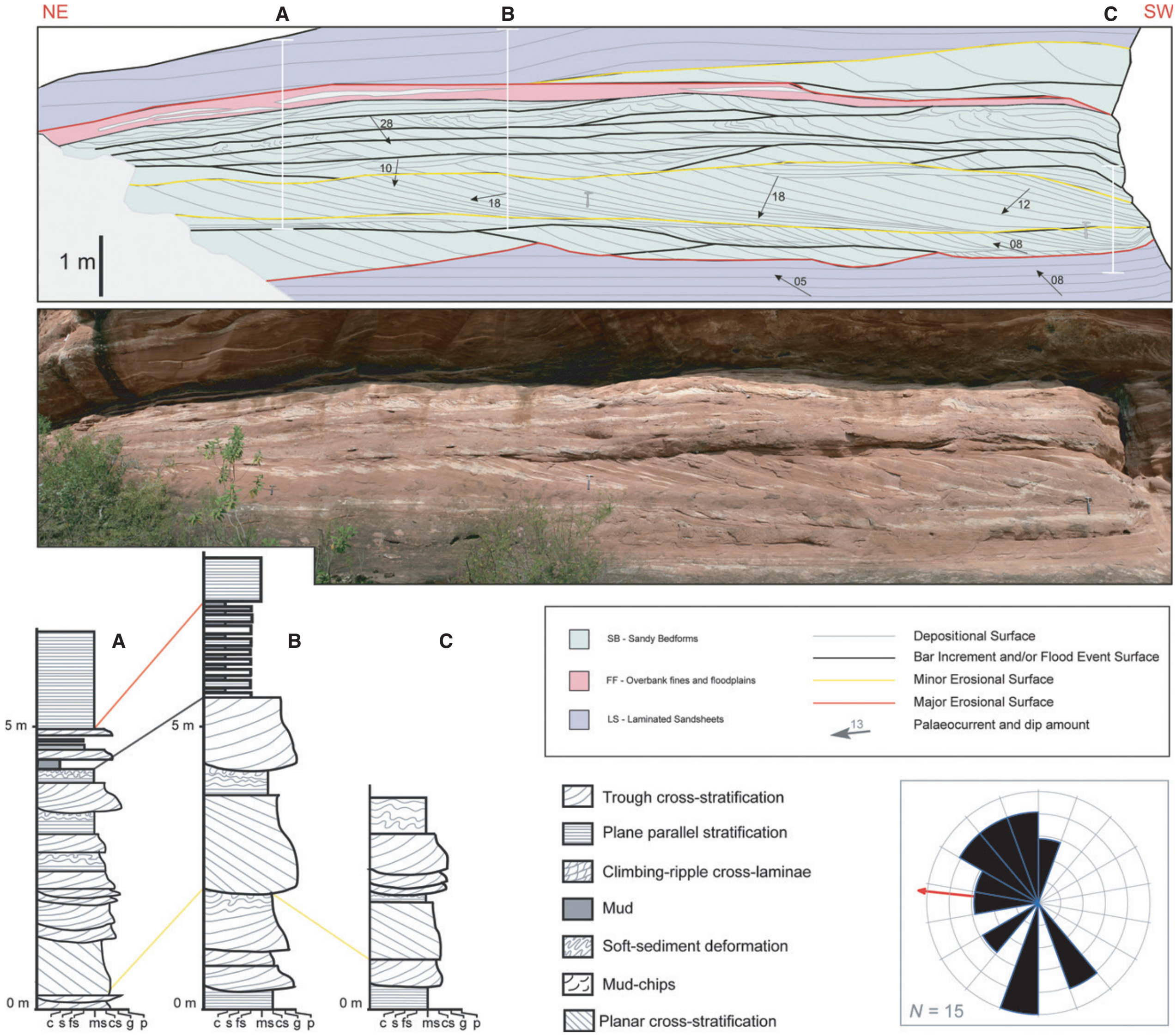

Fig. 14. Architectural elements of the Transverse Fluvial System: sandy bedform and laminated sand-sheet elements, with lenticular overbank-fine and floodplain elements. The outcrop is organized into stacked multi-storey channel complexes comprising sandy bedform elements bounded by erosional surfaces. Associated laterally extensive laminated sand-sheet elements are recorded at the bottom and the top of the panel. Lower right: palaeocurrent diagram based on measured foreset attitudes (n = 15).

