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Tectonic control on fluvial styles: the Balfour Formation of the Karoo Basin, South Africa

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Abstract

The Balfour Formation represents a fully fluvial succession of late Late Permian–earliest Triassic age which accumulated in the foredeep of the Karoo Basin during the overfilled phase of the foreland system. The lack of a coeval marine environment within the limits of the preserved Karoo Basin provides an opportunity to study the stratigraphic cyclicity developed during a time when accommodation was solely controlled by tectonics. The Balfour stratigraphy is composed of a succession of six third-order fluvial depositional sequences separated by subaerial unconformities. They formed in isolation from eustatic influences, with a timing controlled by orogenic cycles of loading and unloading. Sediment accumulation took place during stages of flexural subsidence, whereas the bounding surfaces are related to stages of isostatic uplift. The vertical profile of all sequences displays an overall fining-upward trend related to the gradual decrease in topographic slope during orogenic loading. At the same time, an upward change in fluvial styles can be observed within each sequence, from initial higher to final lower energy systems. The actual fluvial styles in each location depend on paleoslope gradients and the position of the stratigraphic section relative to the orogenic front. Proximal sequences show transitions from braided to meandering systems, whereas more distal sequences show changes from sand-bed to fine-grained meandering systems. The average duration of the Balfour stratigraphic cycles was 0.66 My, i.e. six cycles during 4 My. No climatic fluctuations are recorded during this time, with the long-term climatic background represented by temperate to humid conditions.

Keywords: Orogenic cycles; Fluvial sequences; Fluvial styles; Flexural foredeep

1. Introduction

The main theme of this paper is to assess the extent of the tectonic control on the stratigraphic and sedimentological patterns of a fluvial succession in the Karoo Basin, South Africa. The interest in this topic is sourced from the perennial debate that persists in the sequence stratigraphic literature since the publication of the early Exxon concepts (Mitchum et al., 1977; Vail et al., 1977; Posamentier and Vail, 1988; Posamentier et al., 1988; Van Wagoner et al., 1988) regarding the interplay between tectonics and eustasy in controlling accommodation and stratigraphic patterns in sedimentary basins. While the early models were permeated by the assumption that eustasy is the driving mechanism behind sequence formation, more recent work has emphasized the importance of tectonic processes on base-level

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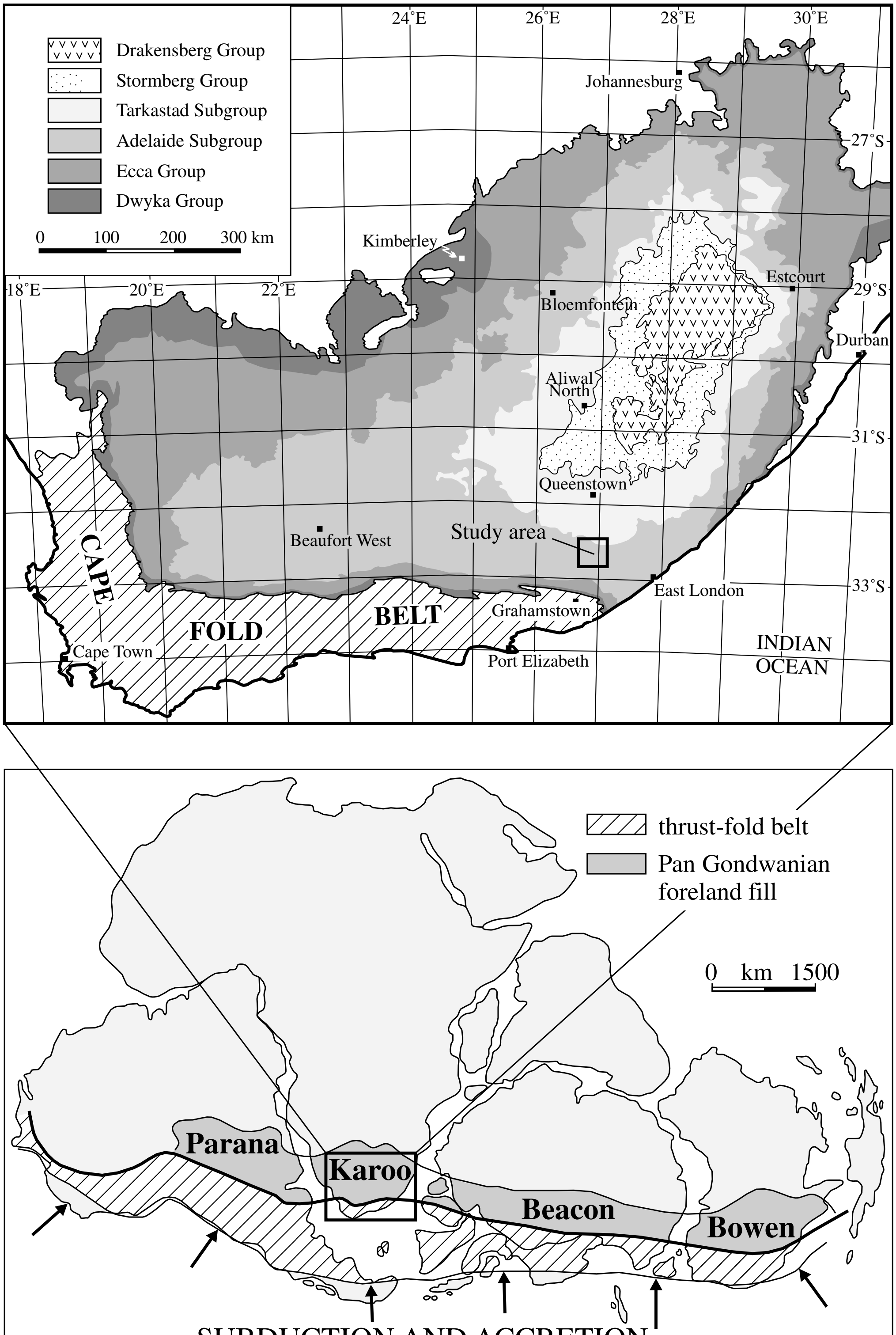


Drakensberg Group
Stormberg Group
Tarkastad Subgroup
Adelaide Subgroup
Ecca Group
Dwyka Group
0 100 200 300 km
24°E
26°E
28°E
30°E
18°E
20°E
22°E
27°S
29°S
31°S
33°S
Johannesburg
Kimberley
Bloemfontein
Estcourt
Durban
Aliwal North
Queenstown
Beaufort West
Study area
East London
Grahamstown
Port Elizabeth
Cape Town
CAPE
FOLD
BELT
INDIAN OCEAN
thrust-fold belt
Pan Gondwanian foreland fill
0 km 1500
Parana
Karoo
Beacon
Bowen
SUBDUCTION AND ACCRETION

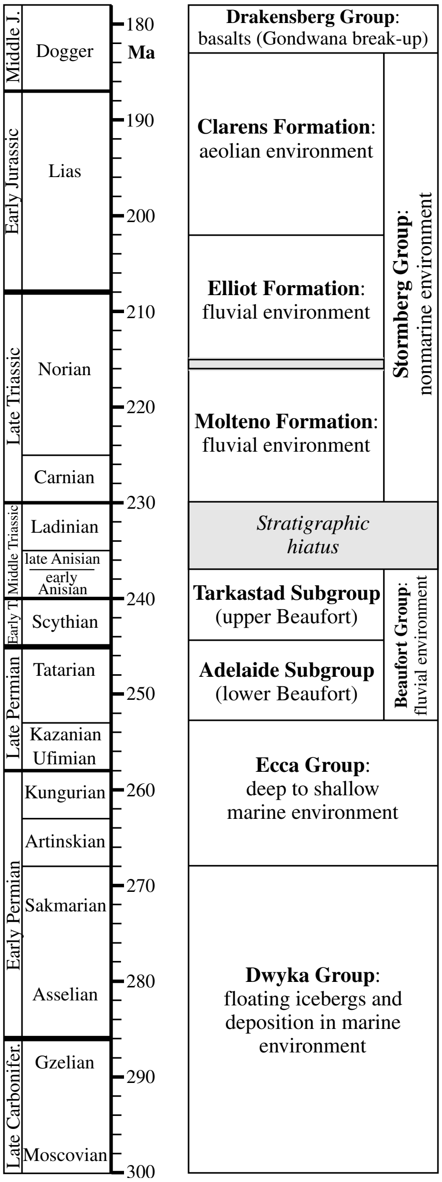


Fig. 2. Stratigraphy and inferred depositional settings of the southern Karoo Basin (modified from Catuneanu et al., 1998). Shaded areas represent time gaps.

changes (e.g. Embry, 1995; Miall, 1997; Catuneanu et al., 2000). This case study offers an opportunity to study fluvial sequences formed in isolation from marine influences, hence with no eustatic control on accommodation.

1.1. Tectonic setting

The Karoo Basin is a retroarc foreland system developed in front of the Cape Fold Belt in relationship to the Late Paleozoic–Early Mesozoic subduction episode of the paleo-Pacific plate underneath the Gondwana plate (Lock, 1978, 1980; Winter, 1984; de Wit et al., 1988; Johnson, 1991; de Wit and Ransome, 1992; SOEKOR, 1996; Fig. 1). In a regional context, the Cape Fold Belt was part of the more extensive Pan Gondwanian Mobile Belt generated through compression, collision and terrain accretion along the southern margin of Gondwana. The associated foreland basin, subsequently fragmented as a result of Gondwana break-up, is preserved today in South America (Parana Basin), southern Africa (Karoo Basin), Antarctica (Beacon Basin) and Australia (Bowen Basin).

