**Reconstructing fluvial style**

**Reconstructing fluvial style in the Beaufort Group, South Africa: Distributive fluvial system or trunk river model?**

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**Keywords**: fluvial hierarchy, stacking patterns, ephemeral deposits, distributive fluvial system, Karoo Basin

**ABSTRACT:** Multi-kilometer scale strike and dip exposures of fluvial deposits from the Permo-Triassic Beaufort Group enable detailed analysis of spatial and temporal changes in fluvial style and stacking patterns. A 145 m thick study succession within the Abrahamskraal Formation comprises a hierarchy of channel-related deposits, from storeys, through channel-belts that are stacked into nine channel-belt complexes within four complex sets. Channel-belts show evidence for both downstream and lateral accretion and include common upper phase plane bedding. Floodplain deposits comprise crevasse splay sandstones and siltstone packages showing upward-fining from green-gray siltstone into distinctive purple claystone, interpreted as a drying-upward trend in shallow ephemeral lakes. The lower stratigraphy is dominated by splay complexes, overlain by increasingly incised and amalgamated channelized systems with little preserved floodplain material. Paleocurrents are consistently to the NE.

While parts of the dataset fit a basin-axial trunk river-dominated system, they better (but not entirely) reflect a prograding distributive fluvial system (DFS). Lines of evidence include the consistent paleocurrents in early (frontal) splays and younger channel-belt complexes, and the presence of splay complexes only in the lower stratigraphy, interpreted as precursors to the prograding fluvial system. Deposition took place under conditions of flashy discharge influenced by high frequency climate cycles, also expressed in the mudrock color changes and distribution of paleosols. These cycles overprint the expected gradual drying-upward trend in overbank deposits proposed in DFS models. The abrupt increase in channel-belt incision, amalgamation and lack of floodplain preservation associated with Complex 6 is interpreted to reflect sequence boundary formation and a basinward facies shift that forced progradation beyond the rate predicted in gradualistic DFS models.

**INTRODUCTION**

Traditional fluvial facies models focused on either humid, perennial rivers or arid, dryland environments (e.g., [Miall 1977](#_ENREF_47); [Cant and Walker 1978](#_ENREF_12); [Tunbridge 1984](#_ENREF_77); [Collinson 1996](#_ENREF_18); [Miall 1996](#_ENREF_49); [Bridge 2003](#_ENREF_9); [2006](#_ENREF_10)). Recent studies of both modern and ancient dryland as well as ephemeral systems have widened the range of facies models ([North and Taylor 1996](#_ENREF_54); [Nanson et al. 2002](#_ENREF_50); [Fielding et al. 2009](#_ENREF_25); [2011](#_ENREF_26); [North and Davidson 2012](#_ENREF_53); [Wilson et al. 2014](#_ENREF_88)), but there remains limited understanding of spatial and temporal stratigraphic patterns and facies distributions in dryland fluvial systems, which requires better 3-D outcrop control.

The interpretation of large scale fluvial dispersal patterns in the ancient record has emphasized trunk river systems that feed deltas (e.g., [Cowan 1993](#_ENREF_19); [Archer and Greb 1995](#_ENREF_4); [Kvale and Archer 2007](#_ENREF_38)), but there has been a recent re-emphasis on the role of large scale fan-shaped systems ([e.g., Stanistreet and McCarthy 1993](#_ENREF_68); [Hartley et al. 2010a](#_ENREF_30); [2010b](#_ENREF_31)). Weissmann et al. ([2010](#_ENREF_82)) proposed that these distributive fluvial systems (hereafter, DFS) can be identified by their radial paleocurrent distribution away from the apex, as well as by a downstream decrease in channel-belt dimensions and grain size. There is an ongoing debate over the relative importance of basin-axial trunk river vs. DFS models in explaining stratigraphic patterns of ancient fluvial deposits ([Nichols and Fisher 2007](#_ENREF_52); [Fielding 2010](#_ENREF_24); [Hartley et al. 2010a](#_ENREF_30); [2010b](#_ENREF_31); [Sambrook Smith et al. 2010](#_ENREF_62); [Weissmann et al. 2010](#_ENREF_82); [2011a](#_ENREF_83); [2011b](#_ENREF_84); [Fielding et al. 2012](#_ENREF_27)), and how the response to changing accommodation, sediment supply and lobe switching that can perturb these models will be expressed in the stratigraphic record. The depositional architecture of fluvial systems preserved in high resolution reflection seismic data ([Carter 2003](#_ENREF_13); [Maynard 2006](#_ENREF_44" \o "Maynard, 2006 #2354); [Hubbard et al. 2011](#_ENREF_33); [Mellett et al. 2013](#_ENREF_46)) can help to inform the debate. However, the river and floodplain processes, and the stacking of small-scale elements, recorded in exhumed ancient fluvial systems provide an essential test for these conceptual models.

Assessment of the validity of these conceptual models at outcrop requires excellent exposure quality and a good planform spread of observations over the stratigraphic interval of interest. Ephemeral systems are largely characterized by dry fluvial channels throughout the year with intermittent or seasonal discharge (e.g., [Tunbridge 1984](#_ENREF_77); [North and Taylor 1996](#_ENREF_54); [Wilson et al. 2014](#_ENREF_88)) and this ephemeral character has significant implications on depositional architecture. Many detailed architectural and stratigraphic studies of ancient ephemeral fluvial deposits are restricted to two-dimensional exposures. Examples include the Miocene Siwalik Group of northern Pakistan ([Willis 1993](#_ENREF_87)) and many Mesozoic examples from the US, such as the Triassic Chinle Formation of Utah ([Blakey and Gubitosa 1984](#_ENREF_5); [Cleveland et al. 2007](#_ENREF_16); [Trendell et al. 2013](#_ENREF_76)) and the Lower Jurassic Kayenta Formation from the Colorado Plateau ([Bromley 1991](#_ENREF_11); [Luttrell 1993](#_ENREF_43); [North and Taylor 1996](#_ENREF_54)). Recent work by Wilson et al. ([2014](#_ENREF_88)) has looked to characterize the depositional architecture and sedimentology elsewhere in the lower Beaufort Group using photo panel interpretations. However, many parts of these outcrop belts are inaccessible, leading to uncertainties regarding paleoflow and facies distributions.

This paper aims to contribute to our understanding of the stratigraphic record of ephemeral fluvial systems by reconstructing river and overbank styles through a well-exposed succession of the Permo-Triassic Beaufort Group adjacent to the town of Sutherland, South Africa (Fig. 1). The outcrop distribution permits full detailed mapping of individual channel-belts and channel-belt complexes with good 3-D constraints in a 145 m thick stratigraphic interval. We document intricate trends and changes in preserved river morphology and style, allowing for better understanding of the interplay between controls on this ancient fluvial succession. The depositional architecture and temporal evolution of the system are described in relation to and tested against both DFS and axial trunk river models.

**GEOLOGICAL SETTING**

The Karoo Supergroup spans from the Upper Carboniferous to the Middle Jurassic and is up to 5,500 m thick in the Laingsburg area. Basal Upper Carboniferous to Lower Permian diamictites of the Dwyka Group are overlain by Permian clastic marine strata of the Ecca Group and capped by the Permo-Triassic fluvial Beaufort Group (Fig. 2). Basin subsidence during deposition of the Dwyka, Ecca and lower Beaufort Group was generated by negative dynamic topography resulting from mantle flow, associated with a subducting slab ([Pysklywec and Mitrovica 1999](#_ENREF_57); [Tankard et al. 2009](#_ENREF_75)).

The Beaufort Group is divided into the Upper Permian Adelaide Subgroup and the overlying Lower Triassic Tarkastad Subgroup ([Stear 1980](#_ENREF_70); [Johnson et al. 1997](#_ENREF_35)). The lower part of the Adelaide Subgroup comprises some 2,500 m of fluvial channel-belt and overbank deposits of the Capitanian (late Guadalupian) aged ([Lanci et al. 2013](#_ENREF_39)) Abrahamskraal Formation and the overlying 1,000 m thick Teekloof Formation ([Johnson et al. 1997](#_ENREF_35)).

