Tectonics and sedimentation in a paleo/mesoproterozoic rift-sag basin (Espinhaço basin, southeastern Brazil)

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Abstract

Sedimentologic, paleogeographic, stratigraphic, structural and tectonic studies in a paleo/mesoproterozoic metasedimentary succession (Espinhaço Megasequence, southeastern Brazil) indicates deposition in a rift-sag basin. Four basin evolution stages are recognized (prerift, rift, transitional and flexural). The four stages can be represented by six unconformity-bounded tectonosequences. The unconformities are recognized in the field and mappable even on a regional scale. The prerift and rift stages of the Espinhaço basin were filled by products of continental depositional systems. The prerift stage probably represents the first product of the rifting process, before the development of the half-grabens that characterize the rift stage. During the rift stage, mechanical subsidence due to lithospheric stretching was predominant and led to episodic rising of the depositional base level. As a result, the basin fill is characterized by coarsening-upward intervals. Paleocurrent patterns indicate that block tilting and half-graben subsidence/uptilt controlled sediment dispersion. The first marine incursion within the Espinhaço basin marks the change in the subsidence regime of the basin. The evolution of the transitional and flexural stages was probably controlled by thermal subsidence due to thermal contraction of the lithosphere during cooling. The transitional stage was characterized by relatively low subsidence rates. Higher subsidence rates and a consequent sea-level rise characterize the flexural stage of the Espinhaço basin, in which three second-order transgressive-progradational sequences can be recognized. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Brazil; Proterozoic; Tectonostratigraphic units; Basin analysis; Tectonics; Sedimentation

1. Introduction

Rift-sag basins represent the tectonic product of aborted passive-margin development (Allen and Allen, 1990). These basins, commonly referred to as aulacogens or failed rifts, display a 'steer's head' geometry due to early rifting and subsequent thermally-driven downwarping (White and McKenzie, 1988). The stratigraphic framework, structural style, and tectonic evolution of rift-sag basins have been interpreted mainly through seismic reflection profiles (e.g. Meyerhoff, 1982; Schlee and Hinz, 1987; Badley et al., 1988). With exceptions (e.g. Eriksson et al., 1993), few
Fig. 1.
examples based on direct field observations have been published.

Deposits of the paleo/mesoproterozoic Espinhaço basin outcrop in the central and western parts of the Serra do Espinhaço, southeastern Brazil (Fig. 1). Because of inversion during the neoproterozoic (Brasiliano/Pan African orogeny), and because of a deep erosional level, the Espinhaço basin provides an opportunity to evaluate the paleogeographic and tectonic evolution of a rift-sag basin through outcrop data. Of particular importance, deposits recording initial rifting are exposed. These constitute a valuable source of data to characterize the three-dimensional architecture of an early half-graben, and to document the relationships between tectonics and sedimentation that might not be available through geophysical studies alone.

This paper presents a model for the tectono-sedimentary evolution of the Espinhaço rift-sag basin, based on geological mapping and integrated sedimentologic, paleogeographic, stratigraphic, structural and tectonic studies, carried out in the central and western parts of the southern Serra do Espinhaço, Brazil (Fig. 1). Early workers (e.g. Pflug, 1965) described the Espinhaço supergroup as a miogeosynclinal sequence. Subsequently, a rift to passive-margin setting was proposed (Pflug et al., 1980), and Martins-Neto (1993), Schobbenhaus (1993), Dussin and Dussin (1995) suggested, based on the ensialic setting and stratigraphic framework, deposition in an intracratonic basin, with an initial rift phase and a subsequent flexural phase. The present paper provides detail documenting the prerift, rift, transitional and flexural stages of basin evolution.

2. Regional setting

The southern Serra do Espinhaço belongs to the external zone of the Araçuaí fold-thrust belt,
along the southeastern margin of the neoproterozoic São Francisco craton, southeastern Brazil (Fig. 1; Brito Neves and Cordani, 1991; Trompette et al., 1992; Schobbenhaus, 1993; Alkmim et al., 1993; Martins-Neto, 1998a). The paleo/mesoproterozoic Espinhaço supergroup (Fig. 2) is the predominant unit in the southern Serra do Espinhaço, overlying the archean basement complex and supracrustal rocks of the archean/paleoproterozoic Rio Paraúna supergroup unconformably (Pflug, 1965). It is in turn unconformably overlain by the neoproterozoic São Francisco supergroup (Fig. 2; Pflug and Renger, 1973; Dupont, 1996; Martins-Neto et al., 1997a,b, 1999a).

