Two stacked parasequences exposed continuously along a 35-km dip section in the Permian lower Waterford Formation, Karoo Basin, South Africa, form basin margin-scale clinothems, and their internal facies distributions have been mapped out from shelf to upper submarine-slope settings. Sedimentary facies changes have been determined by walking out key surfaces between measured sections. The two parasequences (Waterford clinothems WfC 3 and WfC 4) share progradational profiles, but WfC 3 is characterized by a strong fluvial influence, whereas overlying WfC 4 is a wave-storm-dominated delta front system. When correlated basinward, the two clinothems exhibit stratigraphic thickening as well as differing process responses to the increased gradient at the shelf-edge rollover. WfC 3 exhibits synsedimentary, wedge-shaped rotational growth faults. These growth faults trapped sand at the shelf-edge rollover, so minimal sand was delivered to the upper slope; therefore, the clinothem downlaps into the slope mudstones within 7 km of the shelf-edge rollover. In contrast, the top of WfC 4 is marked by closely spaced gullies cut into deformed delta front deposits. The delta front deposits pass into sand-prone slope turbidites 3 km downdip. Locally, these turbidites are truncated by a 60-m-thick turbidite-sandstone–filled slope channel fill. In this case, most of the slope delivery is associated with a wave-dominated process regime. It is important to consider the sequence stratigraphic setting of clinothems in such analyses; WfC 4 represents a minimum accommodation point in a depositional sequence and is overlain by a Type 2 sequence boundary. Despite wave and storm dominance, the low accommodation and high sediment supply at that time is interpreted to have driven sand beyond the gullied shelf-edge rollover. Therefore, the delivery of sediment to deep-water settings is governed by parameters other than the presence and proximity of a fluvial point source, which is heavily advocated in current models for shelf construction.

INTRODUCTION

The shelf-edge rollover zone is critical for understanding the mechanisms and timing of sediment and organic carbon transfer from continents to oceans. The stratigraphic record of the rollover area is complicated by the interaction of current- and gravity-driven sedimentary processes (Johannessen and Steel, 2005), but provides a vital archive for the reconstruction of relative changes in sea level and rates of sediment supply (Helland-Hansen and Hampson, 2009).

Data sets utilized to study the delivery of sediment across the shelf-edge rollover include bathymetric data from present-day shelf margins, seismic reflection data sets from Quaternary to ancient successions that can be tied to well information, and outcrop studies of exhumed ancient basin margin successions. Present-day systems are invaluable in studying both weld and across-strike variability in shelf-to-slope morphology (e.g., O’Grady et al., 2000; Olariu and Steel, 2009; Goff et al., 2010). Typically, these case studies are limited to a single time slice during a period of high sea level when few systems are active at the shelf edge. Understanding how changes in parameters such as eustatic sea level, subsidence rate, sediment supply, and climate affect the depositional architecture and morphology of the shelf to slope transition requires a stratigraphic perspective. High-resolution reflection seismic data sets that illustrate the depositional architecture of the shelf-to-slope profile have significantly increased our understanding of the long-term morphological evolution of basin margins (Saller et al., 2004; Johannessen and Steel, 2005; Ryan et al., 2009). The physical transition from shelf to slope is easily identifiable in horizontally shortened seismic images as a break in slope (Suter and Berryhill, 1985; Sydow and Roberts, 1994; Kolla et al., 2000; Hiscott, 2001; Pinous et al., 2001; Krassay and Totten-dell, 2003; Houseknecht et al., 2009; Ryan et al., 2009). When combined with information from cored wells, integrated studies have allowed the geometries of clinoforms to be defined and mapped, and rates of margin progradation established (e.g., Mountain et al., 2010).

Subsurface and modern data sets suffer from a lack of high-resolution stratigraphic and sedimentological details that permit process-based interpretations to augment the analysis of morphological and architectural change. This gap in data coverage can be filled by the use of large-scale (seismic scale) stratigraphic successions at outcrop where the transition from shelf to slope can be physically defined and characterized (Mellere et al., 2002; Johannessen and Steel, 2005; Carvajal and Steel, 2006; Løseth et al., 2006; Uroza and Steel, 2008; Covault et al., 2009; Hubbard et al., 2010). Few outcrop studies present analysis of multiple stacked shelf-edge systems, where long-term trends and changes in sedimentary processes and transfer mechanisms across the shelf-to-slope transition are considered. Common observations of single shelf-edge successions is that a fluvial process regime at the shelf edge transfers more sediment basinward than a wave-dominated process regime (e.g., Carvajal and Steel, 2009; Dixon et al., 2012b), and successive shelf-edge rollover strata are normally similar in their process response to increased gradient (e.g.,...
Here we report on changes in process regime and sediment transfer mechanisms across stacked shelf-edge rollovers from the seismic-scale outcrops of upper Permian deposits in the Laingsburg depocenter, Karoo Basin, South Africa (Fig. 1). Our objectives are to (1) document the stratigraphic variability in sedimentary facies, stacking patterns, and downdip sediment transfer mechanisms in the transition from shelf to upper slope; (2) examine the influence of erosional and depositional processes, and the distribution of soft-sediment deformation processes, in the resolution gap between core and seismic information in subsurface data sets; (3) assess the criteria used to identify the position of the shelf-edge rollover at outcrop; and (4) evaluate the interplay between controls on the basinward delivery of sediment by comparing stacked parasequences.

GEOLOGIC SETTING

The Karoo Supergroup in the Laingsburg area is 5500 m thick and is divided into the Dwyka Group (late Carboniferous to Early Permian glacial deposits), Ecca Group (Permian clastic marine sediments), and the Beaufort Group (Permian–Triassic fluvial sediments) (Fig. 2A). Accommodation during the time of deposition of the Ecca Group was generated by regional subsidence driven by dynamic topography related to subduction of the oceanic plate (Mitrovica et al., 1989; Tankard et al., 2009).