Extensive research focused on unravelling the sedimentology and paleoclimate of the Beaufort Group by Smith ([1987](#_ENREF_64); [1990](#_ENREF_65)) has been supported by biostratigraphic studies by Smith and Keyser ([1995](#_ENREF_67)) and Rubidge et al. ([2000](#_ENREF_60)) to the east of the study area. Additionally, lithostratigraphic work by Jirah and Rubidge ([2014](#_ENREF_34)) and Day and Rubidge ([2014](#_ENREF_21)) has refined the stratigraphy towards the south margin of the basin. The most recent sedimentological analysis of the lower Beaufort Group in the Sutherland to Laingsburg area is that of Wilson et al. ([2014](#_ENREF_88)), whose study area covered some 7,000 km2. These authors documented six styles of fluvial channel deposits, a largely NE paleoflow direction with some spread and proposed a DFS model for the Abrahamskraal Formation. This studyfocuses on the Abrahamskraal Formation and the informally recognized, sandstone-dominated Moordenaars Member ([Le Roux 1985](#_ENREF_40)) near Sutherland, using outcrops not studied by Wilson et al. ([2014](#_ENREF_88)). Sedimentological comparisons will be drawn explicitly linking this research to that of Wilson et al. ([2014](#_ENREF_88)), where appropriate.

**DATASET AND METHODS**

The Klipkraal Farm hillsides expose fluvial sandstone and mudstone units in a 12 km2 study area where multiple laterally continuous sections oriented strike and dip to overall paleoflow provide 3-D constraints (Fig. 3). Tectonic dip is 1-2° to the east and is consistent throughout the area. Forty-five sedimentary logs were measured at a scale of 1:50 and used to create thickness isopach and facies distribution maps.

Physical correlation of stratigraphic units was further constrained by walking out key stratigraphic surfaces between logged sections identified on photo panels, Google Earth imagery and aerial photographs (Fig. 4A). No single locality covers the full stratigraphic succession, so the type section log is a composite of three main logged sections (Fig. 4B). A paleocurrent database includes planar and trough cross-bedding foresets, cross-ripple lamination, primary current lineation and channel-margin measurements (n = ~1,200). Paleocurrent readings and sand body thicknesses have been referenced spatially within ArcGIS to construct isopach thickness maps and aid in paleogeographic reconstructions. A physical stratigraphic hierarchy based upon lithofacies, paleocurrent indicators and key surfaces has been developed to capture features across multiple scales from bed to depositional sequence (Fig. 5). For sandstones, the hierarchy of architectural elements from smallest to largest includes bed, bedset, storey, channel-belt, channel-belt complex and channel-belt complex set (hereafter, CS). The Klipkraal locality includes nine sandstone units separated vertically by eight laterally extensive, generally poorly exposed mudstone units.

**LITHOFACIES ANALYSIS**

Sixteen lithofacies (Fig. 6) have been identified based on rock type, grain size, thickness, sedimentary structures and color variations (Tables 1 and 2). Eight facies comprise very fine- to lower medium-grained sandstone (S), two are intraformational conglomerate (G) and six are from the mudstone (F) assemblage.

Lithofacies include massive fine-grained sandstone (Sm) (Fig. 6A), planar laminated sandstone (Sh) (Fig. 6B), low angle (< 10°) cross-stratified sandstone (Sl) (Fig. 6C), high angle (> 10°) planar cross-stratified sandstone (Sp) (Fig. 6D), trough cross-stratified sandstone (St), ripple cross-laminated sandstone (Sr) (Fig. 6E), convolute laminated sandstone (Sd) and wavy laminated sandstone (Sw), in accordance with Wilson et al. ([2014](#_ENREF_88)). The conglomerates are matrix supported (either mudstone or poorly-sorted sandstone) with intraformational clasts of reworked calcrete nodules, mudstone and organic material distributed above erosion surfaces (Gl) (Fig. 6F). Mudstone clast horizons (Gm) occur within the channelized deposits and have smaller clast sizes and a predominantly sandy matrix (Fig. 6G). The main mudstone facies are fissile purple mudstone (Fp), poorly sorted purple siltstone (Fpu) (Fig. 6H) and poorly sorted green-gray-blue siltstone (Fggb) (Figures 6I and 6J). Bright green massive mudstone (Fbg) (Fig. 6K), laminated organic-rich dark gray mudstone (Fgl) (Fig. 6L) and sharp-based thinly bedded coarse-grained siltstone or very fine-grained sandstone (Fcs) are also present.

**SAND BODY ARCHITECTURE AND HIERARCHY**

Classifying sand bodies by using a hierarchical scheme simplifies comparison between outcrop analogs and core data from subsurface reservoirs. Fluvial hierarchical schemes (e.g., [Allen 1983](#_ENREF_3); [Miall 1985](#_ENREF_48); [Bridge 1993](#_ENREF_8)) form a conceptual framework between comparably scaled elements, which is especially important when creating geometrical databases ([Bridge 1993](#_ENREF_8)). The analysis of depositional architecture at different scales aids with reconstructing the paleoenvironment and unravelling controls on deposition at a range of spatial and temporal scales ([Miall 1996](#_ENREF_49)).

Similarly to Wilson et al. ([2014](#_ENREF_88)), this paper uses Chevron’s FRAC (Fluvial Reservoir Architectural Classification) Scheme ([Payenberg et al. 2011](#_ENREF_56)), which is based on that of Miall ([1996](#_ENREF_49)), and consists of dividing the stratigraphy into genetically related intervals, each related to scale, environment, key surfaces and facies relationships (Fig. 5). A similar approach was used in fluvial deposits of the Wasatch Formation, Utah, by Ford and Pyles (2014).

*Architectural Elements*

Eight architectural elements (LA, DA, FL, CH, AB, FF, FFL and SS) have been identified based upon lithofacies associations, sedimentary structures, paleocurrent observations, scale, vertical and lateral profile and geometries ([Miall 1985](#_ENREF_48); [1996](#_ENREF_49" \o "Miall, 1996 #270)) (Fig. 7A). We distinguish two types of accretion sets, one with prominent surfaces and depositional elements that dip at a high angle to paleoflow measured from ripple cross-laminated sandstone (Sr) and the other type in which bedding inclination and paleocurrent indicators are aligned. We interpret these very fine- to lower medium-grained sandstone facies (St, Sp, Sl, Sh, Sw, Sm and Sr) as representing lateral accretion elements (LA) and downstream accretion elements (DA), respectively. One distinctive style of accretion element consists of flat lamination (FL) dominated deposits, largely consisting of upper phase plane bedding (Sh). This style exists as an modification to the *laminated sand sheets* proposed by Miall ([1996](#_ENREF_49)) as upper flow regime structures can be observed throughout sand bodies in the lower Beaufort Group forming standalone architectural elements, rather than being locally restricted to deposition at the tops of barforms ([e.g., Fielding 2006](#_ENREF_23)). Commonly, intraformational conglomerates (Gl and Gm) overlie erosion surfaces towards the base of the larger scale aggradational channel-fill elements (CH). Ripple-laminated, coarse-grained siltstones to fine-grained sandstones, or mudstones within the upper sections of erosionally based lenticular bodies commonly fine-upwards and are interpreted as channel-abandonment fill deposits (AB). Channel-fill elements can also be categorized by their axial, off-axial and channel-margin facies associations ([Bridge 2006](#_ENREF_10)). Axial deposits comprise mainly lower fine- to lower medium-grained sandstone (St, Sp, Sl, Sm) and intraformational conglomerates (Gm and Gl), with abundant amalgamation, dm-scale beds and erosion surfaces. Channel margin deposits are very fine- to lower fine-grained sandstone (Sr, Sh and Sl) and thinly bedded (cm-scale). Off-axis deposits are transitional comprising both axial and marginal characteristics.

Purple, green and dark gray siltstone successions are interpreted as floodplain (FF) and floodplain lake (FFL) deposits (Fig. 7B). These purple and green color variations, similar to those described by Stear ([1980](#_ENREF_70)) from the Beaufort Group and by Dubiel ([1987](#_ENREF_22)) from the Upper Triassic Chinle Formation, are interpreted to represent oxidizing and reducing conditions respectively resulting from water table fluctuations. The distinctive purple and green mottling observed within the overbank deposits indicates cycles of oxidizing and reducing processes ([Retallack 1976](#_ENREF_58); [Aitken and Flint 1996](#_ENREF_2)). Distinctive purple horizons, commonly contain rootlet beds, desiccation cracks, gypsum rosettes and pedogenic features, such as rhizoliths, calcrete nodules and slickensides, and are interpreted as palaeosols. Palaeosols are seldom more than 60 cm thick and the original structure of nodules is never completely destroyed to form a thick layer of calcrete, and therefore they are regarded not as mature palaeosols, but of moderate maturity (*sensu* [Leeder 1975](#_ENREF_41); [Nichols 2009](#_ENREF_51)). Sharp-based, thinly bedded sheets of coarse-grained siltstone or very fine-grained sandstone are commonly climbing ripple-laminated indicating high depositional rates. They are interpreted as splay deposits from unconfined flows and crevasse channels (SS) (Fig. 7B).