The maximum age of the Espinhaço supergroup is limited by U/Pb dating of metamorphic zircon in pre-Espinhaço units (1844 ± 15 Ma; Machado et al., 1989), and depositional ages from magmatic zircons in volcanic-bearing units in the lower parts of the Espinhaço supergroup include, (1) 1711 Ma (U/Pb; N. Machado oral commun., 1993; in Schobbenhaus, 1993); (2) 1710 ± 12 Ma (207Pb/206Pb; Dussin and Dussin, 1995); and (3) 1715 ± 2 Ma (U/Pb; Machado et al., 1989). The minimum age of the Espinhaço supergroup is less constrained, and is currently defined by basic intrusions that cut the entire column (ca. 1.1–0.9 Ga; Brito Neves et al., 1979; Machado et al., 1989).

The southern Serra do Espinhaço was deformed and metamorphosed in the Brasiliano/Pan African event (650–500 Ma, Brito Neves et al., 1979; Marshak and Alkmim, 1989; Schobbenhaus, 1993), a major collisional episode that generated a fold-trust terrane throughout the southern Serra do Espinhaço (Herrgesell and Pflug, 1986).
3. Stratigraphic framework

The Espinhaço supergroup is a thick (~4000 m) succession of siliciclastic metasedimentary rocks containing subordinate volcanic intervals (Fig. 2). These have been grouped lithostratigraphically into nine formations (Pflug, 1968; Almeida Abreu and Pflug, 1992). Herein, adopting a genetic stratigraphic approach, the Espinhaço supergroup is referred to as the ‘Espinhaço Megasequence’, which is the record of an unconformity-bounded, single basin-fill cycle. The basin-fill cycle is composed of six tectonosequences, from bottom to top (Figs. 3 and 4), the Olaria tectonosequence (prerift stage), the Natureza, São João da Chapada and Sopa-Brumadinho tectonosequences (rift stage); the Galho do Miguel tectonosequence (transitional stage) and the Conselheiro Mata tectonosequence (flexural stage). Each tectonosequence records linked depositional systems accumulated in a specific tectonic phase of the basin, and is defined by major regional bounding unconformities (Fig. 4; Da Silva, 1993; Martins-Neto, 1995a,b). These unconformities represent periods of significant tectonically induced paleogeographic reorganization.

During the rift stage, mechanical subsidence due to lithospheric stretching controlled basin evolution. The transitional and flexural stages were controlled by thermal subsidence arising from contraction of the lithosphere due to cooling.

The genetic stratigraphic approach adopted herein is based on the definition of a major unconformity-bounded megasequence, allowing recognition and analysis of a true basin entity, even though its life span is not well constrained. Each tectonosequence represents the record of an evolutionary stage of the basin, with its own accommodation history. Contacts are recognized in the field and mappable even on a regional scale (Fig. 5).

4. Prerift stage: Olaria tectonosequence

The prerift stage of the Espinhaço basin is represented by the poorly-exposed Olaria tectonosequence. The unit is ca. 150 m thick. It consists mainly of sheet-like bodies of immature fine-grained, parallel-stratified sandstones (Fig. 6) that contain local current ripples and cross-stratification, and are locally capped by thin layers of...
Fig. 5. Geologic map of tectono-stratigraphic units of the central part of the southern Espinhaço range (see Fig. 1 for location), southeastern Brazil (modified from Reis, 1999; Euzébio, 1999; Martins-Neto et al., 1999b). Inset shows location of Fig. 7.
Fig. 6. Photograph showing sheet-flood sandstones of the Olaria braidplain deposits. Note hammer (circled) for scale.

interpretations are limited by poor outcrop and high strain, the lack of volcanic rocks and of evidence of synsedimentary faults (in contrast to overlying sequences) suggest that the Olaria tectonosequence was deposited in an initial sag that was the product of ductile stretching, before the upper crust had reached its elastic limit. However, clastic dykes filled by conglomeratic sandstones occur at the top of the Olaria tectonosequence. These are truncated at the angular unconformity with the overlying Natureza tectonosequence, and are likely precursors of active shallow-level faulting.

5. Rift stage: Natureza; São João da Chapada; Sopa-Brumadinho tectonosequences

The rift stage of the Espinhaço basin is characterized by three phases all of which are bounded by angular unconformities (Figs. 4, 5 and 7), synrift 1 (Natureza tectonosequence); synrift 2 (São João da Chapada tectonosequence); and synrift 3 (Sopa-Brumadinho tectonosequence).