Within the Ecca Group, the Vischkuil Formation represents distal basin-plain deposits (van der Merwe et al., 2009, 2010), overlain by basin-floor fan deposits of the Laingsburg Formation (Sixsmith et al., 2004). An overlying submarine slope succession of the Fort Brown Formation is dominated by channel-levee complexes and entrenched slope valleys (Figueiredo et al., 2002; Pyles and Slatt, 2007; Dixon et al., 2012a). Continued progradation is marked by the ~400-m-thick Waterford Formation, the focus of this study, which comprises a mixed river- and wave-influenced deltaic succession (Oliveira et al., 2011). The ability to document a complete vertical stratigraphic transition from erosional slope channel-levee systems (Fort Brown Formation) to shelf deltas (Waterford Formation) implies that the shelf-edge rollover will be encountered within the vertical stratigraphic section. Extensive downdip exposures allow the physical identification of the shelf-edge rollover along a clinoform profile.

TERMINOLOGY

Clinoform geometries are common to a number of depositional settings and the focus here is on two scales: (1) shelf-slope basin (margin) scale (hundreds to thousands of
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TEEKLOOF FM.
ABRAHAMSKRAAL FM.
WATERFORD FM.
FORT BROWN FM.
LAINGSBURG FM.
VISCHKUIL FM.
COLLINGHAM FM.
WHITEHILL FM.
PRINCEALBERT FM.

LAINGSBURG FM.

COLLINGHAM FM.
WHITEHILL FM.
PRINCE ALBERT FM.

DWYKA GROUP
CARBONIFEROUS
DEVONIAN
SILURIAN
ORDOVICIAN
PRECAMBRIAN

CAPE SUPERGROUP
KARROO SUPERGROUP

BEAUFORT GROUP
ECCA GROUP
DWYKA GROUP
WITTEBERG GROUP
BOKKVELD GROUP
TABLE MOUNTAIN GROUP

Legend
Sandstone
Shale
Tillite
Granite
Conglomerate
Tuff abundant

Figure 2. (A) Lithostratigraphy of the Western Cape area (redrawn after Wickens, 1994). (B) Schematic stratigraphy of the upper Ecca Group in the Laingsburg depocenter. The lower Waterford Formation detail is based upon the N1 log locality type section and shows the seven studied parasequences. The focus of this study is on Waterford clinothem (WfC) 3 and WfC 4.
meters high), and (2) shelf-delta scale (tens to hundreds of meters high) (Helland-Hansen and Hampson, 2009). The term clinoform is commonly applied to the entire sigmoidal surface shape (Fig. 3), but it was originally applied only to the sloping segment of such a surface (Rich, 1951). The term clinothem is used herein to describe a three-dimensional (3D) body of rock that is bounded by clinoform surfaces (Steel and Olsen, 2002). Clinothems are a key component of sedimentary successions and have been used to interpret the interplay between changes in sediment supply and relative sea level (Vail et al., 1977). This interplay drives the stacking pattern of clinoforms at all scales, such that a shoreline or shelf-delta clinoform can merge with a basin margin–scale clinoform to produce a compound clinoform. The upper clinoform break in slope is referred to as the shelf-edge rollover. The lower clinoform break in slope (the toe of clinoform) has not been identified in this study.

LOWER WATERFORD FORMATION STRATIGRAPHY

Analysis of the 360-m-thick lower Waterford Formation was facilitated through the collection of 17 detailed sedimentary logs (>4.5 km cumulative thickness). Regionally persistent mudstones have been physically walked out between logged sections in order to establish a robust stratigraphic framework along a single well-exposed 35 km dip section (Fig. 1C).

Facies and Facies Associations

The lower Waterford Formation comprises 7, 45–15-m-thick packages (Fig. 2B) that are bounded by regionally correlated mudstones. Within these packages 13 individual facies are recognized that can be grouped into 7 broad facies associations (Table 1; Fig. 4B). Individual packages differ subtly in their stratigraphic profiles and internal facies arrangement. All packages broadly coarsen and thicken upward (asymmetrical), yet the basal 2 fine and thin packages broadly coarsen and thicken upward in their upper 1–3 m, producing a more symmetrical profile. The upward-fining tops consist of the highly bioturbated heterolithic facies, FA 10 (Table 1). Packages are increasing asymmetrically higher in the stratigraphic, and their tops are characterized by either a thin (<1 m) heterolith and bioturbated package, or a sharp top surface.

Generally, the lower coarsening-upward part of each package comprises 0.4–45 m of laminated siltstone and thin, very fine grained ripple-laminated sandstone beds (FA 2 and FA 3; Table 1), overlain by a 0.5–5-m-thick unit of heavily deformed sandy siltstone and silty sandstone. The upper part of a typical package comprises 0.5–8 m of amalgamated sandstones that are dominated by low-angle to concave-upward lamination; locally, however, some units contain persistent unidirectional climbing ripple-laminated sandstone beds. Basal heterolithic successions are interpreted as dilute turbidity current deposits in a prodelta facies association. The deformation structures indicate evidence for downslope mass transport and vertical foundering, and these deposits are interpreted as a deformed lower delta front succession (FA 4–FA 6; Table 1). The low-angle to hummocky cross-stratified deposits are interpreted as wave-dominated upper delta front (FA 7 and FA 8; Table 1), but the climbing ripple-laminated sandstones indicate rapid deposition from flows with a high suspended load (FA 9; Table 1).

The vertical facies succession recorded in each package is typical of parasequences described by Van Wagener et al. (1990), and each parasequence is interpreted as the record of an episode of delta progradation. Each parasequence is bounded by a mudstone or fine-grained-siltstone package interpreted as distal offshore facies (FA 0 and 1; Table 1). These fine-grained packages are considered to represent an increase in water depth, consistent with containing the offshore expression of a flooding surface, and form the basis for stratigraphic correlation (Fig. 5). The seven correlatable parasequences are herein referred to as Waterford clinothems 1–7 (WIC 1–WIC 7). The use of the term clinothem is supported by (1) stratigraphic context, (2) the basinward thickening of physically correlated parasequences, and (3) the departure from the typical vertical clinothem facies succession, examples of which are mapped basinward across the shelf to slope transition.