*Storeys*

A storey comprises bedsets (Fig. 7C) forming channel bar accretion deposits (LA, DA, FL) with associated channel-abandonment fill (AB), such as a point bar with mud plug. In the case of sinuous rivers, storeys will have an initiation margin and a cutbank, related to channel migration within the channel-belt ([Payenberg et al. 2011](#_ENREF_56)).

In a multi-storey sand body a storey boundary, when fully preserved, is marked by a thin siltstone drape on the upper surface of the underlying storey that represents a pause in fluvial deposition. This siltstone is commonly partly to completely eroded, in which case an intraformational conglomerate marks the base of the next storey (Fig. 7D). The absence of floodplain fines between storeys is interpreted as either indicating that there was insufficient time between deposition of successive storeys for floodplain deposits to accumulate or the lack of floodplain material may be attributed to erosion. The scour surfaces between stories are equivalent to the third-order bounding surfaces of Miall ([1996](#_ENREF_49)).

*Channel-belt*

Each channel-belt corresponds to a single, complete cycle of river avulsion ([e.g., Payenberg et al. 2011](#_ENREF_56)). Top surfaces of individual channel-belts are at different stratigraphic levels with evidence of floodplain deposition between the top of one channel-belt and the base of the overlying channel-belt. Channel-belts may consist of only one storey or may be multi-storey. The convex-up upper bounding surface of the storey and the basal surface of minor chute channels are separated by fourth-order bounding surfaces ([Miall 1996](#_ENREF_49)).

The Klipkraal channel-belts preserve a combination of lateral accretion (LA) and downstream accretion (DA) architectural elements, as well as flat lamination (FL) dominated deposits. Within the overbank succession, fourth-order surfaces bound crevasse splays ([Miall 1996](#_ENREF_49)). The erosional base of a channel-belt (Fig. 7E) is marked by a conspicuous erosional surface, equivalent to the fifth-order bounding surface or major channel scour of Miall ([1996](#_ENREF_49)).

*Channel-belt Complex*

A channel-belt complex is made up of a cluster of genetically related channel-belts (Fig. 8). Channel-belts are considered to be genetically related if they share a dominant paleotransport direction and display similar architectures and scale, without which they would be considered a random cluster ([Wilson et al. 2014](#_ENREF_88)). Different channel-belt complexes are typically separated vertically by laterally extensive overbank material, associated with a channel-belt or complex elsewhere in the system. Channel-belt complexes can be subdivided based upon high, moderate and low degrees of amalgamation of their constituent channel-belts (Fig. 5). Styles of amalgamation include laterally and vertically stacked channel-belts (Complex Type A) (Fig. 9) or sub-vertically stacked, aggradational channel-belts (Complex Type B). The hierarchical scheme cannot be easily applied to the overbank deposits at the complex and CS scales.

*Channel-belt Complex Set (CS)*

Complex sets constitute the highest-order hierarchical component recognized. The stacking of two or more genetically related, partially amalgamated channel-belt complexes forms a CS. Valley fills are complex sets, confined by a single composite master surface, but have not been recognized in this study. CSs can also be subdivided based upon high, moderate and low degrees of amalgamation of constituent complexes.

**STRATIGRAPHIC DESCRIPTION**

This section presents descriptions and interpretations for specific mapped units from base to top of the 145 m thick succession. Sedimentary logs and log correlation panels are presented in Figures 10-12. Where appropriate, the quadrants defined in Figure 3 will be used to relate descriptions and accompanying paleogeographic reconstructions. The well exposed channelized deposits and intercalated overbank mudstones have been mapped in 3-D.

*Overbank Interval A*

The basal interval is a minimum of 13 m thick, but the base is not seen. Two light gray planar laminated fine-grained sandstones (0.8 m and 1 m thick) have minimum measured lateral extents of 700 m and are interpreted as crevasse splays (Fcs). Three purple paleosols (Fp) each 15-40 cm thick are present in the lower half of the interval, in association with the purple nodular facies (Fpu) and a 60 cm thick massive mudstone bed (Fbg). The upper 9 m is dominated by green-gray siltstone (Fggb). Bioturbation within this interval is rare and there is a 15 cm thick intermittent nodular horizon towards the top.

*Channel-belt Complex 1*

Complex 1 comprises two channel-belts, which become vertically separated by overbank deposits towards the north-west (Fig. 13A). Maximum complex thickness is 11.35 m, with a true width (perpendicular to paleocurrent) of 800 m. The paleocurrent direction is predominantly north-easterly in the channel-belts. The base of Complex 1 is marked by a 30-70 cm thick brown intraformational conglomerate containing nodules and mudstone clasts overlying an erosion surface that incises up to 3 m into Overbank Interval A.

The constituent storeys within channel-belts consist of Sl, Sr, (rare) Sp and Sm facies, with minor St in the axis, organized into curved-crested dunes (~90 cm preserved dune height). Off-axis the lower channel-belt comprises Sl, Gl and Gm. The upper channel-belt contains two storeys, with a number of mudstone clast horizons (Gm).

In the north-eastern and south-western quadrants (Fig. 3), the complex comprises of climbing ripple-laminated stacked gray-blue coarse siltstone and very fine-grained sandstone beds. The beds thin to 10-15 cm and the overall thickness decreases to 0.7 m, making it difficult to trace laterally. Paleocurrents are north to north-east and consistent with those from the channel-belts. This relationship combined with mapping supports an interpretation that Complex 1 is a terminal splay complex rather than a crevasse splay complex lateral to a larger fluvial channel outside of the study area.

*Overbank Interval B*

 Overbank Interval B, which is 6.4-19.25 m thick, overlies Complex 1 and is dominated by green (and rare gray-green) siltstone (Fggb). A commonly mottled purple siltstone (Fpu) midway through the unit consists of 5-40 cm thick beds with vertical pipe burrows and moderate to intense bioturbation. Two paleosols (Fp) are common towards the top as well as a traceable nodular horizon 2 m beneath the base of Complex 2. Immediately above the mottled purple siltstone is an 85 cm thick coarse-grained siltstone to very fine-grained sandstone deposit (Fcs) with distinct dm-scale climbing ripple-laminated beds with a north-north-easterly paleocurrent direction, interpreted as a splay deposit.

*Complex 2*

Complex 2 comprises two channel-belts, each with two storeys. Main facies are Sh and Sl towards the base, overlain by Sr. At the axis, Complex 2 reaches 8.1 m thick and has a true width of 1,000 m. St is found midway up through the axis with Sp above. The lowermost channel-belt scours into Overbank Interval B with a basal 30 cm thick intraformational conglomerate (Gm). The channel-belts fine upwards with primary current lineations visible on their flat tops. The channel-belts have wings, which are interpreted as deposits of overland flow during peak discharge ([*sensu* Stear 1983](#_ENREF_71)) and show some resemblance to channel-belt Type 4 of Wilson et al. ([2014](#_ENREF_88)).

Towards the south-western and north-eastern quadrants (Fig. 3), the component channel-belts of Complex 2 pass into 1.5 m thick thinly bedded, very fine-grained sandstone, fining-up into coarse-grained siltstone and these channel-belts become difficult to trace laterally (Fig. 13B). Dominant facies are Sr and Sl, with occasional mudstone clasts (Gm) at the base.

The main paleocurrent direction of Complex 2 is towards the north-northwest, where sandstones grade laterally into siltstones. The downstream fining and paleocurrents support an interpretation that Complex 2 represents a terminal splay complex.

*Overbank Interval C*

The 25 m thick Overbank Interval C is distinguished by purple siltstone (Fpu) and five moderate maturity paleosols (Fp), in horizons up to 60 cm thick. This indicates well-drained floodplain conditions ([e.g., Retallack 1988](#_ENREF_59)). The Fpu facies consists of siltstone beds 10-60 cm thick. Thin bedded (~2 cm) bright green Fbg facies occur with green-gray siltstone (Fggb) that has desiccation cracks on bed tops. Dark gray lacustrine (Fgl) mudstones and a single 50 cm thick, climbing ripple-laminated, splay deposit (Fcs) are interbedded with the Fpu and Fp facies. Exposure limitations prevent using the paleosols as regional marker beds.

*Complex 3*

Complex 3 has an estimated width of 1,250 m, is 10 m thick and comprises three multi-storey channel-belts (Fig. 13C). The channel-belts thicken towards the north-east to south-west trending axis of Complex 3 and consist of Sl facies with Sh and Sr (towards the top) and minor St, Sp and Sm. Facies Gl (20 cm thick) is found above the basal erosional surface of the complex, and commonly along storey boundaries. In places the beds appear heterolithic, mottled and intensely bioturbated, with parting lineation apparent towards the tops of channel-belts.