The Cape Orogeny developed along Late Proterozoic structural trends following the weakest and most deformed zones of the continental lithosphere (Tankard et al., 1982; Thomas et al., 1992). Within this setting, the Karoo Basin developed in response to the supralithospheric loading generated as a result of crustal shortening and thickening in the Cape Fold Belt (Fig. 1). As the subduction took place underneath the basin, the Karoo qualifies as a retroarc (Dickinson, 1974) or retro-foreland setting (Johnson and Beaumont, 1995).

The Karoo foreland system is partitioned into three flexural provinces, i.e. foredeep, forebulge and back-bulge (Catuneanu et al., 1998, 1999a). Prior to the break-up of Gondwana, this foreland system extended about 6000 km along the strike and over 1000 km along the dip. Our study area is placed in the proximal part of the Karoo foredeep (Fig. 1), about 340 km south of the stratigraphic hinge line that separated

Fig. 1. Outcrop distribution of the main lithostratigraphic units of the Karoo Supergroup. The Karoo Basin is shown in the context of the Pan Gondwanian foreland system that developed in relation to the Cape Orogeny along the southern margin of Gondwana. The Adelaide and Tarkastad subgroups build up together the Beaufort Group.

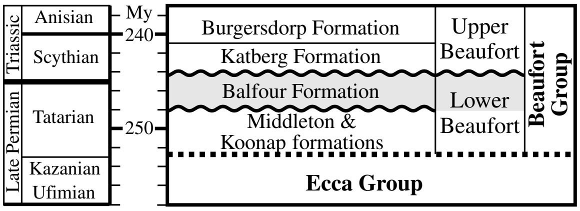


Fig. 3. Stratigraphy of the Beaufort Group in the southern Karoo Basin (modified from Catuneanu et al., 1998). The lower and upper Beaufort equate with the Adelaide and Tarkastad subgroups respectively. Wavy lines represent second-order sequence boundaries (subaerial unconformities). The dotted line signifies a conformable facies contact between coastal deposits and overlying fluvial strata.

the foredeep from the forebulge setting (Catuneanu et al., 1998).

1.2. Stratigraphy

The Karoo Basin (Fig. 1) forms the thickest and stratigraphically most complete megasequence of several depositories of Permo-Carboniferous to Jurassic age in southwestern Gondwana. The maximum preserved thickness of this megasequence adjacent to the Cape Fold Belt exceeds 6 km and the sedimentary succession reflects changing environments from glacial to deep marine, deltaic, fluvial and aeolian (Smith, 1990; Smith et al., 1993). Basinal fill is inherently linked to the orogenesis of the Cape Fold Belt (Hälbich, 1983; Cole, 1992; Catuneanu et al., 1998), which is believed to have formed as a single phase, multiple event orogen (Hälbich, 1983).

The Karoo Supergroup is subdivided into five main groups, i.e. the Dwyka, Ecca, Beaufort (comprising the Adelaide and Tarkastad subgroups), Stormberg and Drakensberg (Fig. 2; Johnson, 1976a; SACS, 1980; Tankard et al., 1982; Cole, 1992; Smith et al., 1993; Catuneanu et al., 1998). The deeper marine facies of the Dwyka and early Ecca groups, including pelagic sediments, dropstones and turbidite fans, accumulated during the underfilled phase of the foreland system. The shallow marine facies of the late Ecca Group corresponds to the filled phase of the basin, which was followed by an overfilled phase dominated by fluvial sedimentation. The terms 'underfilled', 'filled', and 'overfilled' are used in agreement with the definitions of Sinclair and Allen (1992).

This paper focuses on the Balfour Formation of the Adelaide Subgroup (Fig. 3), which represents a fully fluvial succession with no marine correlatives within the limits of the preserved Karoo Basin.

1.3. Previous work

Most of the previous work focused on the lithostratigraphic, petrographic, and biostratigraphic features of the Balfour Formation (Johnson, 1966, 1976a, 1991; Keyser and Smith, 1978; Visser and Dukas, 1979; SACS, 1980; Smith, 1980, 1987, 1990; Stavrakis, 1980; Stear, 1980; Hiller and Stavrakis, 1984; Smith et al., 1993; Groenewald and Kitching, 1995; Kitching, 1995). Named by Johnson (1966) after a village north of Fort Beaufort (Fig. 4), this lithostratigraphic unit includes yellowish and bluish-greenish-grey sandstones interbedded with dark mudstones organized in fining-upward cyclothems. The age of the Balfour sediments is Tatarian to early Scythian (Groenewald and Kitching, 1995; Kitching, 1995). The Formation reaches a maximum thickness of 2150 m in the Fort Beaufort area (Johnson, 1976a). Both braided and meandering fluvial styles were previously recognized (e.g. Visser and Dukas, 1979).

Early attempts to reconstruct the paleoenvironmental conditions during the Balfour time postulated a warm and dry climate (Keyser, 1966). More recent work suggests that the climate was rather temperate to humid, as indicated by the petrographic and sedimentologic studies of Johnson (1976a) and Stavrakis (1980). Analyzing the patterns of change with time in the fossil record, fluvial facies and paleoflow directions, Visser and Dukas (1979) concluded that the climatic conditions were relatively steady during the deposition of the Beaufort Group, and that the climate did not fluctuate significantly enough to overprint the effect of the tectonic control on sedimentation and stratigraphic cyclicity.

The second-order (large-scale) sequence stratigraphic framework of the Karoo sedimentary fill was established by Catuneanu et al. (1998). The Karoo (first-order) sedimentary megasequence was split into eight second-order depositional sequences bounded by major subaerial unconformities. Each of these second-order sequences correlates to a major orogenic cycle of thrusting followed by erosional

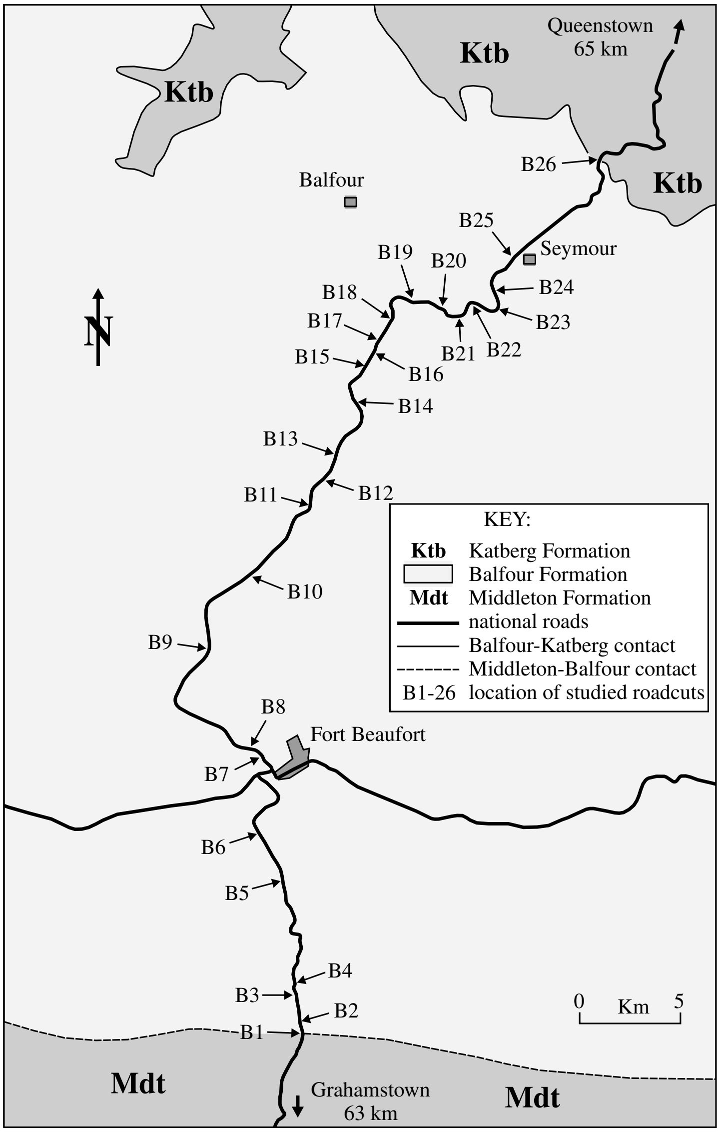


Fig. 4. Detail of the study area (Fig. 1), showing the position of the analyzed outcrops along the Grahamstown – Queenstown road. The geological contact between the Middleton and Balfour Formations is well established in roadcut, but its east–west trend across the study area is still uncertain (dashed line on the map) and inferred from Johnson (1976b). The geological contact between the Balfour and Katberg formations is better constrained in map view (solid line on the map; Johnson, 1976b).

and/or extensional unloading in the Cape Fold Belt, which demonstrates the dependance of large-scale stratigraphic architecture on orogenic tectonism. No attempt was undertaken so far to increase the resolution of sequence stratigraphic analysis to the level of third-order cyclicity.

1.4. Objectives

The Balfour Formation corresponds to one second-order depositional sequence, and it is separated from the underlying Middleton and overlying Katberg formations by major subaerial unconformities (i.e.