relatively constant flow activity (Smith, 1970; Bristow, 1987; Miall, 1994; Best *et al.*, 2003). An aggrading river system bounded laterally by the basin's main fault to the west and by a bajada system to the east, implies a considerable degree of confinement, and suggests that the basin might have experienced high rates of subsidence overall. The interpreted constant and considerable high-water discharge suggests relatively wet conditions at the depositional surface during accumulation of the studied succession. This succession can be ascribed to a typical rift-basin axial fluvial system bounded by basin-margin bajada deposits.

The transverse, distributive fluvial system, which evolved as a contributory system to the main axial river system, is characterized by an abundance of scour surfaces, an amalgamation of forms and sedimentary structures indicative of upper-flow regime conditions. The existence of scarce ponds demonstrated by rare preservation of mud drapes and lenses of mudstone (some with preserved cracks) may indicate the development of a floodplain with lateral and

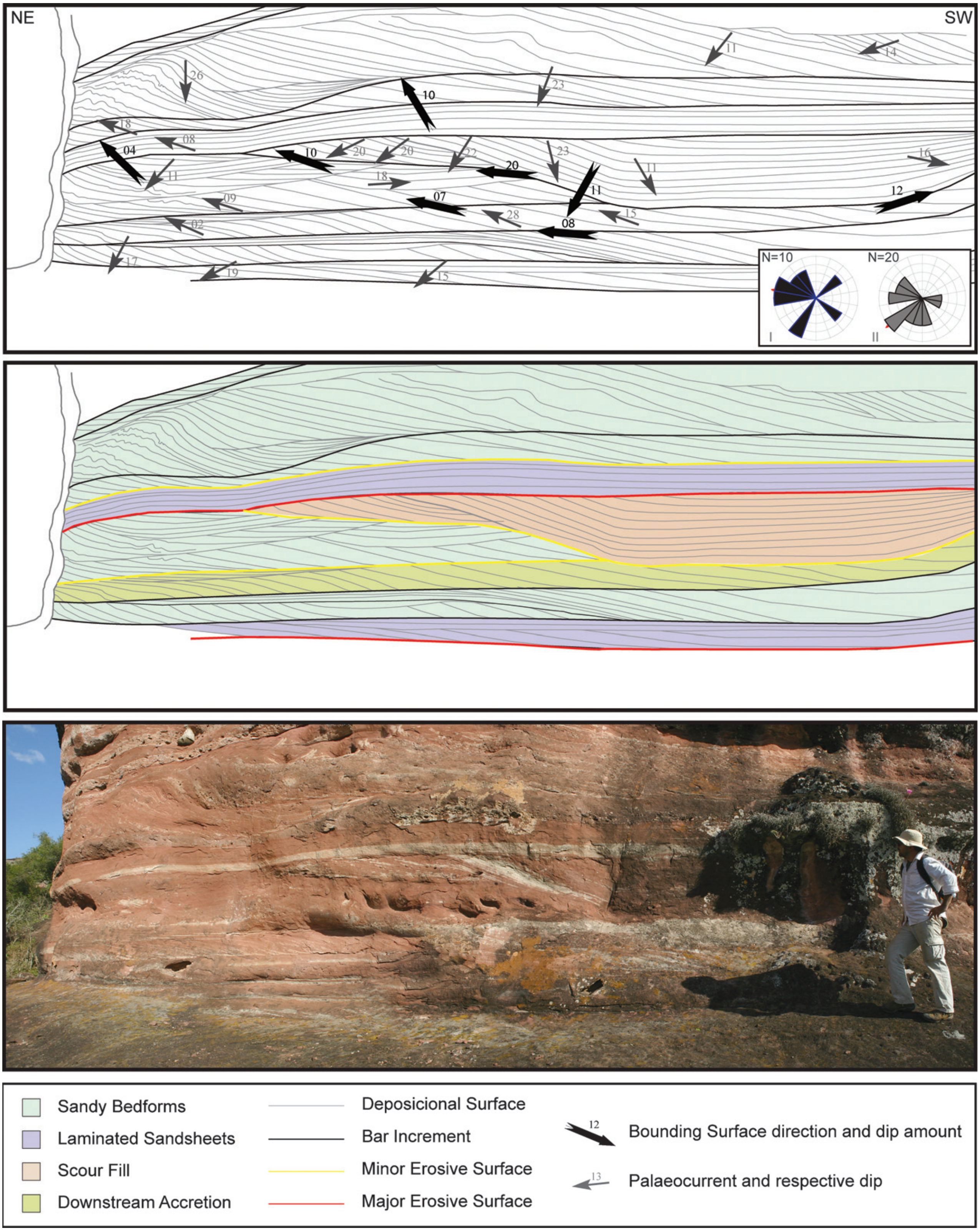

Fig. 15. Architectural elements of the Transverse Fluvial System: typical intercalation of elements of sandy bedforms and laminated sandsheets. Thick arrows denote bounding surfaces between forms (n = 10); thin arrows denote palaeocurrents measured from foresets (n = 20). Note the laterally extensive erosional surface beneath the laminated sandsheet element. Person for scale is 1·80 m tall.