Stratigraphic Correlation and Interpretation

The seven Waterford clinothems are separated from the underlying channelized slope succession (Figueiredo et al., 2010; Hodgson et al., 2011; Brunt et al., 2013) by a regionally extensive 80-m-thick mudstone marker unit. The uppermost channelized slope unit (unit G) is used as a basal datum in this study (Figs. 2B and 5) (Figueiredo et al., 2010). Waterford clinothems 1 and 2 (WIC 1 and WIC 2; Fig. 2B) are 45–25 m thick, and are characterized by a coarsening- and thickening-upward stratigraphic succession of heterolithic siltstone and sandstone beds, with a bioturbated fining- and thinning-upward top, interpreted as prodelta deposits.

The N1 type log (Fig. 2B) shows that WIC 3 (~38 m thick) and WIC 4 (~20 m thick) exhibit asymmetric coarsening- and thickening-upward profiles with a thin (<1 m) upper fining- and thinning-upward sequence. Unlike WIC 1 and WIC 2, the middle sections of these parasequences are dominated by highly deformed strata showing a range of soft-sediment deformation styles. The deformed sections are overlain sharply by undeformed tabular 5–30 cm sandstone beds with erosional bases and symmetrical rippled tops, passing upward into 40–70-cm-thick beds of amalgamated sandstone that are generally massive or exhibit faint convex-upward laminae sets that represent hummocky cross-stratification generated by storm action. WIC 5 (~19 m thick)
lacks any significant soft-sediment deformation, in contrast to WfC 3 and WfC 4. The lower half is dominated by a coarsening- and thickening-upward package of thin, normally graded, interbedded siltstone and very fine sandstone beds (1–4 cm). This is overlain sharply by 1.5 m of tabular bedded sandstone, followed by ~9 m of amalgamated sandstone dominated by parallel, low-angle, and hummocky cross-stratification. The top surface is marked by symmetrical ripples with shallow scours filled with small mudstone blocks, consistent with reworking by wave and storm action. Abruptly overlying this reworked surface is a regionally extensive ~30-m-thick mudstone unit that provides a stratigraphic key marker across the entire study area. It is thinner and more siltstone dominated in the most proximal (western) outcrops, and thicker and more mudstone dominated in the most distal (eastern) outcrops (Fig. 5).

DIP-PARALLEL DEPOSITIONAL ARCHITECTURE OF WfC 3 AND WfC 4

The architectural variability of WfC 3 and WfC 4 as observed along the 37 km oblique dip section of the northern limb of the postdepositional Baviaans syncline (Fig. 1C) is described in detail here; 17 measured sections were logged and all key surfaces were walked out between logs. The following describes the sedimentology and stratigraphy of the Ouplaas (most proximal), N1, Blockhouse, and Hartbeesfontein (most distal) key sections for WfC 3 and WfC 4 (Figs. 1C and 5).

Downdip Character of WfC 3

Ouplaas Section

WfC 3 is 24 m thick with a coarsening- and thickening-upward profile. The lower part of the parasequence is dominated by thin (1–3 cm) beds of siltstone and sandstone (FA 3). Sandstone beds exhibit unidirectional current ripple lamination; commonly these thin beds display symmetrical curved-crest ripples on top surfaces. This lower part of WfC 3 is interpreted as low-density turbidity current deposits in a prodelta setting. Symmetrical ripples are interpreted to have resulted from storm waves that reworked bed tops. The middle 3–8-m-thick part is the parasequence is dominated by multiple beds containing soft-sediment deformation. Individual deformed beds vary in thickness between 0.2 m and 1.2 m and exhibit a range of deformation styles. In the lower part of the deformed package thin beds of poorly sorted sandy siltstone with sharp bases and tops have a structureless appearance and are characterizedly green-gray (FA 4). There is an upward transition to chaotic beds, characterized by deformed sandstone clasts supported by a poorly

| Facies | Description | Interpreted process | Depositional setting | Facies associations |
|--------|-------------|---------------------|----------------------|-------------------|
| FA 0   | Structureless, dark gray fine-grained claystone and siltstone | Deposited by hemipelagic fallout | Distal offshore | Offshore |
| FA 1   | Finely laminated siltstone | Deposited by hemipelagic fallout in an offshore environment | Offshore | |
| FA 2   | Interbedded, ripple and parallel laminated, fine and coarse siltstone | Deposition by low-density concentration turbidity currents | Distal prodelta | Prodelta |
| FA 3   | Interbedded, thin, unidirectional ripple-laminated sandstones and siltstone | Deposited by low-density turbidity currents in a setting below fairweather wave base | Prodelta | |
| FA 4   | Structureless, dark green-gray, poorly sorted, coarse siltstone to very fine sandstone (sandy siltstone) | Debris flow | Margin of mass flow deposit | |
| FA 5   | Dark green-gray, coarse sand to very fine sand matrix, containing heavily deformed and disaggregated rafts and rounded sandstone blocks | Debris flow | Axis of mass flow deposit | Deformed lower delta front |
| FA 6   | Deformed siltstone and sandstone. Deformation ranges in size from small-scale (centimeters) ball and pillow structures and detached pseudonodules, to large-scale (meters) loaded bed bases and larger flame structures. | Sediment deformed in situ by abrupt loading, resulting in the vertical movement of fluids and sediment | Deformed sandstone and/or siltstone with vertical structures | |
| FA 7   | Bedded sandstone, very fine grained, typically 10–30-cm-thick beds that show a range of sedimentary structures, including parallel, climbing and current ripple lamination, as well as hummocky and swaley cross-stratification. Beds are tabular with sharp bases (occasionally erosive) and symmetrical reworked ripple tops | Deposited by high-density turbidity currents with minor storm reworking | Lower delta front | Wave-dominated upper delta front with localized fluvial influence |
| FA 8   | Amalgamated fine-grained sandstone, typically structureless but often with convex-up lamination toward the top. Beds can be defined by discrete changes in grain size or a mud-chip lag. Bases are generally sharp but can be loaded and top surfaces have symmetrical ripples with rounded crests. | Rapid deposition of turbidity currents on exit from confinement | Delta front | |
| FA 9   | Amalgamated very fine to fine sandstone, dominated by low angle climbing ripple laminations. | Deposited by flows depositing rapidly on exit from channel confinement | Distal mouth bar | |
| FA 10  | Heavily bioturbated, thinly bedded sandstones. Observed as fining and thickening upward packages at the top of parasequences. | Deposited by low-concentration turbidity currents | Prodelta | Bioturbated prodelta |
| FA 11  | Clast-supported medium-grained sandstone. Clasts are angular to subangular and consist of siltstone and very fine sandstone. They range in size from 1 to 5 cm and line the erosional channel base. | Deposited by waning erosive flows at the base of a channel | Channel lag conglomerate | Slope channel fill |
| FA 12  | Amalgamated, fine- and medium-grained sandstone deposited within a large erosive surface. | Deposited by high-density turbidity currents | Channel fill | |
| FA 13  | Interbedded sandstones, sigmoidal ripple lamination. Sharp based and occasional erosional. Tops are sharp and unidirectional ripple laminated. Sheet geometry to sandstone beds. | Unconfined turbidity currents deposited beyond the shelf edge | Upper slope turbidites | Upper slope turbidites |
sorted sandy siltstone matrix (FA 5). Both facies are interpreted as debrites (debris-flow deposits). A significant increase in sandstone content in the top 2 m, and a change to flame structures and in situ deformation features (FA 6), is characteristic of the upper part of WfC 3, and suggests limited downslope movement. The relatively undeformed upper section of WfC 3 is dominated by nonamalgamated and amalgamated sandstone beds containing hummocky cross-stratification and wave and current ripple lamination, which suggests deposition in a wave-dominated delta front setting (FA 7 and FA 8). Locally, WfC 3 is overlain abruptly by WfC 4 debrites where the intervening distal offshore mudstone (FA 0) was removed by erosion; however, a thin fining- and thinning-upward package of moderately bioturbated sandstone is locally preserved at the top of WfC 3 (FA 10). This is interpreted to be due to a reduction in sediment supply associated with a rise in relative sea level.