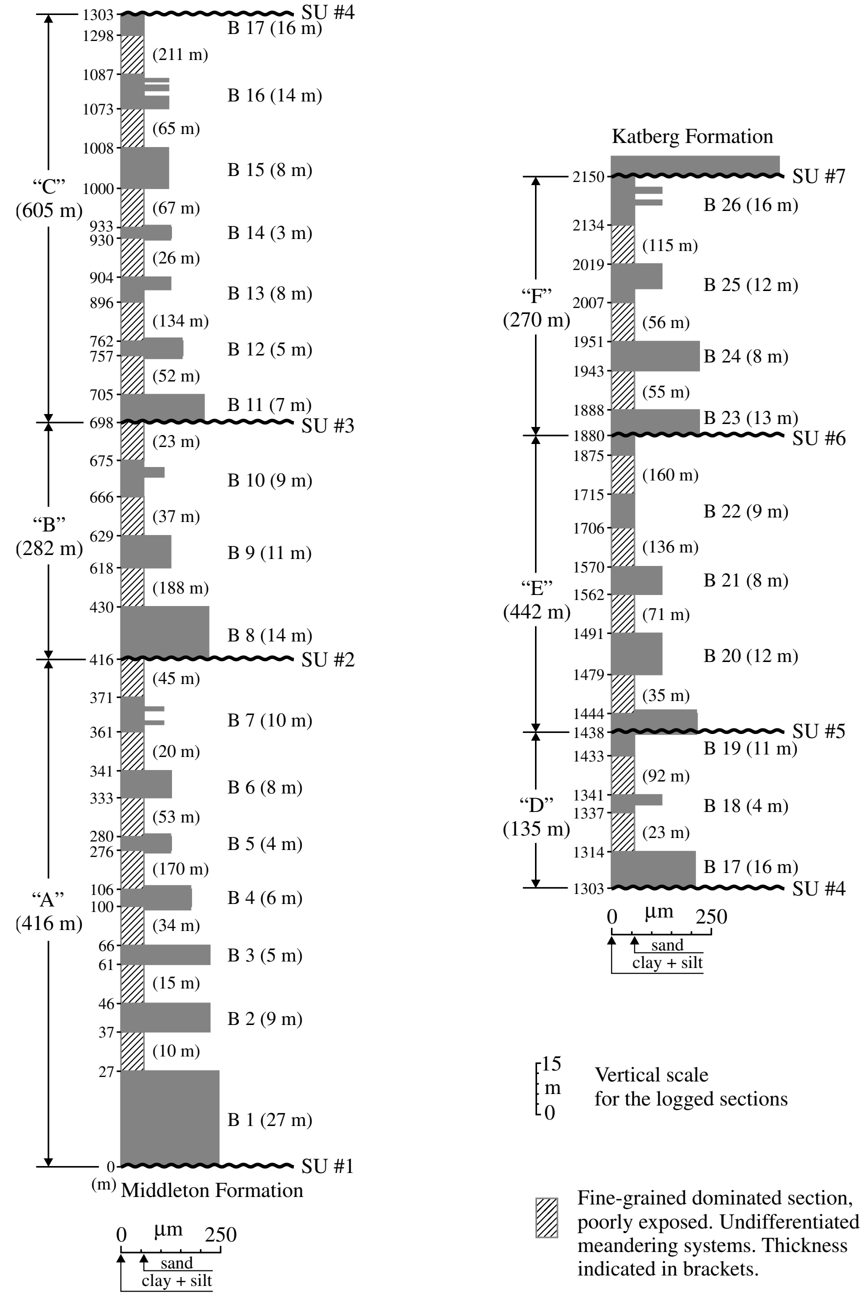


Fig. 5. Generalized vertical profile of the Balfour Formation in the study area, showing dominant grain sizes and stratal thicknesses. B 1–26 represent the field sections (roadcuts) indicated in Fig. 4. Subaerial unconformities (SU) # 1 and 7are the second-order bounding surfaces of the Balfour sequence. The other five prominent subaerial unconformities (SU # 2–6) subdivide the Balfour second-order sequence into six fining-upward successions interpreted here as third-order depositional sequences (A–F). No channel fill sandbodies less than 1.5 m thick are represented in this diagram, due to constrains related to the vertical scale.

second-order sequence boundaries; Catuneanu et al., 1998). The objectives of this study are to: (1) resolve the third-order sequence stratigraphy of the Balfour second-order sequence; (2) analyze the patterns of change in fluvial styles with time; (3) assess the effect of the allocyclic controls on fluvial cyclicity, i.e. mainly the relative importance between tectonics and climate, as eustasy has been ruled out by the absence of marine influences within the limits of the preserved Karoo Basin; and (4) suggest a model to explain the observed stratigraphic architecture.

2. Database

This research is based on outcrop logging and facies analysis performed along the Grahamstown–Queenstown road during the past few years (Fig. 4). The stratigraphic succession is relatively undisturbed by the Cape Orogeny, and consistently youngs from south to north within the study area. Twenty six well-exposed roadcuts were analyzed (B 1–26, Fig. 4). These exposures are separated by fine-grained dominated sections with little or no expression in the landscape. Thicknesses have been measured for the entire succession, and the generalized vertical profile of the Balfour Formation is presented in Fig. 5.

2.1. Vertical profile

Five prominent subaerial unconformities have been identified within the Balfour succession, i.e. surfaces # 2–6 in Fig. 5. These surfaces have regional extent, are associated with truncation and fluvial incision, and separate abrupt changes in lithofacies, sedimentation regimes, and fluvial styles. Invariably, there is a strong contrast between the beds above and below the boundary, with a marked increase in both grain size and fluvial energy across the surface in the younging direction. The five subaerial unconformities separate six fining-upward cyclothems within the Balfour Formation with varying thicknesses in the range of 10^2 m (Fig. 5). Each cyclothem comprises a relatively conformable succession of strata, which represents the product of continuous fluvial aggradation. Minor erosional surfaces may still be recognized within the cylothems, such as at the base of channel fills, but these scours grade laterally into conformable surfaces and do not have a regional significance. For this reason, no further subdivision of the six cyclothems into higher frequency sequences was found to be supported by the field data.

The time control is based on assemblage zones of fossil reptilian fauna with a resolution averaging 2 My per zone (Rubidge, 1995). The total duration of the Balfour Formation is estimated to be 4 My (Rubidge, 1995; Catuneanu et al., 1998; Fig. 3). It is difficult to assess the relative duration of the six fining-upward cyclothems, as well as the ratio between the time represented in the rock record and the stratigraphic hiatus associated with the major subaerial unconformities.

2.2. Sandstone petrography

All the channel fill sandstones of the Balfour succession have been sampled for thin section petrography. Textural analyzes have produced consistent results for all cyclothems, indicating a progressive decrease with time in the average grain size of the sediment load transported by the Balfour fluvial systems within each cyclothem. This defines the fining-upward profiles of the six fluvial sequences in Fig. 5.

Two lithosomes dominate the sandstone petrography for the entire succession, i.e. lithic arenites (<15% matrix) and lithic greywackes (>15% matrix). The percentage of matrix in sandstones is usually close to 15%, which is why the lithosome types vary between arenites and wackes in a non-predictable fashion even within the same outcrop sections. The petrographic analysis revealed no variation trends in the composition of sandstones, indicating no significant changes in the source rocks during the entire Balfour time. The coarse framework of sandstones is mainly represented by lithoclasts (42.3–58.4%), followed by feldspar (22.7–38.3%) and quartz (10.1–28.8%) grains. The dominant grain sizes represented in each section are indicated in Fig. 5.

3. Fluvial styles

3.1. Method

The interpretation of fluvial styles follows the methodology proposed by (Miall (1985, 1996). At a

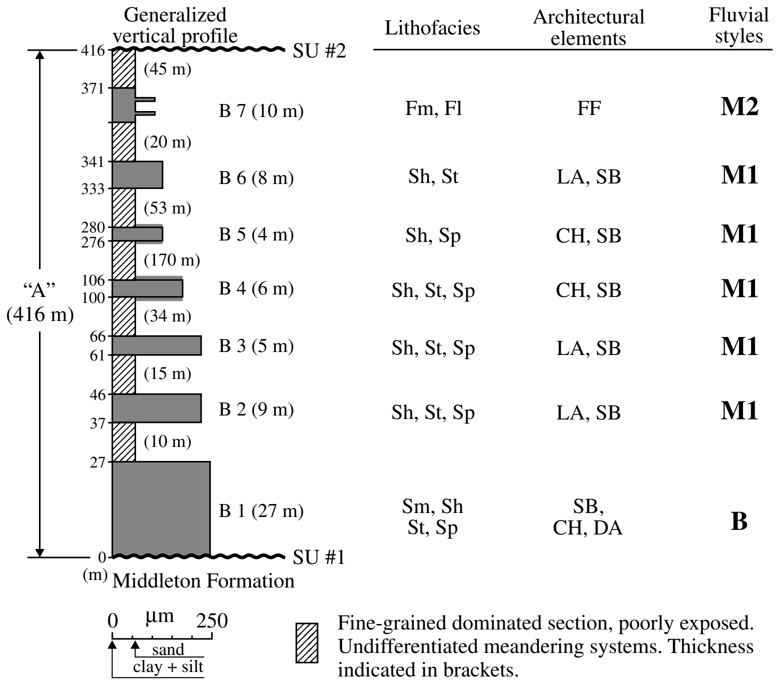


Fig. 6. Generalized profile of sequence A, showing dominant grain sizes, stratal thicknesses, lithofacies, architectural elements and fluvial styles. This is the basal third-order cyclothem of the Balfour second-order sequence, bounded at the base and top by second- and third-order subaerial unconformities respectively (SU # 1 and 2). No channel fill sandbodies less than 1.5 m thick are represented in this diagram, due to constrains related to the vertical scale. Abbreviations: B 1–7 = outcrop sections in Fig. 4; Sm = massive sandstone; Sh = sandstone with horizontal stratification; St = trough cross-bedded sandstone; Sp = planar cross-bedded sandstone; Fm = massive mudstones; Fl = horizontally-laminated mudstones; CH = channel fill; DA = downstream accretion macroform; SB = sandy bedforms; LA = lateral accretion macroform; FF = overbank deposits (floodplain fines); B = sand-bed perennial braided system; M1 = sand-bed meandering system; M2 = fine-grained meandering system.