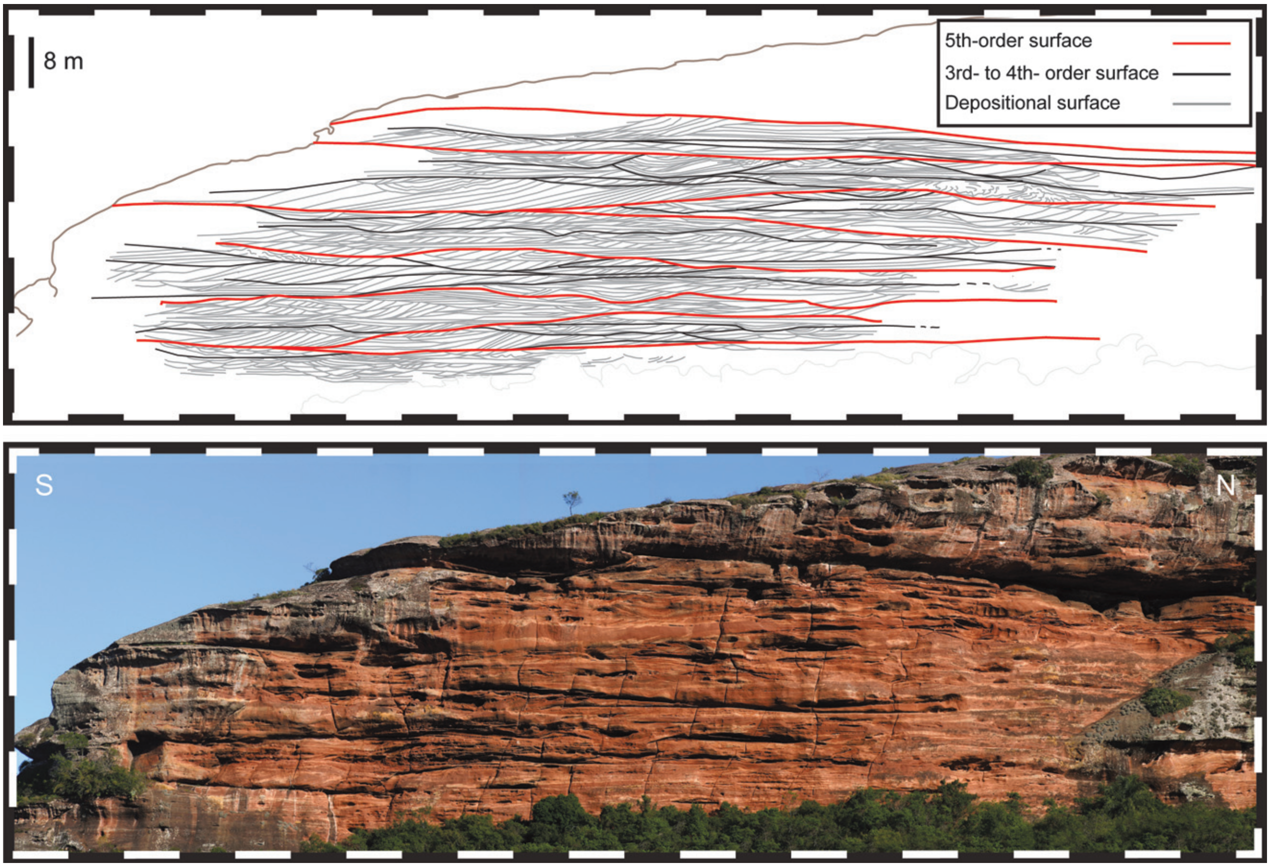

Fig. 16. Interpretation of architectural elements preserved in the Transverse Fluvial System: a series of fifth-order bounding surfaces and channelized incised forms.

associated minor channels that were active only during peak floods (Bristow, 1993; Tirsgaard & Øxnevad, 1998). Increased rates of channel avulsion due to the presence of non-stabilized banks may also explain the occurrences of mud drapes, which would be deposited after minor-channel abandonment (Tirsgaard & Øxnevad, 1998). Some of these mud deposits were reworked, as revealed by the local presence of intraformational mud flakes, probably in response to the cutting of new channels in the immediate aftermath of avulsion events (cf. Steel & Thompson, 1983; Cain & Mountney, 2009). These results collectively indicate considerable discharge variation. The downslope gradient of this contributory river system was probably greater than that of the trunk river, given that the former flowed from one active basin border in the east across the hangingwall, which was tilting down to the west. As a consequence, during peak precipitation, this relatively high-gradient area would be subject to substantial discharge variation; floods would be more easily drained in comparison to those affecting the axial system. An aerially limited region of hydraulic catchment, as revealed by provenance analysis, may also have contributed to a higher discharge variation than that of the axial system with its regional catchment area (cf. Walling & Moorehead, 1989; Orton & Reading, 1993), leading to decreased flow during drier seasons in the transverse system.

Despite the absence of vegetation cover, the studied fluvial systems were apparently able to develop long-lived, major channelized networks. The basin-wide extent of this pre-vegetation fluvial system has allowed the recognition of particularities of the depositional architecture of a Cambrian axial river that was laterally confined by both fault-scarp and bajada deposits; this recognition is important for the study of pre-vegetation fluvial systems. Importantly, this tectonic setting, together with the contemporaneous deposition of two distinct fluvial systems, may have induced the incision of fluvial streams into younger deposits, and systems recording