**NI Section**

At the NI locality (Fig. 1) the lower third of WfC 3 consists of FA 2 and FA 3, interpreted as prodelta facies, overlain by a 5-m-thick debrite (FA 6). In contrast to the Ouplaas section, the middle part of WfC 3 is dominated by a 5-m-thick package of amalgamated, fine-grained sandstone with abundant climbing ripple lamination (FA 9) (mean paleocurrent direction 082°). The climbing ripple lamination suggests rapid deposition from unidirectional tractional currents with a high suspended load. The lack of wave indicators and the high silt and mud content of the sandstones indicate a high terrigenous component; this supports a fluvially dominated distal mouth bar setting with flows depositing rapidly on exit from updip distributive channels (Al-Aasm et al., 1996; Johannesen and Steel, 2005; Olariu and Bhattacharya, 2006; Enge et al., 2010). The abundance of debrites that interfinger with climbing ripple-laminated sandstones is interpreted as the product of rapid deposition and incremental collapse of a steep, river-dominated upper delta front. The top 1.5 m of the unit comprises amalgamated fine-grained sandstone with hummocky cross-stratification and low-angle lamination (FA 8), consistent with a wave-dominated upper delta front. This might reflect progradation and/or overstepping of the delta front over the distal mouth bar at the top of WfC 3 and/or local delta lobe abandonment.

Internally, WfC 3 contains multiple low-angle inclined surfaces (~0.7° using the top of WfC 3 as a horizontal datum) that are 14–16 m in height. Bedsets can be traced between logged sections where they thin, split, and pinch out over a downdip distance of ~1 km.

**Figure 4.** Generalized summary log of a typical coarsening- and thickening-upward parasequence from the lower Waterford Formation showing the five main facies associations observed. (A) FA 3—prodelta, 1.5 m Jacob staff for scale. (B) FA 5—debris flow (downslope transport of mass flow). (C) FA 6—in situ deformed sandstone (deformed sandstone and/or siltstone with vertical structures), notebook for scale. (D) FA 7—bedded sandstone (lower delta front). (E) FA 9—amalgamated, climbing ripple-dominated sandstone (distal mouth bar), compass clinometer for scale. (F) FA 8—thick-bedded, amalgamated, fine-grained sandstone (delta front). (G) FA 10—heavily bioturbated heterolithic siltstone and sandstone (bioturbated offshore), compass clinometer for scale.
The inclined surfaces are eastward dipping, consistent with both the internal and regional paleocurrent directions (Fig. 6). The sedimentology and geometry support an interpretation of river-dominated shelf-delta–scale clinothems. However, low-angle topsets (Steel and Olsen, 2002) are not recognized. Overall, the geometry of the delta-scale clinothems reveals subtle gradient differences between slightly steeper climbing ripple-dominated sandstone clinothems and overlying, lower angle and thinner wave- and storm-influenced clinothems. This change is interpreted to reflect an increase in the degree of wave and/or storm energy reworking to form a lower gradient. Low-angle delta topsets are interpreted to have been removed during transgressive erosion. This interpretation is supported by the sharp-crested symmetrical ripples and the concentration of mud chips within shallow erosional scours on the top surface of WfC 3.

**Blockhouse Section**

This 5.4-km-long dip section comprises pervasively deformed sediments directly downdip of the river-dominated, shelf-delta–scale clinoforms of the N1 section. The zone of deformation starts at the Geelblock log locality in the west (Fig. 1C) and increases in intensity downdip toward the Blockhouse East log (Fig. 1C). Clinothem thickness increases from 38 m at the N1 to ~48 m at the Blockhouse section.

Mapping the transition of WfC 3 from the N1 to the Blockhouse section has shown that WfC 3 maintains a broadly coarsening- and thickening-upward profile, comprising deformed beds and heterolithic sandstones (FA 1 and FA 2), interpreted as prodelta deposits to the river-dominated shelf-delta clinothems of the N1 section. These prodelta deposits are abruptly truncated at the Geelblock log locality by a 10–12-m-thick wedge-shaped unit of intensely contorted fine- to medium-grained sandstone blocks (0.2–3 m diameter) supported by a dark green-gray, poorly sorted sandy siltstone matrix (Fig. 7). Several other wedges of deformed sediments are identified in this area (Fig. 8).