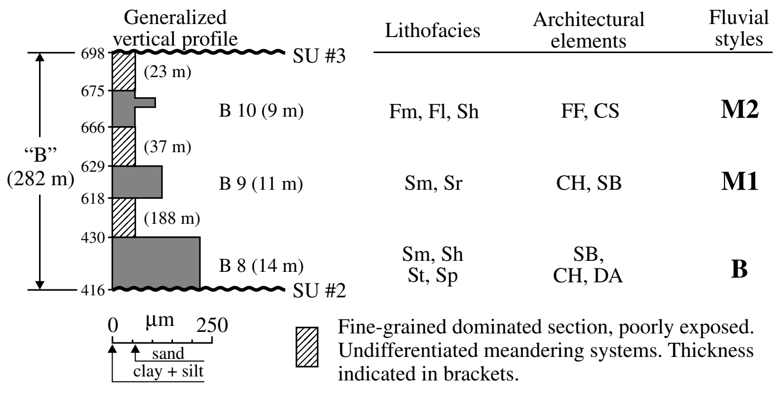


Fig. 7. Generalized profile of sequence B, showing dominant grain sizes, stratal thicknesses, lithofacies, architectural elements and fluvial styles. This is the second third-order cyclothem of the Balfour Formation, bounded at the base and top by third-order subaerial unconformities (SU # 2 and 3). No channel fill sandbodies less than 1.5 m thick are represented in this diagram, due to constrains related to the vertical scale. Abbreviations: B 8–10 = outcrop sections in Fig. 4; Sm = massive sandstone; Sh = sandstone with horizontal stratification; St = trough cross-bedded sandstone; Sp = planar cross-bedded sandstone; Sr = ripple cross-laminated sandstone; Fm = massive mudstones; Fl = horizontally-laminated mudstones; CH = channel fill; DA = downstream accretion macroform; SB = sandy bedforms; FF = overbank deposits (floodplain fines); CS = crevasse splays; B = sand-bed perennial braided system; M1 = sand-bed meandering system; M2 = fine-grained meandering system.

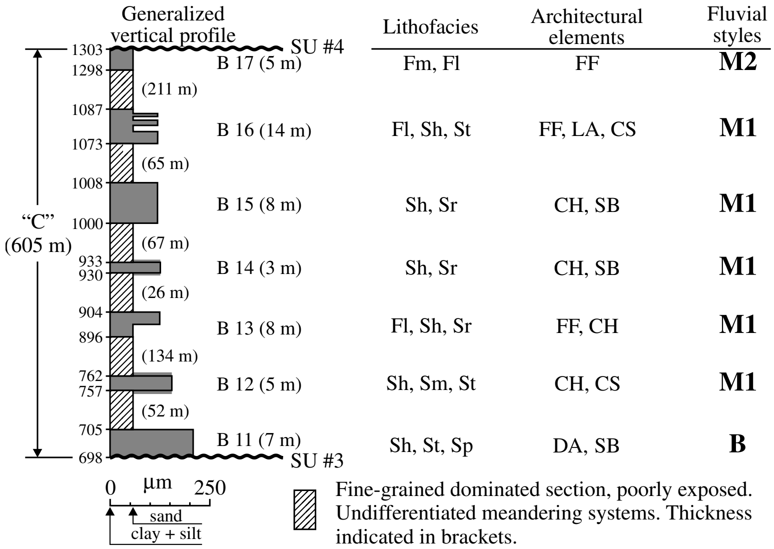


Fig. 8. Generalized profile of sequence C, showing dominant grain sizes, stratal thicknesses, lithofacies, architectural elements and fluvial styles. This is the third third-order cyclothem of the Balfour Formation, bounded at the base and top by third-order subaerial unconformities (SU # 3 and 4). No channel fill sandbodies less than 1.5 m thick are represented in this diagram, due to constrains related to the vertical scale. Abbreviations: B 11–17 = outcrop sections in Fig. 4; Sm = massive sandstone; Sh = sandstone with horizontal stratification; St = trough cross-bedded sandstone; Sp = planar cross-bedded sandstone; Sr = ripple cross-laminated sandstone; Fm = massive mudstones; Fl = horizontally-laminated mudstones; CH = channel fill; DA = downstream accretion macroform; SB = sandy bedforms; LA = lateral accretion macroform; FF = overbank deposits (floodplain fines); CS = crevasse splays; B = sand-bed perennial braided system; M1 = sand-bed meandering system; M2 = fine-grained meandering system.

smaller scale, lithology and sedimentary structures are combined to reconstruct the various fluvial lithofacies. By enlarging the scale of observation, lithofacies are combined into architectural elements. Associations of architectural elements are then used to define the styles of the fluvial systems that led to the aggradation of the observed deposits. Lithofacies and architectural elements have been mapped in all 26 roadcuts, and the results are summarized in Figs. 6–11.

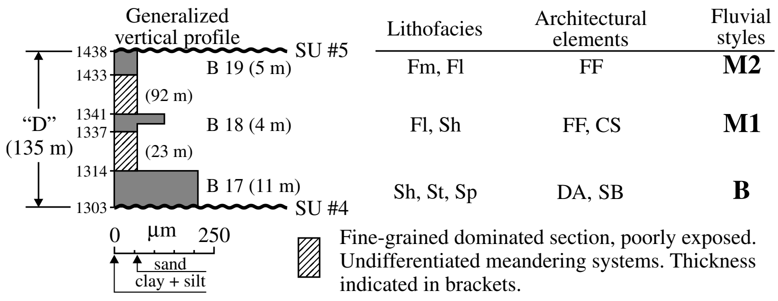


Fig. 9. Generalized profile of sequence D, showing dominant grain sizes, stratal thicknesses, lithofacies, architectural elements and fluvial styles. This is the fourth third-order cyclothem of the Balfour Formation, bounded at the base and top by third-order subaerial unconformities (SU # 4 and 5). No channel fill sandbodies less than 1.5 m thick are represented in this diagram, due to constrains related to the vertical scale. Abbreviations: B 17–19 = outcrop sections in Fig. 4; Sh = sandstone with horizontal stratification; St = trough cross-bedded sandstone; Sp = planar cross-bedded sandstone; Fm = massive mudstones; Fl = horizontally-laminated mudstones; DA = downstream accretion macroform; SB = sandy bedforms; FF = overbank deposits (floodplain fines); CS = crevasse splays; B = sand-bed perennial braided system; M1 = sand-bed meandering system; M2 = fine-grained meandering system.

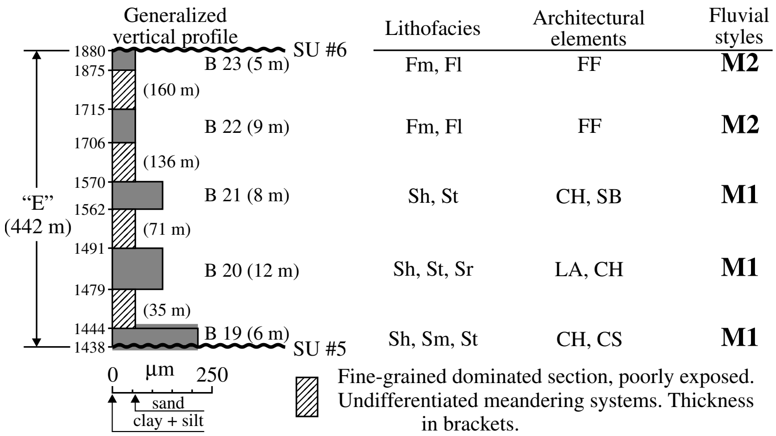


Fig. 10. Generalized profile of sequence E, showing dominant grain sizes, stratal thicknesses, lithofacies, architectural elements and fluvial styles. This is the fifth third-order cyclothem of the Balfour Formation, bounded at the base and top by third-order subaerial unconformities (SU # 5 and 6). No channel fill sandbodies less than 1.5 m thick are represented in this diagram, due to constrains related to the vertical scale. Abbreviations: B 19–23 = outcrop sections in Fig. 4; Sm = massive sandstone; Sh = sandstone with horizontal stratification; St = trough cross-bedded sandstone; Sr = ripple cross-laminated sandstone; Fm = massive mudstones; Fl = horizontally-laminated mudstones; CH = channel fill; SB = sandy bedforms; LA = lateral accretion macroform; FF = overbank deposits (floodplain fines); CS = crevasse splays; M1 = sand-bed meandering system; M2 = fine-grained meandering system.