5.1. Synrift 1 phase (Natureza tectonosequence)

The Natureza tectonosequence is up to 200 m thick (cf. Reis, 1999). Massive and inversely graded clast-supported conglomerates interpreted as debris-flow deposits (Fig. 8a) occur above the

<table>
<thead>
<tr>
<th>Depositional setting</th>
<th>Key lithologies</th>
<th>Sedimentary features</th>
<th>Depositional process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alluvial braidplain</td>
<td>Poorly-sorted, medium to fine-grained sandstones</td>
<td>Parallel-stratification, sheet like geometry</td>
<td>Sheet floods under upper flow regime</td>
</tr>
<tr>
<td></td>
<td>Poorly-sorted, medium to fine-grained sandstones</td>
<td>Trough cross-stratification</td>
<td>3D-dune migration (sensu Ashley, 1990) under lower flow regime</td>
</tr>
<tr>
<td></td>
<td>Poorly-sorted, medium to fine-grained sandstones</td>
<td>Planar cross-stratification</td>
<td>2D-dune migration (sensu Ashley, 1990) under lower flow regime</td>
</tr>
<tr>
<td></td>
<td>Fine-grained sandstones</td>
<td>Ripple cross-lamination</td>
<td>Current-ripple migration</td>
</tr>
<tr>
<td></td>
<td>Pelites</td>
<td>Thin mud drapes</td>
<td>Floodplain deposits</td>
</tr>
<tr>
<td></td>
<td>Fine-grained sandstones</td>
<td>Metric thick bodies</td>
<td>Vertical accretion</td>
</tr>
<tr>
<td></td>
<td>Pelites</td>
<td>Metric thick cross-beds with high-angle (30–35°) truncations</td>
<td>Eolian dune migration</td>
</tr>
<tr>
<td>Lacustrine</td>
<td>Hypermature fine-grained sandstones</td>
<td></td>
<td></td>
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<tr>
<td>Eolian</td>
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basal angular unconformity. The debris-flow conglomerates are associated with clast- and matrix-supported stratified conglomerates considered as traction deposits (Fig. 8b) and are interpreted as having been deposited in an alluvial fan and braided stream depositional system. The conglomeratic deposits are covered by a sandy braided fluvial succession (Fig. 8c) interbedded with eolian sandstones (Fig. 8d, Table 2) (Silva, 1995; Reis, 1999).

Conglomerate sections and the angular character of the unconformity at the base of the Natureza tectonosequence are suggestive of tectonic influence such as block tilting or selective uplift and/or subsidence. This signifies rupture of the upper crust and the development of the first half-grabens in the Espinhaço basin. The limited areal extent of the Natureza tectonosequence suggests a restricted character of the basin at this time. The absence of volcanic rocks infers a stretching factor $\beta$ (White and McKenzie, 1988) of less than 2 for this phase.

5.2. Synrift 2 phase: (São João da Chapada tectonosequence)

The São João da Chapada tectonosequence is up to 300 m thick. Locally, above the angular unconformity (Fig. 9), conglomerates and breccias contain abundant sandstone clasts derived from the underlying Natureza tectonosequence. These have been interpreted as fault-scarp talus deposits formed by cohesionless mass-flows, and are strong indicators of repeated local fault uplift and cannibalization as part of the rifting process (Martins-Neto, 1993).

The onset of volcanism in the evolution of the Espinhaço basin is marked by basic rocks near the base of the São João da Chapada tectonosequence (Hoppe and Otto, 1982; Uhlein, 1991; Schobbenhaus, 1993; Dussin, 1994; Dussin and Dussin, 1995). Layers of hematitic phyllites within these units have been interpreted as volcanic beds altered by Paleoproterozoic subaerial weathering (lateritization) and subsequent metamorphism (Knauer and Schrank, 1993).

The São João da Chapada tectonosequence defines an overall coarsening-upward succession from lacustrine to deltaic to fluvial deposits (Fig. 10). Fine-grained sandstones and pelites at the base, probably deposited in a storm-influenced lacustrine environment, represent rapid subsidence and abrupt basin deepening. These are overlain by sandstone bodies of likely deltaic origin that display a sigmoidal geometry and are arranged in coarsening- and thickening-upward sequences. Prograding over the deltaic/lacustrine deposits are extensive braidplain sandstones that
Fig. 8. Photographs showing deposits of the synrift 1 Natureza tectonosequence, (a) Debris-flow conglomerates. Note inverse grading in the body comprising the lower half of the outcrop; (b) stratified, sheet-flood conglomerates. Note hammer (circled) for scale; (c) horizontally stratified (Sh) and trough cross-stratified sandstones (St) of braided fluvial origin; (d) metric-scale cross-stratified sandstones of eolian origin.

constitute ca. 80% of the São João da Chapada tectonosequence. These signify relatively reduced rates of subsidence (Martins-Neto, 1993, 1994).

The São João da Chapada braidplain deposits (Table 3, Fig. 11a) are characterized by sheet-like bodies of coarse and poorly-sorted sandstones that display unidirectional paleocurrents with remarkably little dispersion throughout the study area (Fig. 11b). The sandstones generally define fining- and thinning-upward sequences and are invariably bounded by low-relief erosional surfaces (Martins-Neto, 1994). Typical sequences start with parallel-stratified and low-angle cross-stratified sandstones (Sh/Sl) and are capped by trough cross-stratified sandstones (St) and locally, mudstone layers, characteristic of high-energy ephemeral streams (e.g. Miall and Gibling, 1978; Tunbridge, 1981, 1984; Lawrence and Williams, 1987; Muñoz et al., 1992). As detailed elsewhere (Martins-Neto, 1994), the superposition of such waning-flood sheet sandstones built up a braidplain that extended ca. 35 km transverse to the regional paleoslope (Fig. 12).