A prominent sharp-based, sharp-topped, 1.0–1.4-m-thick bed forms a datum toward the base of WfC 3 along the Blockhouse section. This marker bed consists of deformed, dark green-gray, poorly sorted, sandy siltstone, with numerous small sandstone pseudonodules. This internal datum enables the stratigraphic position and geometry of the overlying wedge-shaped units of intensely contorted sandstone to be constrained. Separating the basal siltstone datum from the intensely deformed material is a package of dark gray ripple-laminated siltstone (FA 2). Overlying this package is a dark
The fine-grained sandstone-filled wedges that form the upper part of WfC 3 in the Blockhouse section taper and thin to the east. The wedges vary in size from 10 m long and 2–3 m thick to ~140 m long and 19 m thick. To the west the sandstone wedges terminate against steep, broadly eastward-facing surfaces that shallow downward, and are associated with meter-high flame structures in the underlying structureless sandy siltstone. Internally, the wedges are moderately to intensely deformed but contain contorted blocks and bedding that are consistently rotated to be westward facing (Figs. 7A, 7B). Internally, the greatest amount of bed rotation is at the bases of wedges, proximal to the abrupt western margins, but overall, bed dips decrease upward. Not all blocks conform to this westward rotation; a few in the center of the heavily deformed area are orientated randomly. Three of the larger wedges also contain a 2–3-m-thick interval of the massive dark green-gray silty sandstone that is similar to the underlying material (FA 3).

The 2D dip profile of the Blockhouse section means that the wedges are well exposed in cross section, but their 3D geometry is poorly constrained. The distribution and scale of the wedges vary down the section. At the updip end (Geelblock log), wedges are relatively small, widely spaced, and poorly defined; they are usually separated by less deformed amalgamated upper delta front sandstone. At the Blockhouse locality, the size and concentration of the wedges reach a maximum with no separation between individual wedges. Beyond the Blockhouse locality the scale and concentration of the wedges decrease, before passing into undeformed thin-bedded sandstone and siltstone beds at the downdip Blockhouse East log. The top of the wedge fill is commonly less deformed, with a sharp, symmetrical rippled top surface that also marks the top of the para-sequence.

The wedge-shaped units are interpreted as growth fault fills due to their steep updip and shallow downdip margins, the rotation of the internal bedding, the minor top truncation of wedge fills, and the flame structures at the steep western margins. Extensional growth faulting is a common feature of oversteepened shelf-edge settings that are subject to high sediment supply rates (Rider, 1978; Coleman et al., 1998; Wignall and Best, 2004; Maloney et al., 2012). The rotation of blocks within the void created indicates that the development of the growth fault was synsedimentary. None of the identi-
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Figure 7. (A, B) Rotation of bedding within the growth fault fills of Waterford clinothem (WfC) 3 showing preferential rotation to the west. Solid white line indicates the lower datum used to constrain the geometries of the rotational growth faults. (C) Thin beds onlapping the margin of a shallow gully feature that cuts into the top of WfC 4. (D) The stepped margin of a shallow gully cutting into the top of WfC 4.

Figure 7. (A, B, C, D) Rotation of bedding within the growth fault fills of Waterford clinothem (WfC) 3 showing preferential rotation to the west. Solid white line indicates the lower datum used to constrain the geometries of the rotational growth faults. (C) Thin beds onlapping the margin of a shallow gully feature that cuts into the top of WfC 4. (D) The stepped margin of a shallow gully cutting into the top of WfC 4.

Figure 7. (A, B, C, D) Rotation of bedding within the growth fault fills of Waterford clinothem (WfC) 3 showing preferential rotation to the west. Solid white line indicates the lower datum used to constrain the geometries of the rotational growth faults. (C) Thin beds onlapping the margin of a shallow gully feature that cuts into the top of WfC 4. (D) The stepped margin of a shallow gully cutting into the top of WfC 4.

The process response of stacked clinothems to the shelf-slope rollover involves the interaction of extensional faults with the overlying stratigraphy of WfC 4, suggesting extensional faulting of WfC 3 age. The normal sense of throw on the faults is towards the east. However, the intensely deformed nature of the sandstone fill does not allow correlation of beds from the hanging wall to the footwall.

There is a general absence of extensional tectonic features in the Karoo basin fill (Tankard et al., 2009; Flint et al., 2011). The orientation of the growth faults and pattern of sedimentation reported here indicate a close association between sediment deposition at the shelf-edge delta front and the formation and development of the growth fault features; this is consistent with a gravitational driver. Rapid deposition of sand by an advancing river-dominated shelf delta above unconsolidated silt-prone prodelta deposits creates a density instability that results in the movement of sediment. The increase in number and scale of the growth faults toward the Blockhouse log locality, and their subsequent reduction in scale and number beyond, suggests that substrate movement was initiated and enhanced by a gradual increase in gradient eastward through the Blockhouse locality. This is supported by the basinward thickening of WfC 3 in this area.

The trapping of sediment in the growth fault depression, accommodated by movement along the displacement plane, creates additional accommodation through loading and rotation. This model is supported by the presence of relatively undeformed but disaggregated blocks of laminated sandstone that fill the depression created by the growth fault.

Hartbeesfontein Section

Beyond the Blockhouse East logged section, WfC 3 thins and is dominated by siltstone beds with rare thin sandstone beds. This facies change coincides with no further signs of growth fault features, a marked decrease in soft-sediment deformation, and a lack of sandstone beds. WfC 3 gradually thins downdip over the next 7 km, becoming difficult to distinguish from the slope mudstone succession.

Downdip Character of WfC 4

Ouplaas Section

WfC 4 is 23 m thick and dominated by heavily deformed beds consisting of sandstone clasts supported by a poorly sorted sandy siltstone matrix, interpreted as deformed lower delta front (FA 5). The debrite-dominated
package is split by a 5-m-thick undeformed heterolithic siltstone-sandstone package, capped by a single undeformed sandstone bed. Basinward (eastward) of the Ouplaas section, WfC 4 becomes less deformed, with an increase in thin interbedded siltstone and sandstone prodelta deposits in the lower half of the unit. The upper deformed package is retained but is overlain by in situ deformed (FA 6) and undeformed wave-dominated upper delta front sandstone (FA 7 and FA 8). The top of WfC 4 is generally sharp with an abrupt change to thinly bedded siltstone above the amalgamated sandstones.