3.2. Lithofacies

The lithology of the Balfour Formation is dominated by sandstones interbedded with mudstones. Excepting for the better developed sandy successions that can be found at the base of each cyclothem, the thickness of individual sandstone layers is usually less than 10 m. Generally, the sandstone–mudstone ratio decreases from the base to the top of the Balfour Formation, which gives the succession an overall fining-upward profile (also noted by Catuneanu et al., 1998). A note of caution is introduced here with

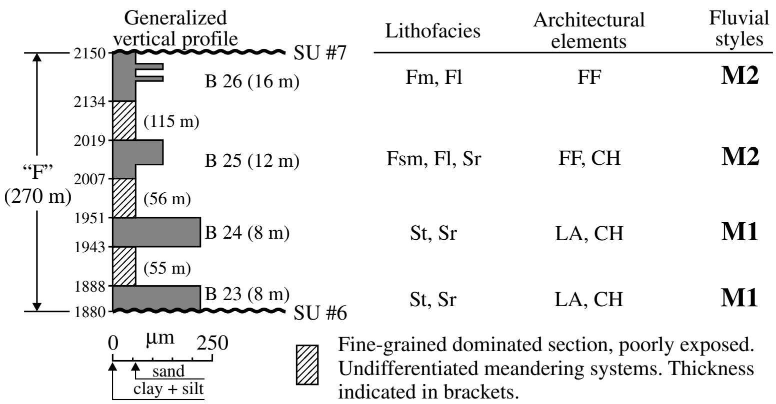
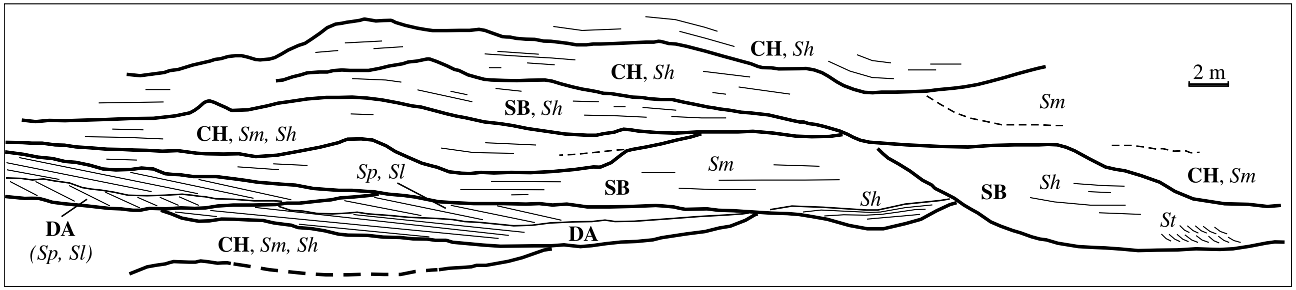
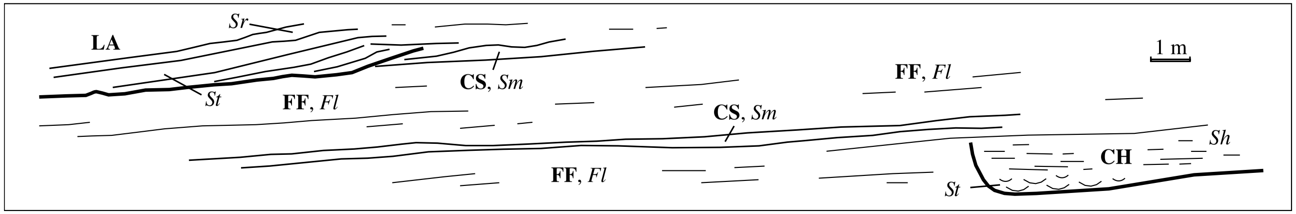


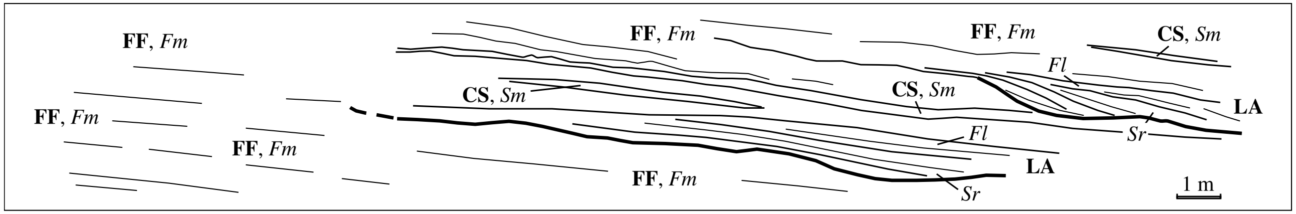
Fig. 11. Generalized profile of sequence F, showing dominant grain sizes, stratal thicknesses, lithofacies, architectural elements and fluvial styles. This is the sixth and last (youngest) third-order cyclothem of the Balfour Formation, bounded at the base and top by third- and second-order subaerial unconformities respectively (SU # 6 and 7). No channel fill sandbodies less than 1.5 m thick are represented in this diagram, due to constrains related to the vertical scale. Abbreviations: B 23–26 = outcrop sections in Fig. 4; St = trough cross-bedded sandstone; Sr = ripple cross-laminated sandstone; Fm = massive mudstones; Fl = horizontally-laminated mudstones; Fsm = massive silty mudstones; CH = channel fill; LA = lateral accretion macroform; FF = overbank deposits (floodplain fines); M1 = sand-bed meandering system; M2 = fine-grained meandering system.



Detail from section B 1, showing the internal architecture of amalgamated braided channels. Fluvial style: deep, perennial, sand-bed braided system.

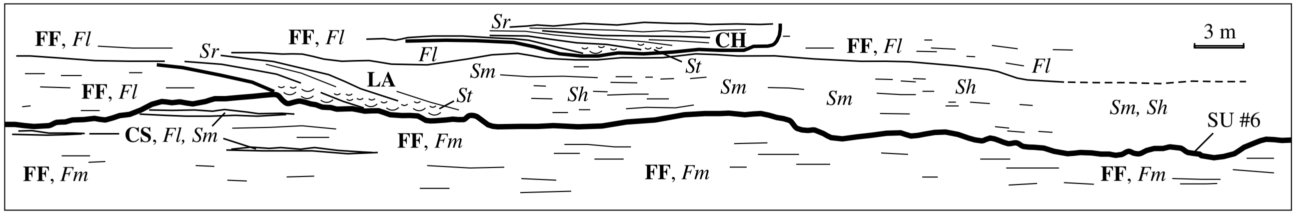


Detail from section B 16, showing the stacking patterns of low-energy fluvial architectural elements. Fluvial style: sand-bed meandering system.



Detail from section B 7, showing the stacking patterns of low-energy fluvial architectural elements. Fluvial style: fine-grained meandering system.

Fig. 12. Stratal architecture of the fluvial styles identified within the Balfour Formation, based on photo mosaics of outcrop sections. No vertical exaggeration. Abbreviations: CH = channel fill; DA = downstream accretion macroform; SB = sandy bedform; LA = lateral accretion macroform; FF = floodplain fines; CS = crevasse splay; Sm = massive sandstone; Sh = horizontally stratified sandstone; Sp = planar cross-bedded sandstone; Sl = low angle cross-bedded sandstone; St = trough cross-bedded sandstone; Sr = ripple cross-laminated sandstone; Fm = massive fines; Fl = horizontally laminated fines.



Detail from section B 23, showing an abrupt change in the sedimentary regime across the sequence boundary (SU #6) from a fine-grained meandering system (below the sequence boundary) to a higher energy sand-bed meandering system. No vertical exaggeration.

Fig. 13. Subaerial unconformity # 6 (Fig. 5) marking regional truncation and an abrupt change in sedimentation regimes. Abbreviations: CH = channel fill; LA = lateral accretion macroform; FF = floodplain fines; CS = crevasse splay; Sm = massive sandstone; Sh = horizontally stratified sandstone; St = trough cross-bedded sandstone; Sr = ripple cross-laminated sandstone; Fm = massive fines; Fl = horizontally laminated fines.

respect to the fact that the younger exposures of the Balfour Formation are placed farther to the north relative to the older sections. This implies a proximal versus distal relationship between the lower and upper ends of the Balfour Formation, respectively, which means that the overall fining-upward profile may only be apparent (see the discussion in Section 6).

The sandstones of the Balfour Formation are either massive (lithofacies Sm), or characterized by sedimentary structures such as horizontal stratification (lithofacies Sh), planar cross-bedding (lithofacies Sp), trough cross-bedding (lithofacies St), or ripple cross-lamination (lithofacies Sr). The distribution and thicknesses of the sandstone layers are illustrated in Fig. 5.

The finer-grained facies mostly include massive (lithofacies Fm) and horizontally laminated (lithofacies Fl) mudstones. The percentage of mudstone increases upwards, both at the level of individual cyclothems and within the overall Balfour Formation (Fig. 5).

The assemblages of fluvial lithofacies present in each outcrop section (B 1–26) are summarized in Figs. 6–11.

3.3. Architectural elements

The most common fluvial architectural elements identified within the Balfour Formation include sandy bedforms (element SB), isolated channel fills (element CH), downstream accretion macroforms (element DA), lateral accretion macroforms (element LA), crevasse channels (element CR), crevasse splays (element CS), and floodplain deposits (element FF). A summary of the main assemblages of architectural elements in each outcrop section is provided in Figs. 6–11.

3.4. Fluvial styles

Based on architectural element assemblages, the following fluvial styles have been identified:

(1) *Perennial sand-bed braided systems*, *deep and shallow*. This fluvial style is dominated by elements SB, DA and CH, and identifies low sinuosity, multiple channel systems with an unconfined character (Miall, 1985, 1996). These represent the highest energy fluvial systems of the Balfour Formation, and occur as amalgamated channels at the base of the fining-upward cyclothems, overlying the major subaerial unconformities. The lithology of this fluvial style is dominated by sandstones, as the preservation potential of the overbank fines is low due to the lateral shift of the unconfined channels. The scarcity of desiccation cracks and paleosol features suggests continuous aggradation and a high position of the watertable relative to the topography for most of the time in the evolution of these fluvial systems, which points towards perennial, as opposed to ephemeral, river types. This observation is also valid for the other two styles of fluvial systems presented below.

(2) *Sand-bed meandering systems*. This fluvial style is characterized by elements LA, FF and CS, but isolated channels (CH, CR) and sandy bedforms (SB) may also be recognized. It designates a lower energy fluvial system, with confined high-sinuosity single channels (Miall, 1985, 1996). When braided systems are missing from one particular cyclothem, sand-bed meandering systems develop at the base of the succession, overlying the subaerial unconformity. The lithology is dominated by finer-grained overbank deposits, although a significant amount of sand is also present relative to the fine-grained meandering systems.

