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SEDIMENTOLOGY, STRATIGRAPHIC ARCHITECTURE AND DEPOSITIONAL CONTEXT OF SUBMARINE FRONTAL LOBE COMPLEXES

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ABSTRACT: Frontal lobes develop during discrete periods of progradation in deep-water systems, and commonly form on the lower slope to base-of-slope. In reflection seismic datasets, they are identified as high amplitude reflectors that are cut as the feeder channel lengthens. Here, an exhumed sand-prone succession (>80% sandstone) from Sub-unit C3 of the Permian Fort Brown Formation, Laingsburg depocenter, Karoo Basin, South Africa, is interpreted as a frontal lobe complex, constrained by its sedimentology, geometry and stratigraphic context. Sub-unit C3 crops out as a series of sand-prone wedges. Individual beds can be followed for up to 700 m as they thin, fine and downlap onto the underlying mudstone. The downlap pattern, absence of major erosion surfaces or truncation, and constant thickness of underlying units indicates that the wedges are non-erosive depositional bodies. Their low aspect ratio and mounded geometry contrasts markedly with architecture of terminal lobes on the basin floor. Furthermore their sedimentology is dominated by dm-scale sinusoidal stoss-side preserved bedforms with a range of low-high angle climbing ripple laminated fine-grained sandstones. This indicates that the flows deposited their load rapidly close to, and downstream from, an abrupt decrease in confinement. The sedimentology, stratigraphy, cross-sectional geometry and weakly confined setting of a sand-prone system from the Giza Field, Nile Delta is considered a close subsurface analogue, and their shared characteristics are used to establish diagnostic criteria for the identification and prediction of frontal lobe deposits. In addition, deposits with similar facies characteristics have been found at the bases of large external levee deposits in the Fort Brown Formation (Unit D). This could support models where frontal lobes form an initial depositional template above which external levees build, which provides further insight into the initiation and evolution of submarine channels.

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INTRODUCTION

Sand-prone deposits in deep-water settings are generally attributed to either high-aspect ratio terminal lobes that form sheet-like deposits in distal areas, or the axial fills of submarine channels, whereas fine-grained material is commonly concentrated in levees or distal lobe fringe settings. This grain-size segregation is attributed to stratified turbidity currents that concentrate the coarser fraction at the base of the flow, whilst the finer fraction can overspill or be stripped into overbank settings thereby narrowing the grain-size range down slope (Piper and Normark 1983; Hiscott et al. 1997; Peakall et al. 2000; Kane and Hodgson 2011). Sand-prone submarine channel-fills and lobes have been widely studied in modern and ancient systems for both academic and industry purposes (e.g. Bouma 1962; Posamentier et al. 1991; Mutti and Normark 1991; Weimer et al. 2000; Mayall and Stewart 2000; Gardner et al. 2003; Posamentier 2003; Posamentier and Kolla 2003; Hodgson et al. 2006; Pyles 2008; Romans et al. 2011; McHargue et al. 2011).

Numerous wedge-shaped, high amplitude depositional elements adjacent to channels do not conform to the simple models of sand distribution in either low aspect ratio channel-fills or high aspect ratio lobes (Fig. 1). Mayall and O'Byrne (2002) documented the occurrence of mud-filled channels flanked by low aspect ratio sandy wedges; superficially similar features have also been described from high amplitude reflection packages (HARPs) at the base of external levees in the Amazon Fan (e.g. Flood et al. 1991; Normark et al. 1997). Within the constraints of seismic data, the high-amplitude reflectors can be interpreted as sand-prone levees that formed through overspill of sand-prone flows from an adjacent channel (Mayall and O'Byrne 2002), or as remnants of precursor or frontal lobes formed by flows that spread laterally outward from a channel mouth before being overlain by a levee as the channel propagated into the basin (e.g. Normark et al. 1997). A plethora of terms have been used to describe similar features, including crevasse lobe/splays, avulsion lobes/splays, frontal lobes/splays and precursor lobes/splays in seismic datasets (e.g. Posamentier et al. 2000; Mayall and O'Byrne 2002; Posamentier, 2003; Posamentier and Kolla 2003, Ferry et al.,

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2005; Wynn et al. 2007; Cross et al. 2009; Armitage et al, 2012). Here, we prefer the term lobe to splay, and make a distinction between *frontal lobes*, which are deposited ahead of a feeder channel that lengthens into the basin and incises through its own deposit, and *crevasse lobes* that are deposited adjacent to a channel and can mark the beginning of a channel avulsion cycle.