The lower two channel-belts are made up of fining-upward sandstones with low angle internal dipping surfaces (< 10°) to the north-north-east. Paleoflow indicators from current ripples (Sr) and cross-stratified dunes (Sl, St and Sp) are to the east, and thus are perpendicular to these low angle surfaces that are therefore interpreted as lateral accretion surfaces (LA). Due to the presence of lateral accretion surfaces the channels are interpreted to be moderate to high sinuosity. Channel-belt 5 is an erosional remnant and in places is fully removed, with ~6.5 m of incision on the base of Channel-belt 6. The lower two channel-belts have up to three adjacent splay deposits with paleocurrents to the north-east and north. Channel-belt 7 trends west-north-west and contains large barforms (~3 m high) with foresets that dip consistently west, interpreted as downstream accretion surfaces (DA). Ripple cross-lamination up the foresets is interpreted as backflow ripples, which are likely to have formed as a result of a vortex and secondary flow up the bedform front ([Boersma et al. 1968](#_ENREF_7)). The youngest storey within Channel-belt 7 consists of flat-lamination dominated accretion deposits (FL) with an abundance of Sh facies.

*Overbank Interval D*

Overbank Interval D is poorly exposed, 17.25 m thick and predominantly gray-green with an occasional blue tinge and purple mottling. Fggb is the main facies with beds 10-40 cm thick. In its thicker sections the interval fines upward from coarse siltstone at the base to fine siltstone with nodules. Two purple paleosols (Fp), 10-50 cm thick, are present in the lower part of the unit, with a 65 cm moderately bioturbated crevasse splay towards the middle.

*Complex 4*

Complex 4 is up to 11 m thick, with a corrected width of 1,200 m (Fig. 13D). It includes three channel-belts which range in width between 250 and 700 m, each narrowing down-dip. Dominant paleocurrent trend is north-eastward.

Main facies include Sl, Sm, and Sh, with minor Sp, Sr, St and Sw. Each channel-belt has an erosive base, with a rounded top and minor bioturbation throughout. The oldest channel-belt, trending north-north-east, has an associated splay (coarse-grained siltstone and very fine-grained sandstone) to the north-east. The splay now only forms an erosional remnant, largely cut out by Channel-belt 9, within the south-eastern quadrant (Fig. 3). This accounts for the complex being absent across part of the north-eastern quadrant, where the channel-belts have slightly different orientations.

*Overbank Interval E*

The interval is 18 m thick and dominated by green-gray-blue fine to coarse siltstone (Fggb), weathering green-brown with a weak fining upward trend. Where it is thickest a red-purple paleosol (Fp) and purple siltstone (Fpu) horizon (~80 cm thick) containing calcrete nodules is commonly present approximately 12 m above the base. A single 0.6-1.7 m thick climbing ripple laminated splay (Fcs) lies in the lower section.

*Complex 5*

Complex 5 is up to 12.25 m thick and at least 1,200 m wide, comprising two channel-belts. Paleocurrents vary between north-north-west and north-east ( Fig. 14A). Complex 5 is absent in the north-eastern quadrant (Fig. 3) and towards the west of the study area due to incision at the base of Complex 6.

*Overbank Interval F*

Overbank Interval F is the thinnest of the fine-grained units (6.3 m), is poorly exposed and widely absent due to erosion at the base of Complex 6. The main facies is green-gray siltstone (Fggb), with a 1.8 m thick Fp facies containing rootlets and a nodular Fpu horizon. This unit is less bioturbated than the underlying intervals.

*Complex 6*

The base of Complex 6 is marked by the deepest incision surface of the entire study area. The complete complex measures 20.35 m thick, with an estimated minimum width perpendicular to paleocurrent of 2 km. Paleocurrents are predominantly towards the north-north-east, but with scatter to the west ( Fig. 14B). The complex contains three channel-belts of ~5 m, 9 m and 6 m thick (lower, middle and upper channel-belts, respectively). They are laterally offset stacked towards the east and contain the greatest abundance of intraformational conglomerates. These high energy Gl and Gm facies are up to 1.4 m thick and contain rounded nodules, mudstone clasts and bone fragments, with laminated sandstone stringers, muddy drapes, and dune scale cross-bedding (dips of up to 22°). Sandstones overlying the intraformational conglomerates contain 10 cm thick siltstone drapes to foresets, deposition during waning flood conditions ([e.g., Fielding et al. 2009](#_ENREF_25)). Beds of siltstone that onlap erosion surfaces are interpreted as marking periods of sediment bypass during high flood stages, as documented in the Chinle Formation of Utah ([Trendell et al. 2013](#_ENREF_76)).

In the north-eastern quadrant (Fig. 3), Complex 6 fully cuts out Overbank Interval F and Complex 5 with more than 9 m of composite erosion (Fig. 11). Complex 6 is architecturally similar to the *unconfined, strongly amalgamated sheet complex* described by Wilson et al. ([2014](#_ENREF_88)) and interpreted to be a product of limited accommodation.

*Overbank Interval G*

Overbank Interval G is 11.35 m thick and poorly exposed. Gray siltstone (Fggb) is the dominant facies indicating a poorer drainage condition compared to the overbank intervals below. Only minor Fpu and two Fp facies are present and no splay deposits are observed.

*Complex 7*

Complex 7 has a minimum true width of 2.2 km ( Fig. 14C), is up to 15 m thick in the west and completely truncates Overbank Interval G and Complex 6 in the north-eastern quadrant (Fig. 3). Of the two channel-belts, the oldest is a 6 m thick erosional remnant with three storeys (~1 m, 3 m and 2 m thick). Paleocurrents trend towards north-west to north-east. The complex contains only minimal Gl facies, suggesting that the rivers were less incisional and of lower energy than in Complex 6. There are no splay deposits within the complex and bioturbation is rare.

*Overbank Interval H*

Overbank Interval H is up to 11.8 m thick and comprises green-gray structureless, very fine-grained to medium-grained siltstone (Fggb), with bed thicknesses varying between 30-50 cm.

*Complexes 8, 9 and Overbank Interval I*

Above Complex 7 exposure is limited, with the youngest complexes and overbank intervals largely exposed in the north-eastern quadrant. Complex 8 is 5.25-8.35 m thick and is erosionally truncated by Complex 9 (2.1-4.5 m thick). Width estimates of complexes 8 and 9 cannot be made due to the poor exposure. Intervening Overbank Interval I is poorly exposed, up to 8.1 m thick and mainly green in color. A 20 m thick, laterally extensive, poorly exposed overbank unit caps Complex 9.

Channel-belts within Complex 8 and Complex 9 are flat topped, a feature commonly recognized by Wilson et al. ([2014](#_ENREF_88)) in the lower Beaufort Group. Lower fine-grained to upper fine-grained sandstone is dominant, with minor intraformational conglomerate. Sl is common throughout, although there are rare examples of Sm. No bioturbation is recognized.

**STRATIGRAPHIC SUMMARY**

Between complexes 1 and 6, there is an overall upward increase in individual channel-belt thickness (< 2 m to > 8 m), complex thickness (8 m to > 20 m) and an increased amount of incision at the base of each successive complex (< 3 m to > 9 m). This incision results in increased amalgamation up-stratigraphy and a greater proportion of channel-belt sandstone to overbank mudstone, along with an increased abundance of intraformational conglomerate facies (Fig. 15). Above Complex 6, the trends appear to reverse, as channel-belt thickness, complex thickness and the amount of amalgamation decreases. Channelized facies vary from thinly bedded climbing ripple-laminated, lower fine-grained sandstones in complexes 1 and 2, to thicker bedded (up to 50 cm) coarser grained deposits (upper fine- to medium-grained) dominated by steeper cross-stratification (dips of up to 22°) up-stratigraphy.

Channel-belts in complexes 5, 6 and 7 are interpreted as having been deposited by lower sinuosity rivers than channel-belts in complexes 3 and 4. The channel-belt deposits of complexes 5, 6 and 7 are characterized by steeply dipping cross-stratified dunes (dips of up to 20°) in the downstream direction and upper phase plane beds. The abundance of these upper flow regime structures combined with a complicated internal architecture support the interpretation of a flashy discharge, characterized by highly variable flow conditions ([Stear 1978](#_ENREF_69); [Turner 1981](#_ENREF_79); [1983](#_ENREF_80); [Stear 1985](#_ENREF_72); [Smith et al. 1993](#_ENREF_66); [Fielding 2006](#_ENREF_23); [Fielding et al. 2009](#_ENREF_25); [Wilson et al. 2014](#_ENREF_88)).