(3) *Fine-grained meandering systems*. This style is fairly similar to the previous one, excepting that it is almost exclusively built by mudstones and siltstones. It is the lowest energy fluvial system of the Balfour Formation, occurring towards the top of the fining-upward cyclothems, underlying the subaerial unconformities. The dominant architectural elements are FF and LA, rarely associated with thin crevasse splays (Miall, 1985, 1996).The stratal architecture of the three styles of fluvial systems, together with the dominant lithofacies and architectural elements, is summarized in Fig. 12 based on photo mosaics of outcrop sections. The sketch in Fig. 13 illustrates the subaerial unconformity # 6 (Fig. 5) that separates the last two cyclothems of the Balfour Formation ('E' and 'F' in Fig. 5), marking regional truncation and an abrupt change in the sedimentation regime.

4. Sequence stratigraphy

The six fining-upward cyclothems identified in Figs. 5–11 build up together the Balfour second-order

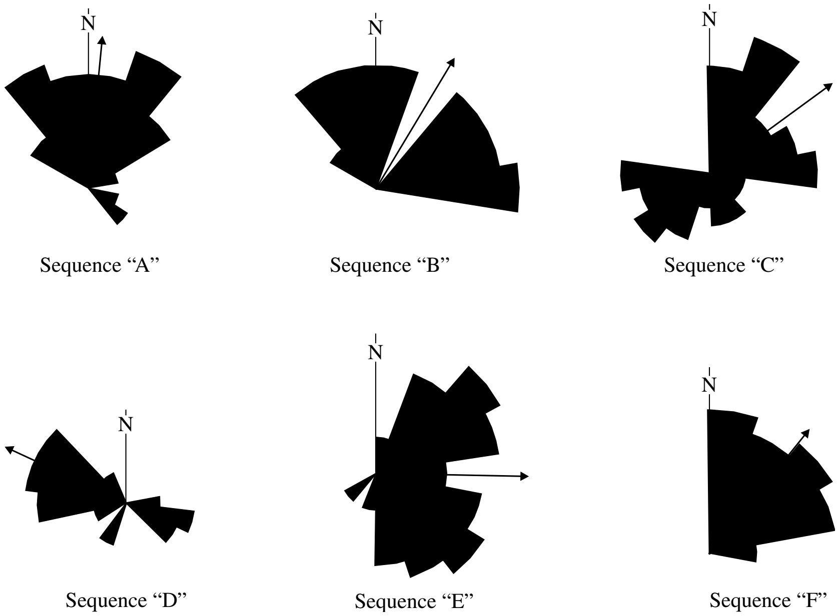


Fig. 14. Paleoflow directions for the six third-order sequences of the Balfour Formation. The number of readings collected to construct the rose diagrams for sequences A–F are 101, 28, 54, 38, 67, and 51, respectively. The arrows indicate the vector mean azimuths. The shifts with 180° in paleoflow directions observed in the case of cyclothems C and D may be related to corresponding changes in the dip direction of the topographic foreslope (Fig. 16). This, in turn, depends on the balance between subsidence and sedimentation rates. Subsidence outpacing sedimentation leads eventually to a topographic foreslope dipping towards the thrust-fold belt (Catuneanu, 2000).

depositional sequence (Catuneanu et al., 1998). Each cyclothem includes a relatively conformable succession of strata in which fluvial styles gradually change from higher to lower energy systems, and are bounded by prominent subaerial unconformities. Hence, these cyclothems are here interpreted as third-order depositional sequences. Paleosols are very rare occurrences within any of these sequences, suggesting continuous subsidence and fluvial aggradation during the accumulation of the six third-order cyclothems. This supports the relatively conformable character of the depositional sequences, as well as the genetically related nature of their fluvial strata.

4.1. Sequence 'A'

Sequence A is 416 m thick, and is bounded at the base by a second-order subaerial unconformity (SU # 1 in Fig. 6, which marks the limit between the Middleton and Balfour Formations) and at the top by a third-order subaerial unconformity (SU # 2 in Fig. 6). The lower part of this depositional sequence includes the most significant sandstone succession of the Balfour Formation, with a thickness of 27 m. Fluvial styles change from braided at the base, to sand-bed and fine-grained meandering towards the top (Fig. 6). The grain size of the sandstone intervals gradually decreases upwards, consistent with the lowering in energy regime of the fluvial systems.

4.2. Sequence 'B'

Sequence B is 282 m thick, and is bounded at the base and at the top by third-order subaerial unconformities (SU # 2 and 3 in Fig. 7). The thickness of the main sandstone successions decreases in the younging direction, together with a corresponding decrease in grain size and fluvial energy levels. Fluvial styles change upwards from braided to sand-bed and fine-grained meandering systems.

4.3. Sequence 'C'

Sequence C is the thickest third-order cyclothem of the Balfour Formation, measuring 605 m (Fig. 8). As with the previous sequences, the bounding surfaces are represented by major (third-order) subaerial unconformities that mark an abrupt increase in grain size and fluvial energy from meandering stream facies, below the boundary, to braided stream facies above (SU # 3 and 4 in Fig. 8). Fluvial styles also change upward from braided to sand-bed and fine-grained meandering systems.

4.4. Sequence 'D'

Sequence D is the thinnest third-order cyclothem of the Balfour Formation, with a measured thickness of 135 m (Fig. 9). It is bounded by the subaerial unconformities # 4 and 5 at the base and top, respectively (Fig. 9). Fluvial styles change from braided (overlying the SU # 4, Fig. 9) to sand-bed and fine-grained meandering systems. The basal braided stream facies includes an 11 m thick multistorey succession of stacked channel fills and downstream accretion macroforms.

4.5. Sequence 'E'

Sequence E shares the same common feature with all the other third-order depositional sequences of the Balfour Formation, i.e. it fines upwards, but it does not include braided stream deposits at the base. Instead, this 442 m thick cyclothem displays a change with time from initial sand-bed meandering systems to younger fine-grained meandering systems (Fig. 10). It is bounded at the base and at the top by subaerial unconformities # 5 and 6, respectively.

4.6. Sequence 'F'

With a thickness of 270 m, sequence F is similar in character to sequence E in that it displays a change with time from sand-bed to fine-grained meandering systems, with no occurrence of braided stream deposits at the base. The lower bounding surface is the third-order subaerial unconformity # 6; the upper sequence boundary is respresented by the second-order subaerial unconformity (SU # 7 in Fig. 11) which marks the sharp limit between the Balfour and Katberg formations, i.e. between the Adelaide and Tarkastad subgroups of the Beaufort Group (Figs. 2 and 3).

4.7. Paleocurrents

Paleoflow measurements give consistent results for individual sequences, but show different patterns from one sequence to another. The six rose diagrams presented in Fig. 14 summarize the paleocurrent data of sequences A–F. Mean azimuths vary considerably from NW (sequence D) to East (sequence E), generally with at least 30° change from one sequence to the next. Most noticeable changes in paleoflow directions are from sequences C to D, D to E, and E to F. The source area is about the same for all sequences, as suggested by the sandstone petrography (Section 2.2), and is located in the Cape Fold Belt that bordered the Karoo Basin to the South (Fig. 1). The changes in the drainage directions with time are most likely related to the strike variability in orogenic loading, which determined corresponding changes in topographic gradients and dip directions (e.g. as suggested in Fig. 3 of Catuneanu et al., 2000; Cant and Stockmal, 1989; Price, 1994; Beaumont et al., 1993).

5. Allocyclic controls

The Balfour fluvial succession accumulated in isolation from any marine influences within the limits of the preserved Karoo Basin (Cole, 1992; Smith et al., 1993, 1998), and therefore eustasy can be ruled out as an external control on accommodation and stratigraphic patterns. This leaves the discussion open for climate versus tectonics as possible allocyclic controls on sedimentation.

5.1. Climatic background

The patterns of climate and climatic changes during the accumulation of the Beaufort Group are as yet poorly constrained and largely speculative. Both arid and humid climates have been postulated so far for this particular stratigraphic interval of the Karoo Basin (Keyser, 1966; Johnson, 1976a; Visser and Dukas, 1979; Stavrakis, 1980), with an emphasis on the latter interpretation in the more recent publications. No significant climatic fluctuations appear to have occurred during the Beaufort time (Visser and Dukas, 1979), and this conclusion is also supported

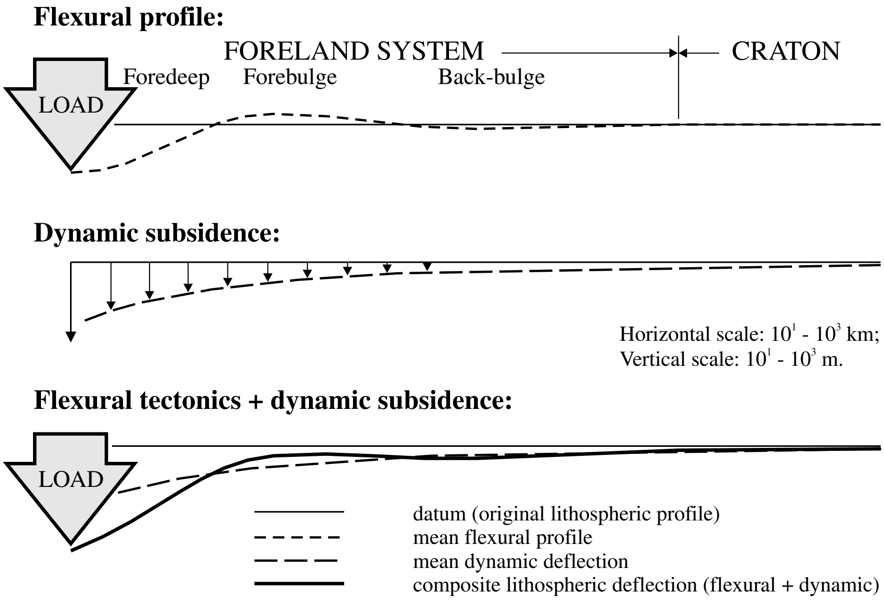


Fig. 15. Tectonic controls on accommodation in a retroarc foreland system (modified from Beaumont et al., 1993; Waschbusch et al., 1996; Catuneanu et al., 1997a; 1998, 1999b). The horizontal scale is variable, depending on the rheology and thickness of the lithosphere. The vertical scale is also variable, depending on the magnitude of supra- and sublithospheric loading. This case study has only to do with the foredeep flexural province of the foreland system. The composite lithospheric profile of the foredeep undergoes subsidence during stages of increased orogenic loading (i.e. thrusting), and uplift during stages of decreased orogenic loading (i.e. erosion and/or extension; not represented here, but illustrated in Fig. 16). Independent of flexural and dynamic tectonics, eustatic fluctuations also affect the amount of available accommodation. However, eustasy is not a relevant control in this case study as the sedimentation regime during the Balfour time was nonmarine within the entire Karoo Basin.

here, based on the following arguments:

(a) No cyclic occurrences of climate-related features has been observed, including carbonate nodules and desiccation cracks. These features are rare and randomly associates with overbank sediments. Other climate indicators include carbonaceous shales, closely associated with *Glossopteris* leaves and long-term floodplain swampy conditions (Johnson, 1976a), which are persistent throughout the succession.