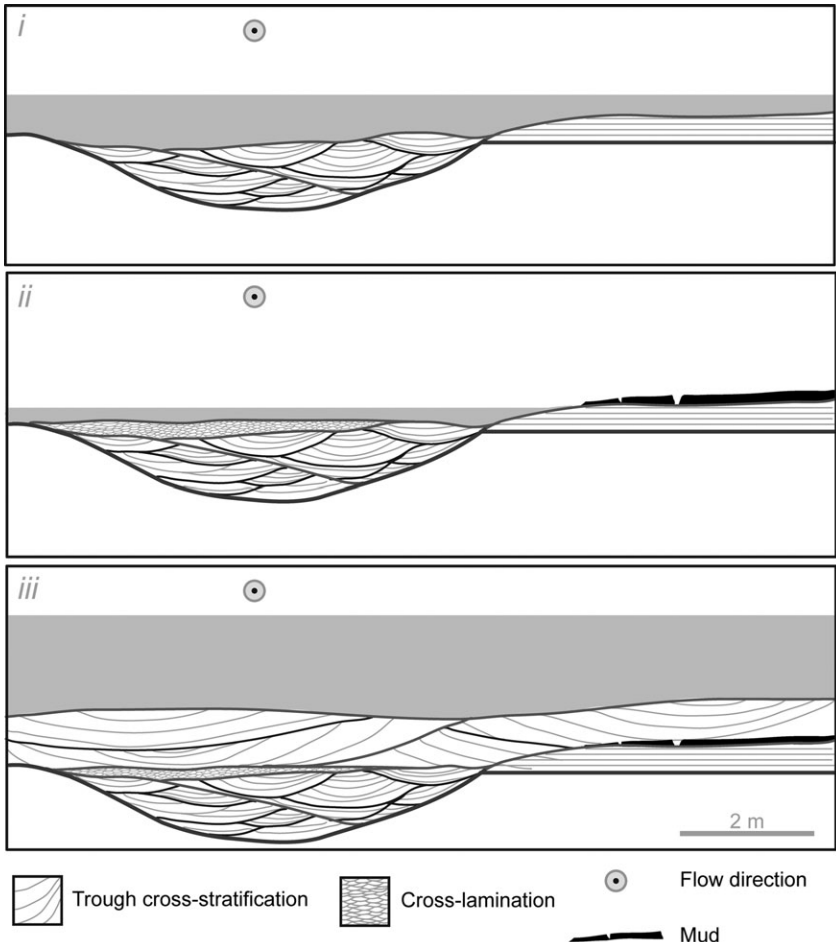

Fig. 17. Idealized depositional model to account for the origin of overbank and floodplain deposits, including mudcracks and ripple forms in the contributory Transverse Fluvial System. Flow direction is towards the reader.

long-lived channels. These results agree with previous models suggesting that pre-Silurian fluvial successions developed wide channels (e.g. Cotter, 1978; Davies & Gibling, 2010). However, it may be that the recognition of the actual styles and particularities of such wide-channel systems can only be achieved through basin-scale studies; this may be particularly difficult for most mainstream preserved river successions, which developed in cratonic settings and consequently are characterized by much less system variability. The presence of demonstrably channelized macroforms led Santos *et al.* (2012) to interpret the axial fluvial system herein described as a channel-braided fluvial system, although it was not possible to determine the actual width-to-depth ratio as an outcome of their study. A considerable body of published work (e.g. Hjellbakk, 1997; Sønderholm & Tirsgaard, 1998; Tirsgaard & Øxnevad, 1998; Long, 2006), together with the findings of this study, demonstrates that pre-vegetation fluvial systems can indeed preserve varied depositional architectures in response to different tectonic, geomorphic and climatic settings. It is plausible to suggest that the laterally extensive genetic units grouped by Cotter (1978) in the term 'sheet-braided' may in fact encompass a series of different styles of pre-vegetation fluvial systems; the lack of vegetation propitiated such laterally extensive channel forms to develop a varied number of possible fluvial styles and these were controlled by tectonic and palaeoenvironmental settings.

The paucity of mud in the systems described here probably relates to the particular characteristics of this basin, which was a hydrologically open system. The axial fluvial system continuously removed finer-grained sediments to distal areas beyond the confines of the basin, via the downstream bypass of fine-grained sediment (Winston, 1978; Eriksson *et al.*, 2006). Alternatively, mud deposits may have experienced repeated deflation (Dalrymple *et al.*, 1985). An increased occurrence of bed-load streams would also have been promoted by the absence of vegetation cover, with little