The older floodplain deposits are typically reddened with pedogenic features. Unit tops are marked by the abrupt juxtaposition of green-gray-blue siltstone over purple siltstone, the surface of which is interpreted to represent a rapid rise in water table. At a bed scale, Overbank Intervals A to C include up to 6 m thick successions of green-gray siltstone that fine upwards into distinctive purple claystone, which we interpret as a drying-upward trend ([Blakey and Gubitosa 1984](#_ENREF_5); [Gallois 2008](#_ENREF_28)). One explanation for the distinctive color cyclicity is that the deposits formed in shallow ephemeral playa lakes that periodically dried up, leaving desiccation cracks overlain by reddened mudstones. The base of each of these interpreted reducing-oxidizing cycles is marked by a paleosurface, representing a break in deposition, perhaps indicating channel abandonment.

Towards the middle of the Klipkraal succession (Complex 3), both the splay deposits and channel-belts become more intensely bioturbated (both vertical and horizontal burrows). There is a marked upward decrease in the number of splay deposits, red beds and paleosols, with none present from Complex 5 upwards. Instead, green-gray siltstones become more common within the younger stratigraphy. These bed- to complex-scale thickness variations and changes in facies and erosion are indicative of an increase in energy and wetness within both the channelized and overbank deposits.

The nine channel-belt complexes have been grouped into four complex sets based on similarities in mean grain size, facies and thicknesses of channel-belt complexes. The same level of hierarchy cannot be accurately applied to the mudstone successions between complex sets due to exposure limitations and therefore the hierarchy is biased towards the channel-belts. This descriptive scheme is not tied to sequence stratigraphy, as shown by the grouping of channel-belt complexes 5, 6 and 7 into one complex set to capture connectivity style, while acknowledging that this increased connectivity is due to an interpreted sequence boundary at the base of Complex 6 (see below). Thicknesses for each complex set are calculated using the type section log in Figure 15 and their key characteristics are discussed below.

*Complex Set 1 (CS 1)*

Complex 1 and Complex 2 share similar sedimentary facies and thickness. Together with Overbank Interval B they are interpreted to form CS 1, which is 19 m thick (Fig. 16). Within the dome quadrant (Fig. 3), the splay deposits of both complexes appear to amalgamate locally to form a splay complex set.

*Complex Set 2 (CS 2)*

Complex 3 and Complex 4 are aggradational units, with similar channel-belt thicknesses, facies proportions and grain size and are interpreted to form CS 2, together with Overbank Interval D. Locally the two complexes vertically amalgamate. CS 2 is 22 m thick and is interpreted as comprising moderate to high sinuosity channel-belts.

*Complex Set 3 (CS 3)*

CS 3 includes Complexes 5, 6 and 7 together with overbank intervals F and G and reaches 36 m thick. Little overbank material is preserved due to the extensive incision; however that which remains is less well-drained with fewer paleosols. All three complexes are amalgamated locally. Splay deposits are absent.

*Complex Set 4 (CS 4)*

Poorly exposed CS 4 comprises amalgamated complexes 8 and 9. In places, Overbank Interval I has been completely removed by erosion at the base of complex 9. From the type section log (Fig. 16) CS 4 has a minimum preserved thickness of 12.05 m. The channel-belts within CS 4 are commonly fine-grained sandstones, with limited bioturbation and a north-eastward paleocurrent trend.

**DISCUSSION**

*Stratigraphic Trends*

The distribution of facies and architectural elements indicates that the channel complexes 1 and 2 (the lower part of CS 1) represent distributive channels that cut into splay deposits. A compensational stacking pattern is evident, where Complex 2 is laterally offset from Complex 1, which may indicate avoidance of depositional relief generated above Complex 1, relocating to the lowest point on the floodplain, in a manner described by Straub et al. ([2009](#_ENREF_73)) for the Mississippi River deposits and Hajek et al. ([2010](#_ENREF_29)) for the late Cretaceous-Paleogene Ferris Formation of Wyoming. Mean paleocurrent directions change up stratigraphy, from north and north-west directed in the two complexes of CS 1, to north-eastwards in complexes 3 to 9 (CS 2 to CS 4). The north-easterly paleoflow is consistent with the regional north-east direction of main Beaufort channel systems ([Johnson et al. 1997](#_ENREF_35); [Wilson et al. 2014](#_ENREF_88)).

Overbank Interval C contains the greatest number of paleosols and the lowest proportion of green siltstone, implying that maximum floodplain dryness is recorded at this part of the stratigraphy. Five moderate maturity paleosols including the thickest paleosol (60 cm) in the measured section are rooted and contain calcrete, signifying prolonged periods of relative climatic stability, which enabled soil development ([Ruskin and Jordan 2007](#_ENREF_61)). Coarse green siltstones of Overbank Interval D are interpreted as poorly drained to lacustrine, resulting in reducing conditions and mark a wetting-upward trend from Overbank Interval C to D. Overbank Interval D contains beds that are moderately to intensely bioturbated and includes a 25 to 35 cm thick bed of dark gray laminated carbonaceous siltstone interpreted to represent a period of localized oxygen-limited, ponded water conditions. Maximum wetness in the succession is interpreted to be within the lower part of Overbank Interval D.

The channel-belts in complexes 5, 6 and 7 (CS 3) display a low- to moderate-sinuosity with abundant examples of downstream accretion (Fig. 7D). Overall the fluvial system shows an increase in energy and grain size range up stratigraphy until the highly incisional Complex 6, consisting of dune-scale cross-bedded sandstones and intraformational conglomerates. Above Complex 6 the trends appear to reverse and the floodplain deposits above Complex 9 reach 20 m in thickness.

*Controls on Stratigraphy*

The stratigraphic organization of the Klipkraal section is discussed in terms of two possible models, both of which show a partial fit to the dataset; these are a trunk river model ([e.g., Cowan 1993](#_ENREF_19)) and a progradational DFS model ([e.g., Weissmann et al. 2013](#_ENREF_85)) (Fig. 16). The effects of autogenic processes, such as lateral channel migration, and far field controls such as climatic variability and sediment supply, are later discussed within the context of these models.

A sequence stratigraphic approach can be used to interpret the evolutionary changes observed up stratigraphy. The Beaufort Group conformably overlies marine deltaic strata of the Waterford Formation and the rivers at least in the lower part of the Beaufort Group were connected to a shoreline towards the north-east ([Smith et al. 1993](#_ENREF_66); [Wilson et al. 2014](#_ENREF_88)). In fluvial sequence stratigraphy regional water table is commonly used as a landward extension of relative sea level ([Shanley and McCabe 1994](#_ENREF_63); [Aitken and Flint 1995](#_ENREF_1); [Swenson et al. 2000](#_ENREF_74); [Catuneanu 2002](#_ENREF_14); [Blum et al. 2013](#_ENREF_6)), with lakes and poorly drained floodplain deposits associated with times of relative sea level rise ([Shanley and McCabe 1994](#_ENREF_63)). Relative sea level fall results in water table fall and river incision, producing typical low accommodation facies associations that include mature paleosols marking interfluve sequence-boundaries ([Aitken and Flint 1996](#_ENREF_2); [O’Byrne and Flint 1996](#_ENREF_55); [McCarthy and Plint 1998](#_ENREF_45); [Hajek et al. 2010](#_ENREF_29)). Rivers increase in grade and deliver sediment to lowstand shorelines ([Shanley and McCabe 1994](#_ENREF_63); [Holbrook et al. 2006](#_ENREF_32" \o "Holbrook, 2006 #2062); [Leleu et al. 2010](#_ENREF_42)). Depending on the amount of relative sea level fall and physiography of the alluvial to coastal plain, rivers may cut valleys during relative sea level fall.

The study section lies approximately 700 m above the Waterford/Beaufort contact and the lower Beaufort succession is characterized by a generally aggradational stacking pattern of channel-belts, with incised valleys only present in the lowermost fluvial stratigraphy ([Wilson et al. 2014](#_ENREF_88)). No marine deposits are reported from the succession and the time-equivalent shoreline during development of the river system was an unknown distance to the north-east of the Klipkraal study area (possibly > 100 km). Regional tectonic dip to the east means that the time equivalent down dip stratigraphy is in the subsurface. The aggradational stacking pattern of the lower Beaufort suggests a balance between subsidence rate and sediment supply through time.

Despite the semi-arid climate, evidence for the maintenance of a high water table level throughout CS 2 includes the high intensity of bioturbation and gray mudstone indicative of poor drainage/standing water conditions in the middle of the section. This ‘maximum wetness’ section is tentatively interpreted to contain the non-marine equivalent of a maximum flooding surface, *sensu* Shanley and McCabe ([1994](#_ENREF_63)). The section also shows the highest volume of preserved floodplain deposits, indicative of high accommodation, but larger scale mapping of this zone is needed to confirm regional significance.