(b) No cyclic color changes occur within the Balfour Formation to suggest fluctuations in the climatic conditions (Smith et al., 1998).

(c) No climatic cycles can be inferred from the fossil content of the Balfour Formation. Most of this succession is assigned to the *Dicynodon* assemblage zone (Rubidge, 1995), which is represented by the same association of fossil flora and fauna throughout the succession. A major shift in the fossil content occurs towards the top of the formation, at the Permo-Triassic boundary, where the *Dicynodon* assemblage is replaced by the *Lystrosaurus* zone (Rubidge, 1995). This faunal shift across the Permo-Triassic boundary was accompanied by a gradual change from generally wet floodplains with high watertables to predominantly dry floodplains (Smith et al., 1998). The wet floodplains with high watertables dominated the entire Balfour time, whereas the dry climate was only established during the accumulation of the overlying Katberg and Burgersdorp formations (Fig. 3; Smith et al., 1998).

(d) The Balfour succession is asymmetrical (fining-upward cyclothems), with abrupt changes across the subaerial unconformities. This is in contrast with what would be expected from climatic fluctuations where the cyclothems tend to be symmetrical (Steel, 1976).

(e) The mean paleoflow directions change across the third-order subaerial unconformities (Fig. 14), suggesting changes in the dip azimuth of the

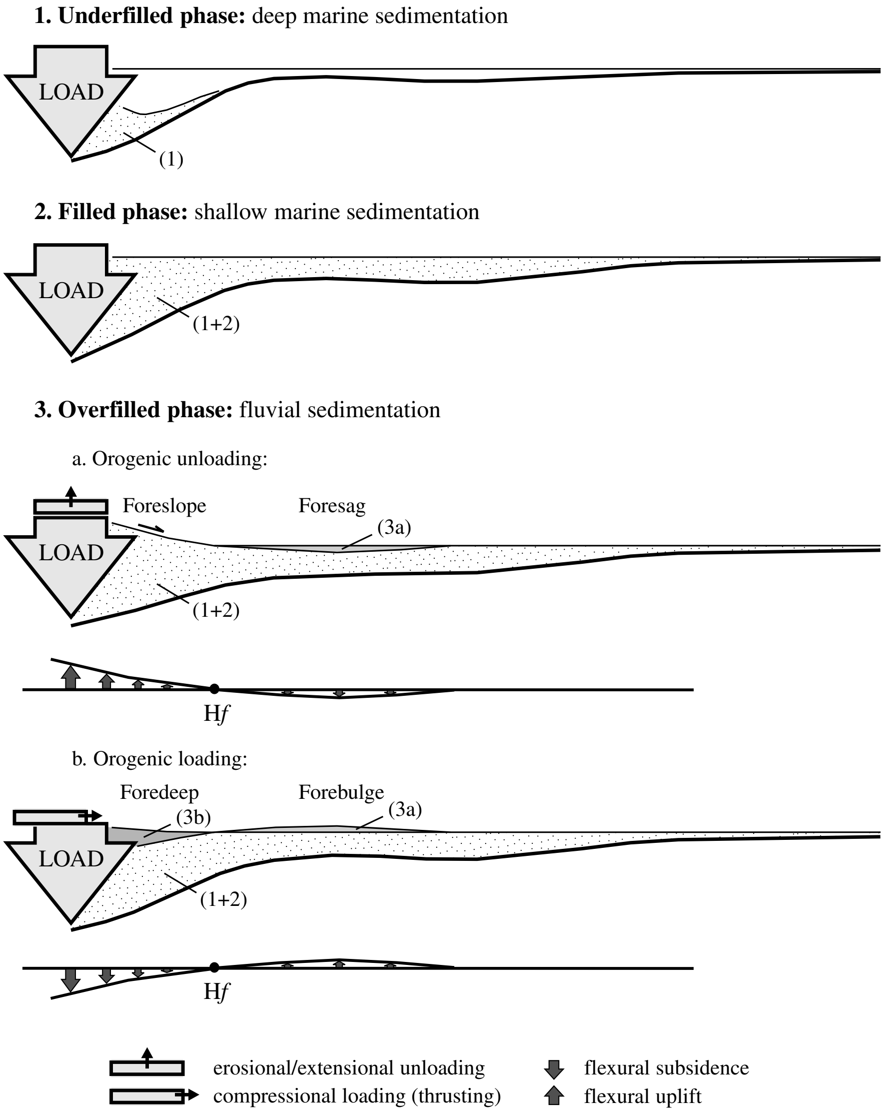


Fig. 16. Sedimentation relative to accommodation in a retroarc foreland system. The concepts of underfilled, filled and overfilled phases are from Sinclair and Allen (1992). During early stages of basin evolution, rapid subsidence overwhelms the sedimentation rates, leading to an underfilled phase of deep marine sedimentation. This corresponds to the Dwyka and lower Ecca times in the Karoo Basin. The available accommodation is gradually consumed by sedimentation as the basin evolves into the filled phase of shallow marine depositional regime. This corresponds to the upper Ecca time in the Karoo Basin. Following the regression of the Ecca Sea, the Karoo was dominated by nonmarine sedimentation until the end of its evolution, which is referred to as the overfilled phase. The Balfour Formation accumulated within the flexural foredeep during the overfilled phase of nonmarine sedimentation. Orogenic unloading leads to flexural uplift and steepening of the topographic slope (foreslope). Orogenic loading results in differential subsidence and the lowering of the topographic gradient. The depocenter migrates between the foredeep, during orogenic loading, and the foresag during unloading. The changes in topographic gradients and sedimentation regimes that resulted in the observed architecture of the Balfour Formation are explained in the text. H*f* = flexural hinge line.

paleotopographic slope from one sequence to another. This is most likely related to differential subsidence and uplift along the strike of the basin, which in turn reflects strike variability in orogenic loading and unloading.

The scarcity of dry climate indicators, together with the information provided by the fossil record (e.g. abundance of *Glossopteris* leaves) and the persistence of carbonaceous shales, point towards a temperate to humid climate that is in agreement with the latest paleoclimate reconstructions for the lower Beaufort times (Johnson, 1976a; Stavrakis, 1980). As no significant fluctuations are indicated by the sedimentologic and biostratigraphic record, these temperate to humid conditions are interpreted here as a long-term climatic background during which the accumulation of the Balfour Formation took place.

5.2. Tectonic model

The fluvial styles interpreted in Section 3.4 indicate perennial streams with a more or less constant discharge, which make sense with the inferred paleoclimatic background. Under constant discharge conditions, changes in fluvial style from braided to meandering may be directly related to a decrease in the slope gradient of the paleotopographic profile (Schumm, 1985), which suggests a tectonic control on accommodation and sedimentation regimes for the third-order Balfour depositional sequences. The tectonic control is also supported by the asymmetry of the vertical profile (Fig. 5), and the changes in paleoflow directions across the sequence boundaries (Fig. 14).

The available accommodation in retroarc foreland systems is controlled by the combined effects of tectonics and eustatic oscillations. No eustatic control may be accounted for in this case study, as the entire Karoo Basin was subject to fluvial sedimentation during the Balfour time. Tectonics is represented by flexural deflections in response to supralithospheric loading (e.g. Beaumont, 1981; Jordan, 1981; Beaumont et al., 1993), as well as by dynamic subsidence related to sublithospheric loading (e.g. Mitrovica et al., 1989; Gurnis, 1992; Waschbusch et al., 1996; Burgess et al., 1997). Both supra- and sublithospheric loading have been documented for the Karoo Basin (Catuneanu et al., 1998; Pysklywec and Mitrovica, 1999). Fig. 15 illustrates the isolated and combined effects of flexural and dynamic tectonics. The final product of the interplay between the two tectonic mechanisms is the composite lithospheric deflection (Fig. 15), which is carried over in Fig. 16 at the base of the foreland sedimentary pile.

Fig. 16 provides an overview of the underfilled, filled, and overfilled phases of retro-foreland sedimentation. The Balfour Formation accumulated during the overfilled phase of the Karoo Basin, following the definitive retreat of the Ecca interior seaway from the South African portion of the original Pan Gondwanian foreland system (Smith et al., 1998). The succession of six third-order depositional sequences, as well as the observed changes in fluvial styles, may be explained in terms of tectonic cycles of orogenic loading and unloading (Fig. 16), as follows below.