5.3. Synrift 3 phase (Sopa-Brumadinho tectonosequence)

The Sopa-Brumadinho tectonosequence records the peak of extensional tectonics in the Espinhaço basin. Deposits of this phase define fault-block related depocenters (see Fig. 5 and also cross-sections in Fig. 16), and consist of siliciclastic metasediments and bimodal metavolcanic rocks (greenstones, hematitic phyllites and rhyolites), reaching thicknesses up to 800 m (Reis, 1999; Martins-Neto et al., 1999b). The unit is limited at its base by a prominent angular unconformity and at its top by a marine transgressive surface. As
Table 2
Facies of the Natureza tectonosequence and interpretation

<table>
<thead>
<tr>
<th>Facies</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massive to inversely graded, clast-supported</td>
<td>Debris flows</td>
</tr>
<tr>
<td>conglomerates</td>
<td></td>
</tr>
<tr>
<td>Parallel-stratified, matrix-supported</td>
<td>Traction deposits</td>
</tr>
<tr>
<td>conglomerates</td>
<td></td>
</tr>
<tr>
<td>Parallel-stratified, poorly-sorted sandstones</td>
<td>Sheet floods under upper flow regime</td>
</tr>
<tr>
<td>Trough cross-stratified, poorly sorted sandstones</td>
<td>Fluvial 3D-dune migration (sensu Ashley, 1990) under lower flow regime</td>
</tr>
<tr>
<td>Planar cross-stratified, poorly sorted sandstones</td>
<td>Current-ripple migration</td>
</tr>
<tr>
<td>Ripple cross-laminated sandstones</td>
<td>Floodplain deposits</td>
</tr>
<tr>
<td>Pelites</td>
<td>Eolian dune migration</td>
</tr>
<tr>
<td>Hypermature fine-grained, metric thick cross-bedded sandstones</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 9. Photographs showing (a) view of the angular unconformity separating the Natureza and São João da Chapada tectonosequences and (b) detail emphasizing the erosional nature of this unconformity.

discussed in the following sub-headings, lacustrine, fan-delta and fluvial sedimentation took place in half-grabens that were compartmentalized by north-trending normal faults and east-trending transfer faults. Subsidence was episodic and controlled by block tilting in asymmetric grabens.

5.3.1. Lacustrine, fan-delta and fluvial deposits

The facies of the Sopa-Brumadinho tectonosequence are arranged in 40–80 m thick sequences that coarsen and then fine upward (Fig. 13a and b). At the base of each sequence are laminated pelites (facies F). These are followed by, graded and stratified sandstone beds (facies Sg); massive, parallel-stratified, trough cross-stratified, and planar cross-stratified sandstones (facies Sm, Sh, St, and Sp); and predominantly debris flow conglomeratic units (Table 4). The conglomerates then fine upward to various sandstone facies (Fig. 13a). Some sequences lack the lower turbiditic graded sandstone component, and laminated mudstones pass directly to stacked streamflood sandstones (e.g. Fig. 13b). Mudlumps, formed by the rapid loading of debris-flows onto water-saturated muds (Dailly, 1976; Lewis, 1997) are locally developed. An approximately 200 m thick section of parallel-stratified, trough cross-stratified and planar cross-stratified sandstones (± pelites) intervenes within the predominantly cyclic succession (Reis, 1999; Martins-Neto et al., 1999b).

Table 4 summarizes the 13 facies of the Sopa-Brumadinho tectonosequence and their interpretation. More detailed descriptions of these facies and the sedimentary processes that generated them can be found in Martins-Neto (1995d, 1996b).

These rocks were likely deposited in a lacustrine fan-delta to fluvial system (cf. Nemec and Steel, 1988). The coarsening-upward and fining-upward
Fig. 10. (a) Outcrop section (see Fig. 7 for location) showing the overall coarsening-upward arrangement from lacustrine to deltaic to fluvial deposits of the São João da Chapada tectonosequence; (b) detail showing the thickening-upward arrangement of the initial deltaic progradation.