Here, the focus is on frontal lobes. Currently, there are no published diagnostic criteria that can be used across different datasets to aid the characterisation and prediction of high amplitude sand-rich wedges, or to discriminate from crevasse lobes or sand-rich levees. In part this is due to the paucity of outcrop examples where sub-seismic observations of sedimentary facies can be made. The limitations of outcrops mean that uncertainties remain in relation to the geographic position, geometry, and stratigraphic relationship of interpreted frontal lobes and the feeder channel (e.g. Etienne et al. 2012; Brunt et al. 2013a). Where lobes develop immediately basinward of the mouth of their feeder channels they can form an important component in the assemblage of erosional and depositional features that can develop in channel-lobe transition zones (e.g. Morris et al. 1998; Wynn et al. 2002).

An exhumed sand-prone deposit (Sub-unit C3) in a lower submarine slope setting with an unusual cross-sectional geometry, and low aspect ratio isopach 'thicks' and 'thins', is identified in the Fort Brown Formation, Laingsburg depocenter, Karoo Basin, South Africa. The study leverages detailed outcrop characterisation from both mapping and behind outcrop research boreholes We consider a frontal lobe complex origin for the units, based on documentation of process sedimentology, stratigraphic architecture, and depositional context. The key differences between frontal lobes and terminal lobes are reviewed, augmented with subsurface data from the Nile Delta. The results provide insight into the origin and evolution of sand-prone wedges associated with channels on the submarine slope, providing diagnostic criteria that will help in the future identification and characterisation of frontal lobes at outcrop and in the subsurface.

GEOLOGICAL SETTING AND STRATIGRAPHY

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The study area is located 14 km west of the town of Laingsburg, Western Cape, South Africa and forms part of the deep-water fill of the Laingsburg depocenter of the southwestern Karoo Basin. The Permo-Triassic Karoo Basin has been interpreted as a retroarc foreland basin (e.g. Cole 1992; Visser 1993; Veevers et al. 1994; Catuneanu et al. 1998; Catuneanu et al. 2005) although more recent work suggests that subsidence during the Permian deepwater phase was driven by dynamic topography associated with subduction (Tankard et al. 2009). The progradational basin-floor to upper-slope succession is over 1.4 km thick (Flint et al. 2011)(Fig.2A), beginning with the distal basin-floor Vischkuil Formation (Van der Merwe et al. 2009; 2010), which is overlain by basin-floor and base-of-slope systems of the Laingsburg Formation (Units A and B; Sixsmith et al. 2004; Grecula et al. 2003a; Brunt et al. 2013a; Prélat and Hodgson 2013). The overlying Fort Brown Formation is a muddy submarine slope succession with slope channel-levee systems containing Units C-G (Grecula et al. 2003b; Figueiredo et al. 2010; 2013; Hodgson et al. 2011; Di Celma et al. 2011; Brunt et al. 2013b; Morris et al. 2014). Exposures are found along the limbs of E-W trending and eastward plunging post-depositional anticlines and synclines, such as the Baviaans syncline (the southern study area, Fig. 2C), and the Zoutkloof syncline (the northern study area, Fig. 2B). Sandstone prone units form topographic ridges between recessively weathered mudstone-prone units. The regional paleoflow direction in Units C and D, recorded from ripple cross lamination and flute casts, is NE-ENE (Hodgson et al. 2011).

Unit C and the overlying 25 m thick C-D regional mudstone has been interpreted as a composite sequence, with Unit C representing a lowstand sequence set that comprises three sequences (Flint et al. 2011). The lowstand systems tracts to these three sequences are sand-prone Sub-units C1, C2 and C3 (Di Celma et al. 2011). The lowstand systems tract of the youngest sequence, C3, is the focus here. C3 is bounded by two regional mudstones that serve as reliable regional markers; an underlying 8 m thick mudstone separating C2 and C3 (the upper C mudstone, which is the combined transgressive and highstand systems tracts to sequence C2), and the overlying ~25 m thick C-D mudstone (Hodgson et al. 2011). Di Celma et al. (2011) mapped a basinward stepping trend from

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Sub-units C1 to C2, with a landward stepping component in the form of C3, suggesting a long-term waxing then waning of overall flow energy and volume through the evolution of the composite sequence.