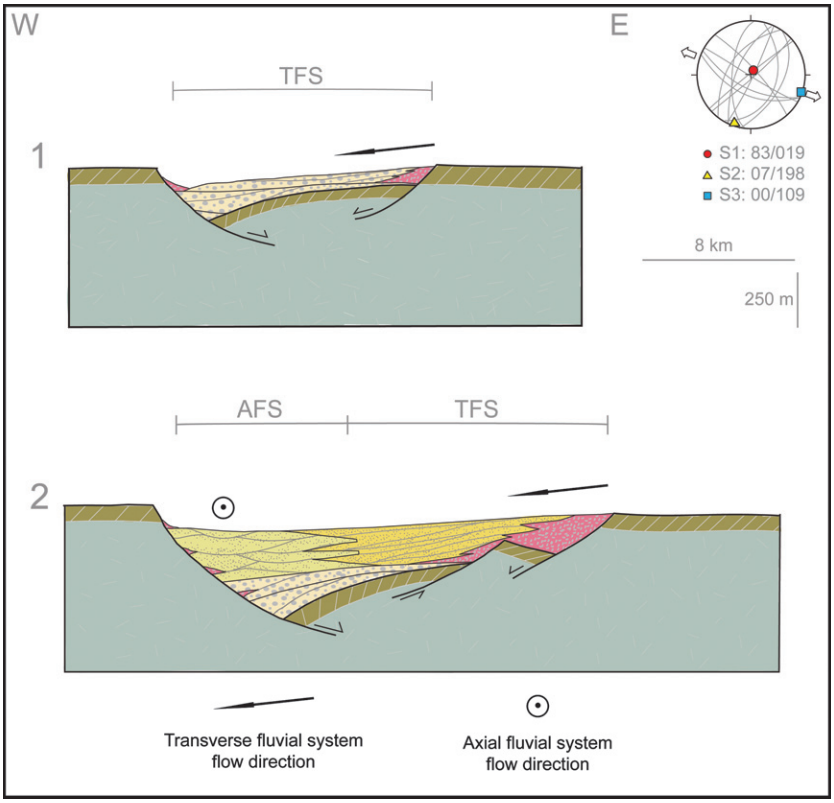

Fig. 18. Two-dimensional interpretation of the evolution of the Guarda Velha fluvial system and the associated basin-scale structures: (1) Early rift; (2) Climax rift. Upper right: example of basin structures associated with the Guaritas rifting event, with the interpreted palaeostress fields (S1 to S3), Schimidt projection, lower hemisphere (n = 18). Note the basin-widening event between (1) and (2).

opportunity for the deposition of mud, which would be transported in suspension and bypassed downstream. The open-system characteristics of the Camaquã basin probably contributed to such bypass. Alternatively, the low proportion of mud in this system might be a result of slower rates of chemical weathering as a result of the absence of deep-penetrating plant-root systems (Long, 2004). However, where and when suitable conditions for accumulation occurred, mud did accumulate locally and was preserved in abandoned channels and incipient floodplains.

CONCLUSIONS

Three fluvial styles have been recognized in the Guarda Velha Formation (Cambrian, southern Brazil) through detailed analysis of lithofacies, depositional architecture, palaeocurrent data and pebble-provenance studies. The lowermost (oldest) recognized fluvial system is related to the initial subsidence of the area during an early stage of rift-basin development and is characterized by conglomeratic braided channels and bars in an arrangement indicative of a distributive fluvial system. The two overlying fluvial systems accumulated coevally but are differentiated on the basis of each having distinct morphological and architectural characteristics, and differing relations to the local tectonic basin setting. One of these systems can demonstrably be shown to be the preserved succession of a perennial major trunk river, with preserved lithofacies and architectural elements indicative of braided channels and associated longitudinal bars that underwent both lateral and downstream accretion. The other system is distinguished mostly by the preservation of deposits indicative of repeated (and probably frequent) high discharge variation and is indicative of a perennial distributive fluvial system aligned transverse to the basin axis that flowed towards and contributed to the major trunk river. Both of these fluvial systems apparently evolved coevally throughout the climax rift-stage and both are interpreted as perennial fluvial streams, despite probably experiencing considerable differences in total discharge and its variability (particularly in the transverse fluvial system). The identification of two distinct, perennial fluvial systems fed by two different source areas, with one of these systems – the transverse river system – having been fed by a relatively local source area (indicated by sources located in the eastern basin margin),