(a) *Orogenic unloading* (erosion and/or extension) results in differential proximal uplift, with higher rates towards the center of loading (Beaumont et al., 1993). This generates a topographic slope (‘foreslope’, Fig. 16) that dips away from the thrust-fold belt, with a gradient that steepens with time as uplift progresses. The fall in base-level is accompanied by fluvial incision and the generation of the major subaerial unconformities observed in the field (SU # 1–7 in Fig. 5). Fluvial systems bypass and downcut into the proximal foreslope, with the sediment load accumulating within the subsiding foresag (Fig. 3). Such temporal correlation between proximal sequence boundaries and distal depositional sequences has been documented in the western Canada foreland system, within similar overfilled successions (Catuneanu and Sweet, 1999).

(b) *Orogenic loading* (thrusting) results in differential foredeep subsidence, with increasing rates towards the thrust-fold belt. As a consequence, the gradient of the topographic profile decreases with time, allowing the transition from higher- to lower-energy fluvial systems. This is a time of base-level rise and fluvial aggradation, resulting in the accumulation of the observed depositional sequences (A–F, Fig. 5). Fluvial aggradation starts within braided-type high-energy streams controlled by the steep topographic gradients inherited from the previous stage of orogenic unloading, and continues in lower-energy meandering streams as the topographic gradient becomes shallower with time. During this stage of

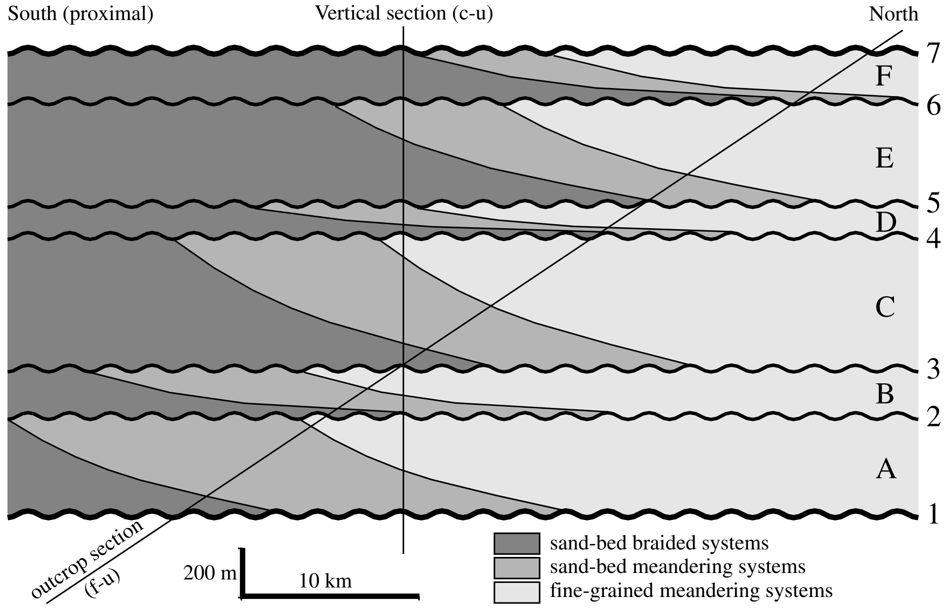


Fig. 17. Conceptual diagram suggesting the internal architecture of the Balfour Formation along a north–south profile through the study area. Wavy lines suggest sequence boundaries (subaerial unconformities). Subaerial unconformities # 1 and 7 are second-order sequence boundaries, i.e. base and top of the Balfour second-order sequence. Subaerial unconformities # 2–6 are third-order sequence boundaries. Sequences A–F are the third-order cyclothems in Fig. 5. Along vertical sections, the Balfour Formation displays an overall coarsening-upward (c-u) profile, in relation to the progradation of the orogenic front during the Balfour time. The outcrop section cuts obliquely across the second-order sequence, exposing proximal facies at the base and distal facies towards the top. As the distance between the bottom and top contacts outcropping in the field (outcrops B 1 and B 26 in Fig. 4) exceeds the amount of northward progradation of the orogenic front during the Balfour time, the vertical profile exposed along the outcrop section displays an overall fining-upward (f-u) trend. The vertical profiles of individual third-order sequences are fining-upward, due to the lowering in topographic gradients during stages of orogenic loading.

compression and thrusting in the adjacent orogenic belt, proximal depositional sequences form at the same time as distal sequence boundaries, as documented in the similar tectonic setting of the western Canada Basin (Catuneanu and Sweet, 1999).

In the light of this model, six orogenic cycles of loading and unloading in the Cape Fold Belt may be inferred during the deposition of the Balfour Formation, with an average duration of 0.66 My (i.e. considering a span of time for the Balfour Formation of 4 My; Fig. 3). The available time control does not allow at this stage to evaluate the ratio between the amount of time represented in the rock record (i.e. depositional sequences) and the time missing within stratigraphic hiatuses (i.e. subaerial unconformities). It is however likely that more time is absorbed within sequence boundaries, as orogenic pulses tend to be shorter-lived events relative to the times of orogenic quiescence that separate them (Catuneanu et al., 1997b).

6. Discussion

Vertical profiles are among the key features used in sequence stratigraphic analysis in order to unravel changes in accommodation and sedimentation regimes through time (Miall, 1997). The logged profile of the Balfour Formation (outcrops B 1–26 in Fig. 4) displays an overall fining-upward trend (Fig. 5), which duplicates at a higher hierarchical level the fining-upward profiles of the individual third-order depositional sequences. A discussion is necessary here to distinguish between the true and apparent trends recorded by the vertical profiles at second- and third-order levels of cyclicity.

Fig. 17 suggests the generalized stratigraphic architecture of the Balfour Formation, indicating the occurrence and lateral shifts of the observed fluvial styles within the sequence framework. At the level of individual third-order cyclothems, changes from braided to meandering streams reflect proximal to distal facies shifts, as well as upwards changes in the fluvial styles. The latter changes are associated with the gradual decrease in topographic gradients during stages of orogenic loading, and explain the fining-upward trends of the third-order cyclothems. As a result of the lowering with time in slope angle and energy levels, the boundaries between fluvial styles gradually shift upstream during the aggradation of each depositional sequence.

At the level of the second-order sequence, the higher energy fluvial systems tend to extend farther to the north with time, in a distal direction, in response to the progradation of the orogenic front. This generates an overall coarsening-upward profile, as proximal facies are gradually brought on the top of older distal facies (Fig. 17). The actual pattern (coarsening- or fining-upward) of the logged outcrop section depends on the ratio between the amount of facies progradation in response to thrust sheet advance, on the one hand, and the distal versus proximal relationship between the youngest and oldest exposed facies, respectively. Previous work indicated that the amount of basinward migration of the orogenic front during the Balfour time is in the region of 10–20 km (Catuneanu et al., 1998). The distance along the dip between the exposures of the bottom and top contacts of the Balfour Formation (outcrops B 1 and B 26 in Fig. 4) is 45 km. This means that the effect of distal versus proximal facies changes outpaces the effect of facies progradation, which generates the observed fining-upward profile (Fig. 17).

It may be concluded that the fining-upward trends displayed by the third-order cyclothems represent the true patterns of their vertical profiles, although slightly exaggerated by the oblique trajectory of the outcrop section (Fig. 17), whereas the logged fining-upward profile of the overall second-order sequence is only apparent, reflecting the more distal position of the younger outcrops relative to the older ones.

7. Conclusions

1. The Balfour Formation represents a second-order fluvial cyclothem accumulated within the foredeep flexural province of the Karoo retroarc foreland system. This cyclothem is built by six third-order depositional sequences separated by prominent subaerial unconformities (Fig. 5).
2. Out of the three allocyclic controls on sedimentation (eustasy, tectonics and climate), eustasy is ruled out by the absence of any marine influences within the limits of the preserved Karoo Basin during the Balfour time.
3. Based on the sedimentologic and biostratigraphic record, temperate to humid conditions are interpreted as the long-term climatic background during which the accumulation of the Balfour Formation took place. No evidence of climatic fluctuations has been found for the Balfour time.
4. The stratigraphic architecture and cyclicity are mainly controlled by tectonic mechanisms, i.e. orogenic cycles of loading (thrusting) and unloading (erosion and/or extension) in the Cape Fold Belt. The average duration of the Balfour cycles is 0.66 My (six sequences during 4 My).
5. The third-order sequence boundaries are related to stages of uplift and fluvial incision during times of orogenic unloading. Differential uplift, with higher rates towards the thrust-fold belt, led to the steepening of the topographic gradient of the proximal foreslope (Fig. 16).
6. The third-order depositional sequences are related to stages of subsidence and fluvial aggradation during times of orogenic loading. Differential subsidence, stronger towards the thrust-fold belt, resulted in the shallowing of the topographic gradients with time (Fig. 16).
7. The decrease in the topographic gradients during stages of subsidence and sediment accumulation induced changes with time in the fluvial styles of each third-order cyclothem, from higher energy sand-bed braided systems to sand-bed and fine-grained meandering systems (Figs. 6–11).
8. The vertical profiles of all third-order cyclothems are fining-upward, reflecting the changes in topographic gradients and fluvial styles. Each third-order subaerial unconformity is associated with an abrupt increase in grain size and fluvial energy across the boundary, in a younging direction.
9. The overall vertical profile of the Balfour second-order sequence is coarsening-upward in response to the progradation of the orogenic front. The outcrop profile displays an overall fining-upward

trend due to the distal position of the younger exposures relative to the older ones (Fig. 17).

10. Such analyzes of changing fluvial styles with time are worth doing for industry-oriented projects, as the amount and distribution of sandy reservoirs largely depend on the style of the fluvial systems which led to their accumulation.

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