**N1 Section**

At the N1 locality WfC 4 is 26 m thick with a coarsening- and thickening-upward asymmetrical profile (Fig. 2B) that is similar in character to the Ouplaas section but with a slight basinward increase in the thickness of the lower heterolithic deposits (FA 2 and FA 3). The lowermost 1.5 m consists of thinly laminated fine and coarse siltstone overlain by a 7.5-m-thick coarsening- and thickening-upward package of interbedded fine siltstone and very fine grained sandstone. Beds are normally graded, 2–4 cm thick, and have unidirectional ripple lamination and symmetrical rippled top surfaces (FA 2 and FA 3). These characteristics are consistent with a prodelta setting with sediment delivery by low-density turbidity currents and minor reworking by storm waves. An overlying 3-m-thick package comprises structureless, dark green-gray, coarse siltstone to fine sandstone beds 0.7–1.1 m thick, interbedded with 0.01–0.3-m-thick undeformed ripple-laminated sandstone beds (FA 4). The middle portion of WfC 4 comprises two packages (4.8 and 5.6 m thick) of detached and deformed sandstone pseudonodules supported in a matrix of dark green-gray sandy siltstone (FA 5), interpreted as debrites. The upper debrite package grades upward into in situ deformed sandstone and finally undeformed amalgamated sandstone with internal hummocky cross-stratification. This suggests deposition in a wave-dominated upper delta front environment (FA 6), consistent with progradation of a wave- and storm-dominated shoreline. The top 2.8 m of WfC 4 is marked by a fining- and thinning-upward package of thinly bedded sandstones that are moderately bioturbated, giving this package a mottled appearance (FA 10), and is capped by offshore mudstone. WfC 4 does not exhibit similar shelf-delta–scale clinofoms as seen at this locality in WfC 3, or any evidence for proximity to a fluvial input point.

**Blockhouse Section**

WfC 4 at the Blockhouse locality is 24 m thick, compared to ~25 m thick updip. Closely spaced scour surfaces cut down from the sharp
top surface into deformed lower delta front facies that dominate the upper portion of the parasequence in this area (i.e., no undeformed delta front deposits; Figs. 7C, 7D). The erosion surface and fill of two complete scourls situated stratigraphically above the most intensely deformed zone (the largest growth fault) in WfC 3 have been characterized in detail along a 2.5 km dip section (Fig. 9). Closely spaced short measured sections hung from lower (base WfC 4) and upper datums (top WfC 5) were used to constrain scour dimensions. The distance between the deepest points of the scours is 430 m; scour 1 is 186 m wide and 9.8 m deep and scour 2 is 275 m wide and 13.6 m deep. The scour margins are marked by steps, interpreted to indicate multiple erosive events cutting into the underlying deformed sandstones (Fig. 7D). The western margins are slightly steeper than the eastern sides. Scour orientation is 038° (scour 1) and 028° (scour 2), consistent with the north-northeast–east-northeast paleocurrent trend recorded throughout the lower Waterford Formation. The stepped morphology, the orientation with regional paleoflow, and the paleogeographic context support an interpretation that the scours represent straight shelf-edge to upper slope gullies.

The basal fills of scours 1 and 2 are dominated by fine-grained stratified dark gray siltsone that forms a drape marking the parasequence boundary flooding surface between WfC 4 and WfC 5. The fill thickens and coarsens upward and comprises heterolithic fine-grained sandstone beds that onlap the margins of the gullies (Fig. 7C). Beds are commonly sharp based and occasionally erosive, and bed tops commonly exhibit symmetrical ripples. Internally, beds exhibit climbing ripple lamination, suggesting rapid deposition from density currents that preferentially concentrated in the topographic lows of the gullies. The accumulation of fine-grained sediment at the bases of the scours indicates that the gully features were cut but remained unfilled before being later filled by deposits of the advancing delta front of WfC 5.

**Hartbeesfontein Section**

East of the Blockhouse section (basinward of the shallow gullies) WfC 4 exhibits distinctly different facies and architecture, and increases in thickness from ~24 m to a maximum of ~35 m (Figs. 5, 10A, and 10B) at the Vleifontein Station log (Fig. 1C). The main deformed lower delta front package splits into discrete <1-m-thick deformed beds that thin toward and pinch out within a 1.4-km-wide area of no exposure occupied by the present-day Geelbek River. The increase in clinothem thickness coincides with a marked change in facies from soft-sediment deformed lower delta front deposits to undeformed heterolithic sandstones and siltstones (FA 13; Figs. 10A, 10B). The sandstone beds are extensive and tabular, typically 7–15 cm thick, with sharp or erosive bases and asymmetric rippled top surfaces. Sandstone beds are well sorted, weakly normally graded, with climbing (sigmoidal) ripple lamination, locally are stoss-side preserved; these characteristics are consistent with an interpretation of rapid deposition from turbidity currents. This basinward-thickening wedge of turbidites is sharp based with a broadly aggradational profile.

Just beyond the point at which the basinward-thickening wedge of turbidites reaches its maximum thickness, these deposits are incised by a 1-km-wide and 55-m-deep sandstone-filled incision surface (Fig. 11A) that cuts down from the top of WfC 4, and is the same stratigraphic surface as the gully features observed updip along the Blockhouse section. The erosive basal surface cuts down into the muddy slope succession beneath the turbidite wedge (Fig. 12B) and is marked by a distinct increase in grain size and a discontinuous clast-supported intraformational pebble conglomerate (Fig. 12B) (FA 11) at the deepest point of erosion. The incision surface is asymmetric in cross section, with a shallow western margin and a deep eastern margin that is mantled by a large amount of carbonate nodule clasts. However, there is little asymmetry to the fill, which consists of thick, amalgamated medium- to fine-grained sandstones that are generally structureless and/or dewatered, but that occasionally display localized current ripple- and cross-laminated units (Fig. 12C).