Table 3
Facies of the São João da Chapada braidplain deposits (codes modified after Miall, 1978)

<table>
<thead>
<tr>
<th>Code</th>
<th>Characteristics</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gm</td>
<td>Massive to parallel-stratified conglomerates</td>
<td>Migration of longitudinal bars</td>
</tr>
<tr>
<td>Sh/Si</td>
<td>Parallel-stratified to low-angle (&lt;10°) cross-stratified sandstones</td>
<td>Sheet floods under upper flow regime</td>
</tr>
<tr>
<td>St</td>
<td>Trough cross-stratified sandstones</td>
<td>3D-dune migration (sensu Ashley, 1990) under lower flow regime</td>
</tr>
<tr>
<td>Sp</td>
<td>Planar cross-stratified sandstones</td>
<td>2D-dune migration (sensu Ashley, 1990) under lower flow regime</td>
</tr>
<tr>
<td>Sr</td>
<td>Ripple cross-laminated sandstones</td>
<td>Current-ripple migration</td>
</tr>
<tr>
<td>F</td>
<td>Pelites</td>
<td>Floodplain deposits</td>
</tr>
</tbody>
</table>
sequences are interpreted to represent repeated episodes of rapid flooding (basal laminated mud units) followed by progradation of fan lobes which evolved from distal (subaqueous) to proximal (subaerial) environments. The fining-upward parts represent the abandonment phases of the depositional lobes. Discriminating between lacustrine and shallow marine deposits is commonly difficult in Precambrian strata (e.g. Eriksson et al., 1998). A lacustrine origin is favored in the present example because pelitic rocks of facies F define a number of isolated N–S elongate lenses.

5.3.2. Tectonically-driven cyclicity

The lacustrine, fan-delta and fluvial coarsening-upward and fining-upward sequences are considered to represent repeated tectonically-driven pulses (see e.g. Blair and Bilodeau, 1988). Accordingly, flood surfaces and pelitic rocks at the base of each sequence are the immediate response to fault-induced subsidence of the basin floor, and subsequent fan-delta progradation records a delayed response, reflecting erosional stripping of relatively uplifted source areas. Fining-upward trends at the top of the sequences signify a reduction in source-area relief during continued tectonic quiescence.

Those successions where fan-delta progradation initiated with sandy turbidity currents (e.g. Fig. 13a), may indicate deeper lakes formed by greater subsidence, whereas those in which laminated pelites pass directly to streamflow sandstones (e.g. Fig. 11).
Fig. 12. Schematic paleogeographical reconstruction of the São João da Chapada braidplain. L, longitudinal; T, transverse (sensu Miall, 1981). Not to scale (modified after Martins-Neto, 1993).

Fig. 13b) may imply shallower lakes. Smaller-scale pulses may be recorded by thin pelite layers interbedded with some of the sandstones near the base of the sequences (Fig. 13a and b and Fig. 14a). Although post-depositional processes have strongly modified the original thicknesses of these layers, thickness variation suggests varying subsidence pulse magnitudes.

5.3.3. Half-graben geometry

In regional cross section, fan development is asymmetric. In the west, diamond mining operations have exposed the spatial and angular relationships between two fan-deltas (Fig. 14a). The younger lobe (Lavrinha mine) forms a wedge positioned basinward of an older fan segment (Diamante Vermelho mine). Correction for tectonic tilt using marine deposits of the overlying Galho do Miguel tectonosequence as a paleohorizontal datum, yields a primary dip of ca. 10°–15° for the older fan segment and ca. 5°–10° for the younger fan. These results are compatible with published data of recent fan slopes (cf. Wells, 1984; Blair and McPherson, 1994). Basinward stepping and increasing angle of tilt with age (reflecting progressive rotation due to faulting) is characteristic of many fans, modern and ancient (e.g. Hooke, 1972; Steel et al., 1977; Heward, 1978a,b; Kleinspehn et al., 1984; Blair, 1987). In contrast to these basinward stepping lobes, to the northeast, at the Brumadinho mine (Fig. 14b), clast-supported talus breccias form vertically stacked linear bodies in direct fault contact with older rocks. The two types of fans (Fig. 15) as well as the geologic map and the cross-section A–A′ in Fig. 16 indicate an asymmetric-graben geometry, with the Diamante Vermelho/Lavrinha system representing hanging-wall sourced fans at the unfaulted ramping margin, and the Brumadinho fans marking footwall sourced fans at the faulted border (cf. Hooke, 1972; Gawthorpe and Colella, 1990).