The upward increase in incision at channel-belt bases, reaches a maximum at the base of Complex 6, which exhibits 9 m of erosional relief. Coupled with the low degree of preservation of floodplain fines at this level, these observations are consistent with a minimum accommodation state and the base of complex 6 is interpreted as a sequence boundary ([*sensu* Shanley and McCabe 1994](#_ENREF_63)). The implication of a sequence boundary is that a substantial period of time is locked up on this surface and there is no genetic relationship between the strata below and the strata above ([Van Wagoner et al. 1990](#_ENREF_81)). This means that, while useful for understanding sand body connectivity in a hydrocarbon reservoir sense, CS 3 should not be regarded genetically as one complex set.

Similar fluvial architecture to CS 3, from the temperate to humid Balfour Formation, higher in the Beaufort Group, has been described as tectonically influenced ([Catuneanu and Elango 2001](#_ENREF_15)). However, in the Klipkraal section the absence of significant thickness changes and the uniformity of architectural patterns do not support a tectonic control on the stratigraphic cyclicity; although the scale of the study area may be too small to accurately reject this. At a higher resolution the regular (0.5 m to 6 m thick) drying upward cycles may reflect high resolution climatic cycles superimposed on the accommodation/sediment supply balance.

**Axial Trunk River Model.—**In this scenario the splay deposits of complexes 1 and 2 would represent crevasse splays fed by crevasse channels, all lateral to a larger scale longitudinal trunk river system. The predominantly NW-directed paleocurrents in these lower units compared to the north-east flow directions in the overlying, larger scale, more incisional channel-belts would fit this model. The compensational stacking of channel-belt/splay complexes in the lowermost stratigraphy is interpreted to be a result of autogenic channel avulsion, supported by no distinct grain size variation between Complex 1 and Complex 2 and an absence of significant erosion. The larger channel-belts in CS 3 (predominantly within complexes 6 and 7) would represent the migration of the axis of the trunk river system into the study area. However the architecture and facies distributions, including the maximum wetness zone and the deep incision associated with Complex 6, may indicate modification of a simple trunk fluvial system by allogenic factors, such as subsidence and climate. Arguments against a trunk river model include the consistent paleocurrents in early (frontal) splays and younger channel complexes, and the presence of splay complexes only in the lower stratigraphy, interpreted as precursors to the prograding fluvial system. In an axial river system that reoccupied the flood plain area multiple times, we would expect splay systems to precede each reoccupation of the floodplain by the trunk river.

**Progradation of a Distributive Fluvial System (DFS).—**An alternative hypothesis to the trunk river and lateral splays model to explain the stratigraphic evolution of the Klipkraal succession is that of a DFS. Distributive fluvial systems, if progradational, are marked by an upward increase in grain size, and an upward trend towards increasingly well-drained floodplain and increased channel-belt amalgamation ([Nichols and Fisher 2007](#_ENREF_52); [Weissmann et al. 2011b](#_ENREF_84); [Davidson et al. 2013](#_ENREF_20); [Weissmann et al. 2013](#_ENREF_85)). As documented above, the Klipkraal stratigraphy shows an upward-coarsening and increase in channel-belt size and clustering, which fits a prograding DFS model. The maximum incisional base of Complex 6 may represent the point of maximum alluvial progradation, followed by gradual retreat or lateral switch in the axis of the DFS to explain the upward decrease in sandstone amalgamation and content from Complex 7 upwards (Fig. 17).

A major river channel can form part of a larger DFS as it shifts position across the fan or it can be an axial trunk river system with sediment supplied by a DFS ([Hartley et al. 2010a](#_ENREF_30); [Weissmann et al. 2010](#_ENREF_82)); as such, the DFS and axial system can coexist in time, but the two models remain mutually exclusive. A key difference between a trunk river model and a DFS model is that in the DFS scenario the lower stratigraphy of CS 1 and CS 2 would be interpreted as distal distributive terminal splay systems, rather than lateral crevasse splays from a trunk river. If the terminal reaches of a DFS are beneath the study section and CS 1 represents the distal reaches of a DFS, the model predicts the paleosols to be poorly-drained, rather than the moderately mature, well-drained soils observed. Likewise the paleosols within CS 3 are not well-drained and so do not fit with the predicted character of proximal floodplain deposits in a DFS model.

A similar up-section increase in grain size, amalgamation and channel-belt thickness has also been described by Trendell et al. ([2013](#_ENREF_76)) for the Triassic Chinle Formation of Utah and is interpreted as recording deposition in a progradational DFS ([Weissmann et al. 2013](#_ENREF_85)). Just like for CS 1, the Blue Mesa Member of the Chinle Formation has also been interpreted as distal DFS deposits ([Trendell et al. 2013](#_ENREF_76)) due to the increased mudstone to sandstone ratio, more mature sediments and high accommodation setting. The documented up-section increase in well-drained floodplain within the Chinle Formation ([Trendell et al. 2013](#_ENREF_76)) contrasts with the poorly-drained overbank conditions observed in the upper zones at Klipkraal (CS 3 and CS 4). These increasingly well-drained paleosols from the Chinle Formation are attributed to deposition in more upland positions during fan or avulsion-complex progradation, rather than any change in climate ([Trendell et al. 2013](#_ENREF_76)). Turner ([1977](#_ENREF_78)) suggested that the lower Beaufort Group was also subjected to repeated river avulsions. Various studies associate these unstable, avulsive systems with semi-arid climatic settings and highly variable, flashy discharges (e.g., [Kelly and Olsen 1993](#_ENREF_37); [Trendell et al. 2013](#_ENREF_76)), like those responsible for depositing the Klipkraal succession.

The progradational DFS model (e.g., [Nichols and Fisher 2007](#_ENREF_52); [Hartley et al. 2010b](#_ENREF_31); [Weissmann et al. 2011b](#_ENREF_84); [2013](#_ENREF_85)) offers limited consideration to base level change, in contrast to more traditional trunk river-dominated models (e.g., [Wright and Marriott 1993](#_ENREF_89); [Shanley and McCabe 1994](#_ENREF_63); [Holbrook et al. 2006](#_ENREF_32)). The gradual up-section increase in grain size, amalgamation and thickness of channel-belts and complexes in the lower to middle succession is interpreted to represent a progradational DFS, influenced by climatic cycles that are preserved in the floodplain deposits as small-scale drying upward cycles, not fully in phase with the progradation. At the base of CS 3, the abrupt increase in channel-belt connectivity and reduced preservation of floodplain deposits is interpreted as a low-accommodation system, similar to that described by Wilson et al. ([2014](#_ENREF_88)). We therefore conclude that the stratigraphy preserves the partly competing effects of accommodation, sediment supply and lobe switching, along with high-frequency climate cyclicity, all superimposed on a weakly prograding DFS. We propose that the DFS model also needs to better incorporate the effects of these mechanisms on progradational stratigraphy..

*Limitations of the Dataset*

The Klipkraal stratigraphy only represents a minor part of the Abrahamskraal Formation and distributive fluvial systems span tens to hundreds of km in radius ([Nichols and Fisher 2007](#_ENREF_52)). Criteria used to distinguish prograding DFSs in the modern and ancient record, such as the characteristic upward increase in grain size, amalgamation and proportion of sandstone (e.g., [Trendell et al. 2013](#_ENREF_76" \o "Trendell, 2013 #2286); [Weissmann et al. 2013](#_ENREF_85)), cannot be fully applied here. The study area provides only a glimpse into the evolution of the larger depositional system and subsequently may be too small to objectively decide between the models of an axial trunk river and a major river associated with a prograding DFS. However, when this dataset is integrated into the more regional (7,000 km2) study of Wilson et al. ([2014](#_ENREF_88)), which showed consistent paleocurrents to the NE with some spread, the evidence for a DFS model increases. This is further supported by regional radial paleocurrent dispersal patterns reported by earlier workers ([Jordaan 1990](#_ENREF_36); [Cole and Wipplinger 2001](#_ENREF_17)). Significantly, Wilson et al. ([2014](#_ENREF_88)) found no evidence for any axial trunk river deposits in the larger Beaufort area.

The 3-D control afforded by the outcrop belt highlights the lateral and stratigraphic variability in fluvial-overbank architecture, and the challenge in untangling the interplay of controls on fluvial stratigraphy. The study section demonstrates the relationship between several allogenic forcing factors on fluvial deposits, which principally include accommodation driven by subsidence and changes in sediment supply.