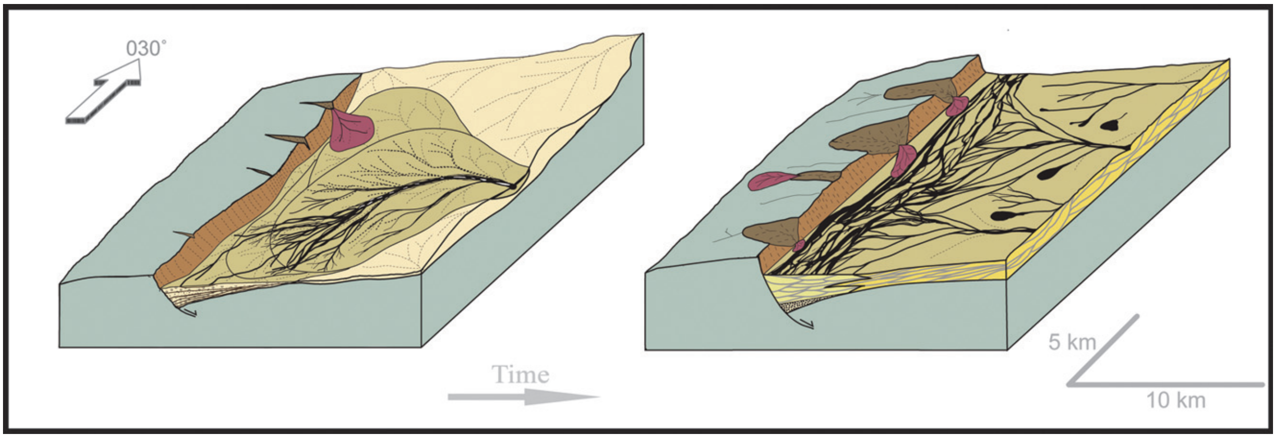

Fig. 19. Reconstruction of the palaeogeographic evolution of the Guarda Velha fluvial system.

suggests a regional semi-humid to humid palaeoclimate for the regional depositional setting.

Although several aspects of the behaviour and preserved architectural style of pre-vegetation fluvial deposits are known to mimic those of modern-day arid fluvial systems, the Guarda Velha Formation demonstrates that simultaneous deposition of different facies assemblages in a pre-vegetation fluvial plain can give rise to apparently contrasting interpretations of the external controls on deposition. This may be the case where different parts of the fluvial plain are fed by distinct catchment areas and are located in different positions in relation to the basin axis, resulting in different patterns of discharge variation occurring simultaneously in the axial river system and its contributory system. Different rates of subsidence and accommodation generation controlled by tectonic basin setting probably served as a primary control on the preservation of the different depositional architectures.

The succession preserves a great variety of types of bedform elements, many nested hierarchically within channelized elements. Despite the absence of vegetation cover, the fluvial systems discussed here were able to develop long-lived, major channelized networks; this is different from many Cambrian fluvial systems interpreted in the literature as sheet-braided styles (e.g. Todd & Went, 1991; Davies *et al.*, 2011), although those were preserved in different tectonic settings (cratonic basins). Other Cambrian fluvial systems in the literature, such as the Rozel Conglomerate Formation from the British Channel Islands (Went, 2005), were also able to develop channelized elements. Apparently, to date, the Guarda Velha Formation is the only example in the literature documenting the preservation of the inter-fingering relation of pre-vegetation axial and transverse systems. The preservation of such varied fluvial styles characterized by channel elements with high width-to-depth ratios similar to those described for ‘sheet-braided’ styles (e.g. Cotter, 1978; Davies *et al.*, 2011) was probably determined by the tectonic context (i.e. rift basin), demonstrating that new studies on pre-Silurian deposits can still provide valuable information for discussions regarding the form of the landscape on the continents prior to land-plant colonization. These results collectively suggest that the ‘sheet-braided’ fluvial style encompasses a varied number of pre-vegetation fluvial styles, each with distinct preserved architectures characterized by channel elements which exhibit high width to depth ratios. In this way, the present authors propose that the term ‘sheet-braided’ should be expanded in order to contain a number of different sub-groups containing distinct pre-vegetation fluvial styles.

Existing facies models for pre-vegetation fluvial systems are not necessarily effective in accounting for climate and palaeoenvironmental controls. Resolution of climate and environmental signatures for these kinds of fluvial systems is not straightforward, and must consider spatial variation of depositional architecture and relation to palaeocurrent and provenance data. Pre-vegetation fluvial systems can be as complex as many present-day fluvial systems, despite the absence of vegetation cover. This work has applied implications, including the development of more sophisticated predictive depositional models with which to characterize subsurface reservoir intervals developed in pre-Silurian fluvial successions.