The scale of the incision surface, the basal mudstone clast conglomerates, and the turbiditic fill supports an interpretation of a slope channel fill. It is possible from the small number of paleocurrent measurements available and the orientation of the channel margins to infer a northeastward paleoflow. The doubling in thickness of WfC 4 associated with the basinward-thickening wedge of turbidites suggests that this was an area of increased accommodation basinward. Coupled with the evidence for localized erosion and bypass, the Hartbeesfontein section is interpreted to be beyond the shelf-edge rollover for WfC 4, on the upper slope. WfC 4 progressively thins and pinches out into the slope mudstone succession over the next 6 km downdip, beyond the Spitskop log section (Fig 1C).

**Position of the Shelf-Edge Rollover**

The zone of extensional deformation coincident with basinward thickening along the Blockhouse section of WfC 3 is compelling evidence...
for a downdip increase in gradient. The context provided by the extensive outcrop shows river-dominated shelf-delta–scale clinoforms updip of the deformation zone. Basinward thickening through the zone of deformation is observed, followed by thinning and pinching out of WfC 3 into muddy slope deposits beyond the deformation zone. The Blockhouse section is interpreted as the shelf-edge rollover zone for WfC 3.

For WfC 4, the contextual setting of shoreface deposits updip of a discrete zone of gully incision and a basinward-thickening package of turbidites incised by an upper slope channel places the shelf-edge rollover position in the same Blockhouse area. This interpretation is supported by the thickening of clinothems at (WfC 3) and beyond (WfC 4) the Blockhouse locality (Fig. 5); this is a key geometric criterion (Dixon et al., 2012a) and is consistent with an increase in accommodation beyond the shelf-edge rollover.

**Variability Between Clinothems WfC 3 and WfC 4**

Differences in processes and architecture between clinothems WfC 3 and WfC 4 at the shelf-edge rollover highlight the stratigraphic variability possible between successive clinothems (Fig 13). Both show broadly progradational profiles with similar thickness and shelf-edge rollover positions. However, WfC 3 is characterized by a strong fluvial influence and shelf-delta–scale internal clinoforms. In contrast, the character of WfC 4 indicates a wave-storm-influenced delta front setting. Along the Blockhouse section, WfC 3 and WfC 4 exhibit quite different process responses to the pre-existing shelf break. Amalgamated sandstones at the top of WfC 3 are heavily deformed and segregated into a series of rotational growth fault structures consistent with the increase in gradient encountered at the shelf-edge rollover.

In contrast, rotational growth fault features did not develop along the Blockhouse section in WfC 4, although soft-sediment deformation is widespread. WfC 3 thins and downlaps into the slope mudstone succession. WfC 4 thickens beyond the shelf-edge rollover; this is associated with a change in process to extensive turbidity current deposits that are incised by an upper slope channel, and is consistent with increased sediment supply beyond an incised shelf-edge rollover. WfC 4 thins and pinches out into the slope mudstone succession 10 km beyond the pinchout of WfC 3.

**DISCUSSION**

Architectural and sedimentary facies change along a dip profile is commonly described based on a single basin margin clinothem (e.g., Uroz and Steel, 2008; Charvin et al., 2010) or a succession of clinothems that appear similar at seismic resolution (Pyles and Slatt, 2007). Successive clinothems are commonly reported to have similar facies associations and architecture (Mellere et al., 2002; Dixon et al., 2012a). The two stacked clinothems described and interpreted here record significantly different process responses to sedimentation at a similar geographic shelf-edge rollover position.

**Controls on Clinothem Architecture**

The interpreted rollover zone of WfC 3 is marked by a 5 km dip length zone of extensional deformation and basinward clinothem thickening (Figs. 7A, 7B, and 8). Sand was trapped in the depressions created by extensional growth faults at the shelf edge, contributing to limited sand supply directly basinward of the rollover. WfC 4 is wave and storm dominated and is characterized by a narrower (~2 km dip length) shelf-edge rollover zone with widespread erosion and gullying coincident with basinward thickening and significant amounts of sand transferred beyond the shelf-edge rollover (Figs. 7C, 7D, and 9).

The presence of fluvial feeder systems close to the shelf-edge rollover has been shown to play a key role in the delivery of sand beyond the rollover (Morton and Suter, 1996; Johanneszen and Steel, 2005; Carvajal and Steel, 2009). Fluvial systems are able to supply a significant amount of sediment to a focused area at the shelf edge. They also have the potential to incise and degrade the shelf-edge rollover zone and...
Figure 11. (A) Schematic correlation showing the upper slope channel from the Hartbeesfontein section. Log sections are hung from the maximum flooding surface above Waterford clinothem (WFC) 5. (B) Hartbeesfontein channel geometry corrected for vertical exaggeration.
promote the initiation of turbidity currents on the upper slope through hyperpycnal flows or mouth bar collapse. Fluvial systems are therefore effective at delivering sediment beyond the shelf edge through gravity-driven processes. It has also been suggested that a dominance of storm and wave processes at the shoreline reduces the potential for delivery of sediment beyond the shelf edge due to (1) the along-margin distributive effect of these processes on sand dispersal patterns and (2) the limited potential to incise the shelf-edge rollover and create conduits due to the lack of focus (Carvajal and Steel, 2006). Therefore, wave- and storm-dominated settings have been proposed to be important in the development of thick packages of sediment along the shelf edge with limited downslope sediment supply (Carvajal and Steel, 2009).

Given that deltas in both the studied clinoflumes reached the rollover area, a simple prediction following the established conceptual model above would be that the fluvial-dominated WfC 3 would supply more sediment beyond the shelf-edge rollover with the development of turbidites downdip. Although only a 2D oblique-dip panel constrains the interpretation presented here, the data show that in this case the wave-dominated clinoflume was more efficient at supplying coarse-grained sediment across the shelf-edge rollover.