**CONCLUSIONS**

The observed up-section progradation occurs over a relatively narrow succession (145 m) with splay deposits only abundant in the lowermost intervals (Fig. 15). If these splays happened to correspond to deposition within part of a major trunk river system, their presence would be expected throughout the entire stratigraphic section as precursors to each channel reoccupation, which is not seen here. The findings outlined in this study of the lower Beaufort Group, combined with the prevalence of upper flow regime structures within what are largely interpreted low sinuosity channel-belts with a narrow paleocurrent range, favor the model of a DFS. This is further supported by regional radial paleocurrent dispersal patterns ([Jordaan 1990](#_ENREF_36); [Johnson et al. 1997](#_ENREF_35); [Cole and Wipplinger 2001](#_ENREF_17)) and the recent work of Wilson et al. ([2014](#_ENREF_88)) who concluded that the large-scale architecture of the Beaufort system is consistent with deposition in an aggrading fluvial megafan.

In summary, the Klipkraal section best reflects a prograding DFS under conditions of flashy discharge influenced by high frequency climate cycles, also expressed in the mudrock color changes and distribution of paleosols (Fig. 17). These cycles complicate the gradual drying upward trend in overbank deposits proposed in DFS models. The abrupt increase in channel-belt amalgamation and lack of floodplain preservation associated with channel-belt CS 3 is interpreted to reflect sequence boundary formation and a basinward facies shift that forced progradation beyond the rate predicted in DFS models. The next stage in refining DFS models will be the incorporation of the effects of base level transit cycles on the robust long term progradation model.

**ACKNOWLEDGEMENTS**

The authors are extremely grateful to Chevron Australia Pty Ltd. for financially supporting this research. Andrew Wilson, John Kavanagh, Laura Fielding, Ashley Clarke and Janet Richardson are acknowledged for their assistance in the field, as are the farmers in the Sutherland area for kindly permitting access to their land. In addition we would like to thank all members of the Beaufort Project, namely Tobias Payenberg, Anne Powell, Andy Palfrey, Jösta Vermeulen and Emma King. Thanks also to Brian Willis, Bryan Bracken and Kristy Milliken for helpful discussions. This manuscript has benefited from thorough and helpful reviews by Timothy Lawton, Colin North and Associate Editor Martin Gibling.

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Table 1.—*Sandstone (S) and intraformational conglomerate (G) lithofacies classification scheme adopted within the Abrahamskraal Formation, lower Beaufort Group, SW Karoo Basin. Modified after Miall (*[*1996*](#_ENREF_49)*).*

|  |  |  |  |
| --- | --- | --- | --- |
| **Facies** | **Lithology** | **Sedimentary Structures** | **Interpretation and Environment of Deposition** |
|  Sm | Sandstone (v.f-m) | Massive/ structureless sandstone | Structureless sandstone may form as a result of weathering or the uniform grain size. Internal structures often destroyed due to intense bioturbation (localized), dewatering or weathering. Alternative interpretation of insufficient time available for bedform development, for example small channel bank collapse. |
|  Sh | Sandstone (f-m) | Planar laminated sandstone. Parting lineations (pcl) common | High flow velocities, often in shallow water depths, deposit under upper flow regime plane bed conditions, destroying dunes and ripples. Primary current lineation often produced by turbulent eddies near the water surface. Paleocurrent direction parallel to lineation.  |
|  Sl | Sandstone (f-m) | Low angle (< 10°) cross -stratified sandstone | Large scale dunes and barforms. Sl may form from lateral migration of the channel and lateral migration of point bars (lateral accretion surfaces), in more sinuous systems. |
|  Sp | Sandstone (f-m) | High angle (> 10°) planar cross-stratified sandstone | Commonly located towards the base of channel-belts. Represents the migration of 2-D dunes that form at lower flow velocities than trough cross-stratified sandstone (dune height is proportional to water depth). Alternatively may form due to lateral migration of point bars in a fluvial channel or from deposition in erosional scours.  |
|  St | Sandstone (f-m) | Trough cross-stratified sandstone | In-channel migration of 3-D dunes (bedload transportation), where deep scours are common. Often located at the base of a point bar and dunes may have a sigmoidal profile. Trough cross-stratification is formed by linguoid ripples. |
|  Sr | Sandstone (f), siltstone (c) | Ripple cross-laminated sandstone *(asymmetrical climbing; symmetrical; wave; rib and furrow; ripple tops)* | Ripples represent low flow regime conditions and they correspond to the transportation of sand through the channel due to water currents flowing over the surface of the sediment. Bi-directional wave motion creates straight-crested symmetrical wave ripples (weaker flows), whereas the more sinuous-crested current ripples are produced by uni-directional currents (stronger currents). Rib-and-furrow is produced by the downstream migration of current ripples. Ladder-back ripples are secondary ripple sets that form between larger ripple troughs. Ripples can be deposited on tops of levees or in crevasse channels as the flood energy subsides, for example at the top of a sheet-like proximal splay sand. Alternatively ripples may form in channel-fills during stable flow conditions or throughout a waning flow on barform tops, such as point bars. Commonly associated with the upper part of Sl facies. |
|  Sd | Sandstone (f), siltstone (c) | Convolute laminated sandstone | Deformation of bedding and/or laminations. May create localized brecciation. High deposition rates lead to loosely packed sediment prone to deformation. Convolute beds and laminations and dish and pillar structures are formed from dewatering. Flame structures occur from denser sand/coarse silt being deposited on top of less dense fine silt.  |
|  Sw | Sandstone (f) | Wavy laminated sandstone | Often associated within vertical facies changes from parallel laminations to wavy laminations to climbing ripples. The wavy laminae may be the product of previously rippled surfaces.  |
|  Gl | Matrix-supported (siltstone to f. sandstone) with clasts  | Matrix-supported intraformational conglomerate comprising mud clasts, concretions and rare bone fragments. | Basal channel lag deposits often formed during bank collapse from erosion of the outer river bend (high energy flows and migration of the channel). Alternatively due to channel-belt avulsion when there is power to erode the banks and after avulsion the channel then cuts into its new banks. Lags are deposited when the river can no longer support the transport of bedload. This coarser sediment is commonly deposited at the base of cross-beds, for example on the lee side of dunes at the base of the foresets or at the base of the channel-belt. Stratified sandstone stringers within lags are likely to be down-cutting bedset toes. Thicker conglomerates represent axial deposition. |
|  Gm | Mudstone clasts, matrix supported (f. sandstone) | Mudstone clast horizon, aligned | Mudstone rip-up clasts from underlying bed. Mudstone clast horizons often found nearer to channel margins. Mid-channel formation as floods mobilise the mudstone clasts. Sand re-enters the system afterwards. |
| v.f, very fine-grained; f, fine-grained; m, medium-grained; c, coarse-grained |

Table 2*.—Mudstone (F) lithofacies classification scheme adopted within the Abrahamskraal Formation, lower Beaufort Group, SW Karoo Basin. Modified after Miall (*[*1996*](#_ENREF_49)*).*

|  |  |  |  |
| --- | --- | --- | --- |
| **Facies** | **Lithology** | **Sedimentary Structures** | **Interpretation and Environment of Deposition** |
|  Fbg | Siltstone (v.f- f), claystone | Bright green massive mudstone | Interpreted as reducing conditions within the overbank and commonly associated with purple mudstones (Fp). |
|  Fp | Siltstone (v.f-m), claystone | Fissile purple mudstone | Moderate maturity paleosols comprising pedogenic features, such as rhizoliths, calcrete nodules and slickensides, are interpreted as distal overbank facies that have reddened post-deposition. |
|  Fpu | Siltstone (v.f-c) | Poorly sorted purple siltstone | Located within distal overbank deposits and channel abandonment, interpreted as oxidising conditions. May be mottled green. |
|  Fgl |  Siltstone (m), claystone | Laminated organic-rich dark gray mudstone  | Interpreted to represent low energy conditions or standing water, for example a rise in the water table or increased precipitation. Indicative of lacustrine fill and/or ponded water, such as an oxbow lake.  |
|  Fggb | Siltstone (v.f-c), claystone | Poorly sorted green-gray-blue siltstone | Overbank deposits, representing reducing conditions. Massive beds and structured beds are interpreted as proximal and distal splay deposits, respectively. Often mottled purple. |
|  Fcs | Siltstone (c), sandstone (v.f-f) | Sharp-based thinly bedded coarse siltstone or very fine sandstone | Unconfined sheet-like splay deposits, within the overbank environment. Interpreted as flood events, as sediment (largest first) is deposited on the floodplain. Often occurs on the outer bend of a meandering river where the water energy is greatest. |
|  T | Ash (f) | Tuff deposit | Interpreted as sub-aerial volcanic ash fall that has consolidated following a volcanic eruption.  |
| v.f, very fine-grained; f, fine-grained; m, medium-grained; c, coarse-grained |

**FIGURE CAPTIONS**

Fig. 1.—A) Topographic map of the SW Karoo Basin, South Africa, using SRTM [elevation](http://en.wikipedia.org/wiki/Elevation) data superimposed upon Google EarthTM Landsat. Warm colors relate to higher elevations, cool colors refer to lower elevations. The Great Escarpment and the town of Sutherland are highlighted. B) Google EarthTM Landsat image displaying the 3-D control that the outcrops afford.