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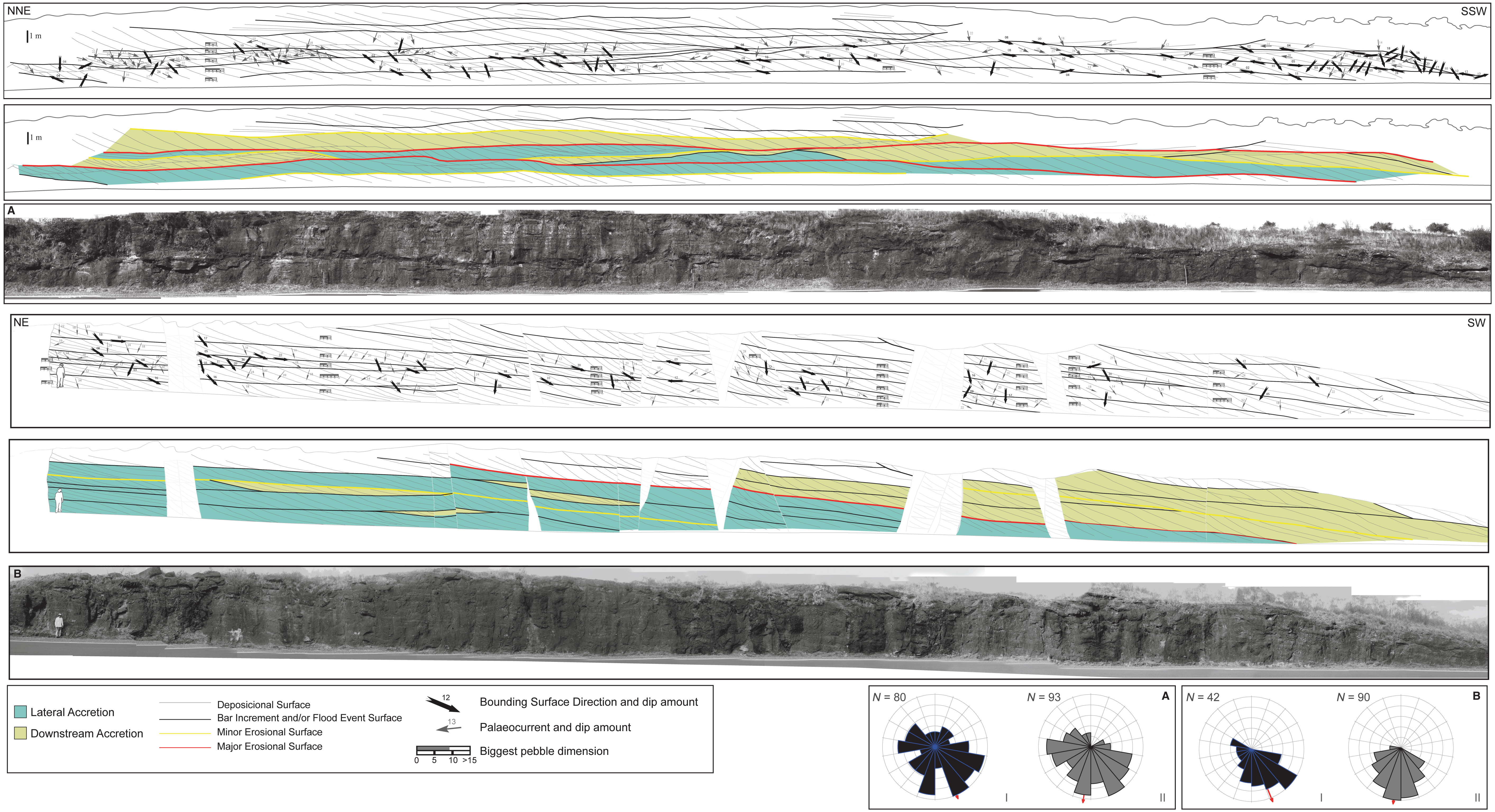
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