Basinward sand supply across the shelf-edge rollover can occur in wave- and storm-dominated settings during highstands of sea level under a number of circumstances: (1) if a narrow shelf significantly reduces delta transit times to the shelf edge (Piper and Normark, 2001), (2) where there is strong longshore sand transport into canyons that incise into the shelf (Boyd et al., 2008; Covault and Graham, 2010), (3) under high sediment supply conditions where shelf redistribution processes are weak (Weber et al., 1997), (4) where a submarine canyon has incised across much of the shelf (Lobo et al., 2006; Fernández-Salas et al., 2007; Covault and Graham, 2010), and (5) where extreme storms can produce strong storm-surge ebb currents that incise shoreface sandstones and canyon walls and resuspend and redistribute sediment offshore (e.g., Dail et al., 2007; Goff et al., 2010; Rogers and Goodbred, 2010).

An increase in sedimentation rate through time has the potential to influence the architecture of successive clinoflumes. There is no evidence for incision of the shelf-edge rollover in the fluvial-dominated WfC 3, but it appears that the rate of sediment input was high enough to drive synsedimentary growth faults, resulting in sand being sequestered around the rollover area. In contrast, WfC 4 was able to step farther into the basin possibly due to a higher rate of sediment supply; this period of maximum regression is consistent with a significant amount of sediment transfer across the shelf edge. This point is expanded upon in the following.

Subaerial Exposure of the Shelf-Edge Rollover?

Changes in relative sea level have been widely invoked as one of the main factors controlling clinoflume architecture and facies distribution (Steel and Olsen, 2002; Pörębski and Steel, 2006; Ainsworth et al., 2008; Steel et al., 2008). Lowering of relative sea level results in reduced accommodation on the shelf (Posamentier et al., 1988) and promotes incision of the fluvial feeder system into the shelf (e.g., Posamentier and Vail, 1988; Van Wagoner et al., 1990; Mutti
Many clastic basin-fill successions pass upward from slope to shelf settings, and therefore any 1D section should pass through the shelf-edge rollover at some stratigraphic position, unless the basin margin has a ramp geometry. Given the regional context provided by the large outcrop extent of WFC 3 and WFC 4, a number of criteria have been derived to define the shelf-edge rollover zone in a mixed influence system along a 2D dip profile. Attention has also been drawn to the potential variability of successive clinothems. Therefore, attempting to identify the shelf-edge rollover from a 1D section or from outcrop with limited lateral exposure will be subject to significant limitations.

1. Without regional depositional dip context, recognizing gradient change across the shelf to slope transition will not be possible because the change is subtle.

2. Distinguishing turbidites deposited beyond the shelf-edge rollover from delta front turbidites associated with inner shelf deltas is challenging without being able to record their run-out distances, and could lead to misinterpretation of the position on the slope-shelf profile.

3. Basinward thickening of clinothems coincident with a change to sediment gravity flow deposits is a key criterion for identifying the rollover (Dixon et al., 2012a), and this is difficult to determine in one dimension.

4. The occurrence of abundant soft-sediment deformation has been attributed to proximity to the shelf-edge rollover (e.g., Stow, 1994; Galloway, 1998; Lee et al., 2009; Pratson et al., 2009; Oliveira et al., 2011). However, as shown in the regional correlation of WFC 3 and WFC 4, soft-sediment deformation is abundant from the most proximal exposures at Ouplaas to the Blockhouse section, a distance of ~25 km, without significant thickness changes in the packages. These features are attributed to instability on the slopes of inner shelf deltas.

5. Landward-rotated growth fault features are common in shelf-edge deltas (Rider, 1978; Coleman et al., 1998). The abrupt thinning of deformed packages beyond the inferred shelf-edge rollover further indicates that the presence of soft-sediment deformation does not indicate...
Figure 14. Evolution of Waterford clinothem (WfC) 3 and WfC 4 through time on encountering the shelf-edge rollover. WfC 3 encountered the shelf-edge rollover, but sediment was trapped in rotational growth faults, preventing progradation onto the upper slope. WfC 4 was able to supply sediment beyond the shelf-edge rollover and cut shelf-edge gullies as well as a turbidite-filled slope channel, despite the shelf never becoming subaerially exposed within the shady area.
proximity to the shelf-edge rollover, but rather that the scale and process of deformation are more accurate indicators of proximity to the shelf-edge rollover zone (Oliveira et al., 2011).

CONCLUSIONS

The large-scale outcrops of the Waterford Formation have enabled a set of criteria to be developed for the identification of exhumed shelf-edge rollovers on a large, low-gradient basin margin. These criteria vary as a function of the river- or wave-dominated process regime of the parasequence at the shelf edge. The criteria include widespread erosion or gullying, extensional growth faults, an increase in large-scale soft-sediment deformation, and basinward thickening of parasequences (associated with increased amounts of thin turbidite beds) over a zone of several kilometers in a basinward direction. Although the criteria were developed for a low-gradient setting, they may also offer a reference point for other, more complex basin margins or other outcrop settings with limited dip or lateral exposure. Although the literature is replete with examples in which soft-sediment deformation is used to suggest proximity to the shelf-edge rollover (Oliveira et al., 2011), this study shows that the presence of soft-sediment deformation alone is not an adequate criterion with which to define the shelf-edge rollover; in the case of the lower Waterford Formation it is simply a common feature of delta-scale clinothems on the shelf.

Process regime and architecture may vary significantly between successive shelf-edge rollover successions. High sediment supply to the shelf edge in a river-dominated parasequence drove extensional deformation of the shelf-edge rollover that provided an effective trapping mechanism for sand, and limited transfer of sediment beyond the shelf-edge rollover. The overlying parasequence is wave and/or storm dominated, but the lower accommodation setting of this parasequence was an important factor in delivery of sediment over the shelf edge, probably in combination with longshore redistribution. The mechanism of sand supply to the upper slope was via a network of gullies (below seismic resolution) and longshore redistribution. The mechanism of gullies (below seismic resolution) and longshore redistribution. The mechanism of gullies (below seismic resolution) and longshore redistribution. The mechanism of gullies (below seismic resolution) and longshore redistribution. The mechanism of gullies (below seismic resolution) and longshore redistribution.

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