5.3.4. Synsedimentary faults

East-trending transfer faults can be recognized (Figs. 5 and 16). Paleocurrent patterns illustrate the control exerted by transfer faults and fault-bounded blocks on sediment dispersal (Fig. 16). North of an east-trending transfer fault located
Fig. 13. Measured sedimentological sections of the Sopa-Brumadinho tectonosequence (a and b). Section 1 (a) was measured in the Diamante Vermelho and Lavrinha diamond mines (see also Fig. 14a) and section 2 (b) was measured in the Sopa mine (see Fig. 1 for location of the localities). (c) Paleocurrent data from the Sopa-Brumadinho tectonosequence (rose diagram summarizes 319 measurements from cross-stratified sandstones from the whole unit in the studied area). Modified after Martins-Neto (1993).
Table 4


<table>
<thead>
<tr>
<th>Code</th>
<th>Characteristics</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>UG-CS</td>
<td>Ungraded clast-supported conglomerates</td>
<td>Cohesionless debris flows</td>
</tr>
<tr>
<td>IG-CS</td>
<td>Inversely graded clast-supported conglomerates</td>
<td>Cohesionless debris flows</td>
</tr>
<tr>
<td>NG-CS</td>
<td>Normally graded clast-supported conglomerates</td>
<td>Cohesionless debris flows</td>
</tr>
<tr>
<td>CS-CS</td>
<td>Crudely stratified clast-supported conglomerates</td>
<td>Hyperconcentrated flows</td>
</tr>
<tr>
<td>TB-CS</td>
<td>Talus-breccia clast-supported conglomerates</td>
<td>Fault-adjacent talus breccias</td>
</tr>
<tr>
<td>S-MS</td>
<td>Sand matrix-supported conglomerates</td>
<td>Cohesionless debris flows</td>
</tr>
<tr>
<td>M-MS</td>
<td>Mud matrix-supported conglomerates</td>
<td>Cohesive debris flows</td>
</tr>
<tr>
<td>Sm</td>
<td>Massive sandstones</td>
<td>Hyperconcentrated flows</td>
</tr>
<tr>
<td>Sh</td>
<td>Parallel-stratified sandstones</td>
<td>Sheet floods under upper flow regime</td>
</tr>
<tr>
<td>St</td>
<td>Trough cross-stratified sandstones</td>
<td>3D-dune migration (sensu Ashley, 1990)under lower flow regime</td>
</tr>
<tr>
<td>Sp</td>
<td>Planar cross-stratified sandstones</td>
<td>2D-dune migration (sensu Ashley, 1990)under lower flow regime</td>
</tr>
<tr>
<td>Sg</td>
<td>Graded-stratified sandstones</td>
<td>Turbidity currents</td>
</tr>
<tr>
<td>F</td>
<td>Pelites</td>
<td>Vertically accreted lacustrine deposits</td>
</tr>
</tbody>
</table>

Several minor north-trending normal faults are preserved in the Sopa-Brumadinho deposits. These structures do not cut overlying beds, demonstrating that they formed as synsedimentary growth faults (Fig. 17). East-trending ‘release faults’ (Destro, 1995) are normal faults that terminate against, and accommodate differential displacement along, the north-trending structures (Fig. 18).

5.3.5. Bimodal volcanic rocks

Mafic and felsic volcanic rocks form local interbeds in the Sopa-Brumadinho tectonosequence. The rhyolites and their intrusive counterparts (Borrachudos Suite) display a metaluminous to subalkalic character and are enriched in K, Fe, Nb, Y, Zr, Ga and light REE (Dussin, 1994; Dussin and Dussin, 1995). According to Dussin and Dussin (1995), the geochemical data and isotopic compositions of Nd ($^{143}$Nd/173Sm between $-10.1$ and $-6.2$) and of Sr ($^{87}$Sr/$^{86}$Sr = 0.7057) indicate partial melting of crustal sources, typical of continental rift settings.

6. Transitional stage: Galho do Miguel tectonosequence

The first marine incursion within the Espinhaço Basin, represented by deposits of the Galho do Miguel tectonosequence, marks the beginning of the transitional stage (Martins-Neto, 1993). A regionally mappable transgressive surface separates these deposits from the underlying rift succession (Figs. 5, 14, 16 and 19). The Galho do Miguel tectonosequence contains basal shallow-marine deposits that onlapped underlying units from the east, and extensive eolian sand sheets that prograded from the west (Table 5).

Wave and storm-dominated siliciclastic shelf deposits define a lower transgressive succession and an upper progradational succession (Table 5, Fig. 20a). Paleocurrent data (Fig. 20b) and facies distribution suggest a north-trending shoreline and east-dipping paleoslope. In the transgressive succession, shoreface, transition-zone and offshore deposits can be recognized. In the prograda-
tional succession, a complete offshore to coastal suite of facies is developed (offshore, transition zone, lower shoreface, upper shoreface, beach, eolian). In contrast to underlying units, overall rates of sediment supply were low relative to rates of subsidence and/or sea-level rise. The initial transgressive succession probably reflects an inadequate sediment supply compared with the rate of relative sea-level rise, whereas the progradational succession probably resulted from sediment supply exceeding relative sea-level rise.

The paleogeography of the Galho do Miguel tectonosequence was strongly controlled by the final disposition of earlier rift stages. This is illustrated by the distribution of eolian deposits (Figs. 5 and 21). Above synrift 3 (Sopa-Brumadinho tectonosequence) depocenters, the dune fields prograded eastward, whereas above structural highs eolian deposits are thin or absent, and eolian dunes did not reach the eastern parts of the Espinhaço range.