Fig. 2.—A) Cape lithostratigraphy, redrawn after Wickens ([1994](#_ENREF_86)), showing the stratigraphic position of the fluvial Abrahamskraal Formation, lower Beaufort Group within the Karoo Supergroup. The Beaufort Group conformably overlies deltaic strata of the Waterford Formation. B) Schematic representation of the Abrahamskraal Formation based on the Great Escarpment and Sutherland area stratigraphy.

Fig. 3.—Topographic map of the Klipkraal study area relative to the town of Sutherland (in gray). The R354 road is outlined in red. The map is divided into quadrants and the base of each logged section (labeled KK-1 to KK-45) is highlighted by a red dot.

Fig. 4.—A) Aerial image of the Klipkraal study area displaying the locations of correlation panels X-X′, Y-Y′ and Z-Z′, labeled in white. Numbers relate to correlation panels presented in Figures 10-12 and colored dots represent log locations. B) Type section sedimentary log is a composite of three log sections (from KK-31, KK-35, KK-39 and KK-42) as the complete stratigraphy is not represented in any one area.

Fig. 5.—Fluvial hierarchy used in this study. The scheme separates channel-related from floodplain-related features and characterizes small scale architectural elements, up to larger channel-belt complex set (CS) scale. Hierarchical scheme and schematic diagrams are based on observations and descriptions by Miall ([1996](#_ENREF_49)), Bridge ([2006](#_ENREF_10)) and Payenberg et al. ([2011](#_ENREF_56)).

Fig. 6.—Representative lithofacies from the Abrahamskraal Formation. Tables 1-2 outline the lithofacies codes and interpretation of depositional environment. A) Massive fine-grained sandstone (Sm). B) Planar laminated sandstone (Sh), with primary current lineations highlighted on the bed surface. C) Low angle (< 10°) cross-stratified sandstone (Sl). D) High angle (> 10°) planar cross-stratified sandstone (Sp). E) Climbing ripple cross-laminated sandstone (Sr). F) Matrix supported conglomerate with intraformational clasts of reworked calcrete nodules and mudstone that is interpreted to represent a channel-belt lag deposit, overlying a large erosion surface (Gl). G) Poorly-sorted, angular mud clasts within a predominantly sandy matrix (Gm). H) Poorly sorted purple siltstone (Fpu). I) Poorly sorted green-gray-blue siltstone containing a 60 cm thick nodular horizon (Fggb). J) Green-gray siltstone (Fggb) containing desiccation cracks on bed top. K) Bright green massive mudstone (Fbg), mottled purple. L) Laminated organic-rich dark gray mudstone (Fgl).

Fig. 7.—Outcrop photographs displaying key facies, architectural elements and characteristics from bedset scale through to channel-belt scale. For facies abbreviations refer to Tables 1 and 2. A) Lateral accretion (LA) surfaces are present within a large-scale channel-belt, which cuts into floodplain fines (FF) and floodplain lake (FFL) deposits beneath. B) Floodplain fines (FF) comprise purple, green and gray siltstone successions (Fggb and Fp) and laterally extensive splay deposits (SS) are defined by the climbing ripple cross-laminated very fine-grained sandstone. C) Bedset scale features, bounded by the yellow line. Flat lamination (FL) dominated elements and larger scale aggradational channel-fill elements (CH) are labeled. D) Downstream accretion elements (DA) overlying an erosional storey boundary, outlined in yellow. DA example comprises Sl, Sm, Gl and Gm facies. E) Erosional base of channel-belt (highlighted in yellow) overlain by channel-fill elements (CH), comprising Gl, Sm, Sl and St facies.

Fig. 8.—Outcrop photographs displaying architectural elements and characteristics from channel-belt complex to channel-belt complex set scale. Sedimentary log locations are overlain in black (Fig. 8A) or white (Fig. 8B). A) Image from the SE quadrant (Fig. 3) from part of the Z to Z′ correlation panel (Fig. 4). Individual complexes (Cx 3 to 8) and architectural elements (FF, floodplain fines; FFL, floodplain lake deposits; DA, downstream accretion dominated deposits) are labeled. B) Photograph from the NE quadrant (Fig. 3) from part of the Y to Y′ correlation panel (Fig. 4). Individual channel-belt complexes (Cx 4 to 9) and floodplain fines (FF) are labeled.

Fig. 9.—Detailed photo panel interpretation of Complex 3 with sedimentary log positions and channel-belt bounding surfaces overlain. Each of the three channel-belts is labeled, along with corresponding architectural elements (LA, lateral accretion surfaces; DA, downstream accretion surfaces; FL, flat lamination dominated deposits). The lithofacies distribution for Complex 3 is shown in the logs and accompanying pie charts. Complex 3 displays laterally and vertically stacked channel-belts (i.e., Complex Type A, Fig. 5).

Fig. 10.—Correlation panel X-X′, displaying sedimentary logs from the dome at Klipkraal (refer to Fig. 3). Each complex (Cx 1 to 6) is separated into individually numbered channel-belts where possible. Overbank intervals are labeled (A to E) and the panel location is presented in Fig. 4A.

Fig. 11.—Correlation panel Y-Y′, representing sedimentary logs from the north-eastern quadrant at Klipkraal (refer to Fig. 3). Complete section is ~2 km in length. Each complex (Cx 3 to 9) is separated into individually numbered channel-belts where possible. Overbank intervals are labeled (C to I) and the panel location is presented in Fig. 4A.

Fig. 12.—Correlation panel Z-Z′, showing sedimentary logs from the main south-western and south-eastern quadrants at Klipkraal (refer to Fig. 3). Complete length of section is ~5 km. Each complex (Cx 1 to 9) is separated into individually numbered channel-belts where possible. Overbank intervals are labeled (A to I) and the panel location is presented in Fig. 4A.

Fig. 13.—A) Paleogeographic reconstruction of Complex 1, comprising two channel-belts with north-easterly paleocurrents. Complex 1 is in the sub-crop towards the north-east. B) Complex 2, made up of two channel-belts, each with two storeys. Complex 2 is sub-crop towards the north-east. C) Complex 3, comprising three channel-belts. D) Complex 4, consisting of three channel-belts. Channel-belt 8 has an associated splay deposit that forms an erosional remnant cut by channel-belt 9.

 Fig. 14.—Paleogeographic reconstruction of Complex Set 3 (complexes 5 to 7) during deposition. A) Complex 5, comprising two channel-belts with variable north-north-west and north-easterly paleocurrents. Complex 5 is absent towards the north-east and west, due to incision at the base of Complex 6. B) Complex 6, made up of three channel-belts. Complex 6 fully cuts out Complex 5 towards the north-east. C) Complex 7, containing two channel-belts with north-westerly and north-easterly paleocurrents.

Fig. 15.—Schematic sedimentary log from the Klipkraal type localities (refer to Fig. 4). Each channel-belt complex (Cx 1 to 9) and overbank interval (A to I) is labeled with descriptive text to characterize the up-stratigraphy changes in thickness, color, and number of splays and paleosols.

Fig. 16.—Schematic stratigraphic log with fluvial hierarchy overlain. Both sequence stratigraphic and distributive fluvial system (DFS) model interpretations are shown. List of abbreviations: Transgressive System Tract (TST), Maximum Flooding Surface (MFS), Highstand System Tract (HST), Sequence Boundary (SB), Lowstand System Tract (LST).

Fig. 17.—Conceptual image depicting the evolution of the Abrahamskraal Formation based on the progradational distributive fluvial system (DFS) model. The schematic diagrams are based on observations made in this study, and are modified after Nichols and Fisher ([2007](#_ENREF_52)), Trendell et al. ([2013](#_ENREF_76)) and Weissmann et al. ([2011a](#_ENREF_83); [2013](#_ENREF_85)). A) Complex Set 1 (CS 1) is interpreted as terminal distal deposits and signifies gradual progradation of the DFS. B) CS 2 is interpreted as medial DFS deposits and represents continued gradual DFS progradation. C) CS 3 is interpreted as proximal DFS deposits. The incisional base of Complex 6 is considered as the point of maximum alluvial progradation, marked by a sequence boundary and a basinward shift in facies. D) An upward decrease in sandstone amalgamation and content from Complex 7 upwards (refer to Fig. 15) is interpreted as gradual retreat or lateral switch in the axis of the DFS. E) Schematic cross-section through the four complex sets (CS 1 to 4). Sediment was transported hundreds of km from Patagonia during deposition of the Abrahamskraal Formation.