The Galho do Miguel tectonosequence marks the change from predominantly mechanical, locally compensated subsidence to thermal, regionally compensated subsidence. This transitional stage was characterized by relatively low subsidence rates by comparison to the previous and subsequent stages. The resultant decrease in accommodation space caused enlargement of the basin, as the sediment supply was maintained. In addition, increased flexural rigidity due to lithospheric cooling likely favored basin widening.

7. Flexural stage: Conselheiro Mata tectonosequence

The deposits of the flexural stage of the Espinhaço basin belong to the ca. 900 m thick Consel-
Fig. 15. Sketch showing the spatial relationship between depositional lobes in half-grabens, (a) progradational relationship between hanging-wall-derived fans at the flexural border (see Fig. 14a and section AA’ on Fig. 16) and (b) aggradational relationship (vertically stacked) between footwall-derived fans at the fault border (see Fig. 14b and section AA’ on Fig. 16) (modified from Heward, 1978b).

heiro Mata tectonosequence. The base of this unit is defined by a maximum flooding surface, which marks the greatest expansion of the Espinhaço sea (Martins-Neto, 1995b; Espinoza, 1996). Locally, the lower boundary is defined by multiple shoaling-upward sequences 10–20 m thick (Fig. 22; Espinoza, 1996).

According to Dupont (1995), three depositional sequences with a transgressive base and a progradational top can be recognized in the Conselheiro Mata tectonosequence (Fig. 23). The first sequence (250–400 m thick) contains transgressive barred nearshore deposits and progradational beach to shallow-marine deposits (Dupont, 1995; Espinoza, 1996). The second sequence (250–350 m thick) comprises transgressive shelf deposits overlain by progradational alluvial plain to coastal successions (Dupont, 1995). The third sequence (200–300 m thick) is defined by transgressive mixed siliciclastic–carbonate shelf deposits overlain by coastal to fluvial sediments (Batista et al., 1986; Dupont, 1995). The top of the third depositional sequence marks the final filling up of the Espinhaço basin. The thicknesses (ca. 300 m) and the estimated time (some 10 million years) for deposition of each sequence suggest that they may represent tectonically controlled second-order cycles. These second-order cycles could be the
Fig. 16. Geological map of the Sopa-Guinda area (simplified from Reis, 1999; Martins-Neto et al., 1999b) showing paleocurrent diagrams for different localities (see text for explanation), as well as schematic, not-scaled cross-sections. Numerals adjacent to the rose diagrams represent number of measurements. Symbols in the sections are consistent with the map, except the gray fill, which represents lacustrine pelites of the Sopa-Brumadinho tectonosequence.
8. Discussion

Some aspects regarding the evolution of the Espinhaço basin remain uncertain. One important question concerns the larger-scale structure of the rift stage. The dimensions of the half-grabens described above indicate that they are relatively minor structures, and evidence of linkage to a master fault is lacking. However, the predominance of eastward-directed paleocurrents in deposits related to lateral-transport systems (Leeder and Gawthorpe, 1987) may indicate a master fault located to the east, outside the study area (see Martins-Neto, 1994, 1996b). Thick conglomeratic successions in the eastern domains of the Espinhaço range may be related to such a master fault, but full documentation is inhibited by intense Brasiliano/Pan African deformation.

A second question concerns the apparent limited thickness (ca. 1300 m) of synrift deposits. Synrift volcanic rocks provide a rough estimate for the inferred basin stretching factor of 2–3, predicting a thicker synrift fill. The relatively thin observed deposits may be partly due to syndepositional cannibalization, as illustrated by abundant intraformational clasts at the base of the São João da Chapada tectonosequence. In addition, only the external and consequently thinner portion of the synrift wedge, close to the rift flexural border, occurs in the studied area (Fig. 24). The postulated rift master fault located in the eastern domains of the Espinhaço range may also account for the thin synrift stratigraphic
Fig. 19. Outcrop section and interpretation sketch showing transgressive surface separating lacustrine pelites and a small deltaic lobe of the rift stage from shallow-marine transgressive deposits of the Galho do Miguel tectonosequence (transitional stage) (modified after Martins-Neto, 1993).

Table 5
Summary of the depositional characteristics of the Galho do Miguel tectonosequence

<table>
<thead>
<tr>
<th>Depositional setting</th>
<th>Key lithologies</th>
<th>Sedimentary features</th>
<th>Depositional process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eolian</td>
<td>Hypermature fine-grained sandstones</td>
<td>Metric to decametric thick cross-beds; ripple marks; bimodal lamination</td>
<td>Eolian dune migration by combination of sand-flow and sand-fall</td>
</tr>
<tr>
<td>Beach</td>
<td>Medium-grained sandstones with heavy-minerals levels</td>
<td>Parallel-lamination or stratification locally with internal inverse grading; low-angel truncations; ripple marks</td>
<td>Beach lamination (Clifton, 1979), grain segregation within high-energy flows during wave backwash</td>
</tr>
<tr>
<td>Upper shoreface</td>
<td>Amalgamated well-sorted, fine- to medium-grained sandstone beds with heavy-minerals levels</td>
<td>Parallel lamination; wave ripples; locally small-scale, trough and planar cross-stratification</td>
<td>Intercalation of storm and fair-weather wave-induced processes</td>
</tr>
<tr>
<td>Lower shoreface</td>
<td>Amalgamated well-sorted, fine-grained sandstones</td>
<td>Parallel to slightly undulated lamination; hummocky cross-stratification; wave ripples</td>
<td>Amalgamated storm events</td>
</tr>
<tr>
<td>Transition zone</td>
<td>Fine-grained sandstones interbedded with pelites</td>
<td>Parallel stratification; hummocky cross-stratification; wave ripples</td>
<td>Discrete storm beds (Dott and Bourgeois, 1982; Walker et al., 1983) interbedded with fair-weather muds</td>
</tr>
<tr>
<td>Offshore</td>
<td>Sericitic phylites (metamorphosed mudstones) with centimetric sandstones/siltstones layers</td>
<td>Sheet-like layers with normal grading from sandstones to siltstones</td>
<td>Vertical accretion of mud bellow storm wave base with intervening turbidity currents</td>
</tr>
</tbody>
</table>
Fig. 20. (a) Measured sedimentological sections of the base of the Galho do Miguel tectonosequence. Transgressive section measured 15 km north from Gouveia and progradational section measured 2 km south from Guinda. (b) Paleocurrent diagrams, where the measurements from cross-stratifications and asymmetrical wave-current ripples represent directions of bedform migration and measurements from symmetrical wave ripples represent crest directions.
Fig. 21. Cross-stratified sandstone of the Galho do Miguel eolian deposits.

thickness measured in the central part of the Espinhaço range.

The full life span of the Espinhaço basin remains unknown and further geochronologic data are required. Available geochronologic data indicate rifting at ca. 1720 Ma. Using maximum intervals derived from the literature of ca. 50 million year for rifting and ca. 200 million year for thermal subsidence (Brunet and Le Pichon, 1982; Allen and Allen, 1990; Perrodon and Zabec, 1990; Bond et al., 1995; Klein, 1995), final filling of the Espinhaço basin may have taken place at ca. 1500 Ma, giving a spread of ca. 200–250 million year for the basin life span, which is compatible with published data on average duration for first-order, basin-fill cycles (e.g. Krapez, 1993; Miall, 1997). High resolution geochronologic data are also required to test the validity of the tectonosequences described herein and to calibrate potential future studies directed towards quantifying rates of sedimentation and subsidence.

9. Conclusions

Field-based sedimentologic, paleogeographic, stratigraphic, structural and tectonic studies in the paleo/mesoproterozoic Espinhaço basin, southeastern Brazil, indicate deposition in a rift-sag basin. The basin evolved in four stages (prerift, rift, transitional and flexural), as represented by rocks of the Espinhaço Megasequence. The Espinhaço Megasequence can be divided into six tec-

Fig. 22. Sedimentological section measured along the Pedreira creek at the eastern border of the Serra do Cabral (see Fig. 1 for location), showing the coarsening-upward rhythms which characterize the marine transgression at the transition between the Galho do Miguel and Conselheiro Mata tectonosequences (modified after Espinoza, 1996).
sequence includes the record of linked depositional systems, and is bounded by regional unconformities. These unconformities mark times when tectonically controlled reorganization of basin paleogeography took place.

The prerift and rift stages of the Espinhaço basin are recorded by continental deposits in alluvial braidplain, lake and alluvial fans/fan-delta environments. During the rift stage, mechanical subsidence due to lithospheric stretching predominated.

The evolution of the transitional and flexural stages was probably controlled by thermal subsidence from contraction of the lithosphere due to cooling. The transitional stage was characterized by relatively low subsidence rates. This induced a decrease of the accommodation space and, as the sediment supply was maintained, caused an enlargement of the basin. The basal and top portions of the transitional stage are represented by shallow-marine deposits, whereas the middle part contains thick and extensive eolian deposits.

Higher subsidence rates and the consequent sea-level rise characterize the flexural stage of the Espinhaço basin. Shallow-marine shelf deposits predominate in this stage. Three depositional sequences with a transgressive base and a progradational top can be recognized. The basal transgressive parts represent initially rapid subsidence rates, whereas the progradational tops reflect the
relatively slow subsidence rates and overfill of the accommodation space. These sequences probably correspond to tectonically controlled second-order cycles.

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