On the north and south limbs of the Baviaans syncline (Fig. 2C), C1 and C2 are primarily thin-bedded siltstones and fine-grained sandstones. C1 is attributed to frontal lobe processes, and the strata are up to 15 m thick (Di Celma et al. 2011). C2 is interpreted as an external levee deposit (up to 42 m-thick) that partially confined a channel system filled with thick bedded structureless sandstones and internal levee deposits (up to 80 m thick) (Di Celma et al. 2011; Kane and Hodgson 2011; Hodgson et al. 2011; Morris et al. 2014). To the north, in the Zoutkloof farm area (Fig. 2B), Di Celma et al. (2011) noted that Unit C1 attains a maximum thickness of 65 m, comprising meter-scale packages of tabular bedded sandstone interpreted as terminal lobe deposits. The overlying C2 succession (60 m thick) consists of thin bedded sandstone and siltstone, with some amalgamated sandstone beds towards the base, and is interpreted as an external levee deposit with the genetically related channel-fill units that trend eastwards (Di Celma et al. 2011). The impact of this depositional relief on sedimentation patterns in C3 is discussed below.

METHODS

The geometry and facies distribution of Sub-unit C3 have been mapped from the Baviaans farm area for 22 km downdip, covering an area of 175 km^2 (Fig. 2B; 2C) in which it ranges in thickness from ~60 m on the northern limb of the Baviaans syncline to zero where it downlaps onto the underlying upper C mudstone, and is typically 10-20m thick in the study area. Field-based sedimentological and stratigraphic observations include 56 measured sections (2.7 km cumulative thickness); 7 sections on the southern limb of the Zoutkloof syncline, 36 on the northern limb of the Baviaans syncline and 13 sections on the southern limb of the Baviaans syncline – the CD Ridge (Fig. 2). The geometry of C3 was mapped using the stratigraphic top of C2 as a lower datum and the base of Unit D as an upper datum (except in areas where D is an entrenched slope valley, Hodgson et al. 2011). Sub-unit C3 has

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been described in detail in cores from two research boreholes (Bav 1A and Bav 6), drilled behind outcrops of the CD Ridge allowing for outcrop to subsurface correlation and calibration (Fig. 2D; Morris et al. 2014).

SUB-UNIT C3: SEDIMENTARY FACIES ASSOCIATIONS

The deposits of the Laingsburg and Fort Brown formations have a narrow grain-size range; from hemipelagic mudstone to a maximum grain-size of fine-grained sand. Within the confines of the study area, Sub-unit C3 consists mainly of thinly bedded sandstone and siltstone. C3 overlies the upper C mudstone across a gradational contact, characterized by thin (<1 cm) alternating beds of sandstone and siltstone; the unit is sharply overlain by the C-D mudstone. Four main sedimentary facies associations have been identified within Sub-unit C3: **FA1 –** Siltstone-prone thin-bedded deposits; **FA2 –** Sandstone-prone thin-bedded deposits; **FA3 –** Sandstone-prone thick bedded deposits; and **FA4 –** Structured sandstone (see Figure 3).

C3 is characterized by a distinct succession of sedimentary facies associations (Fig. 4A); FA1, is preserved as the basal meter of C3 throughout the study area (Fig. 4A) and in core (Fig. 5A). Overlying FA1 is the coarser grained FA2, FA3 and FA4 facies associations (Fig. 4A). This succession consists of very coarse siltstone-to-very fine-grained sandstone beds that are 0.05-0.4 m thick, organised into 0.1-0.4 m thick bedsets that are characterized by sinusoidal laminae and climbing ripple laminae (Fig 4E). Paleoflow directions measured from these structures are towards the N/NE (030-130 degrees). In the Bav 1A core (Fig. 5), the sinusoidal laminae of FA3 are defined by concave-up through sub-parallel and low angle to convex-up laminae-sets (Fig. 5E). There are multiple cm-scale erosion surfaces present, across which some minor truncation of laminae is observed throughout the unit (15 recorded from the 15.5 m thickness of C3 in Bav 1A); however, major (meter-scale) erosional surfaces are not identified in core or at outcrop. Commonly, the upper

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contact of C3 comprises a bed of very fine sandstone 0.4-0.7 m thick, which locally contains climbing ripple cross-lamination or dewatering structures.

Facies Association Interpretation

The stratigraphic context of Sub-unit C3 in a submarine slope setting is well established (Flint et al. 2011; Hodgson et al. 2011; Di Celma et al. 2011). The thin-bedded nature, subtle normal grading and tractional structures of the thin-bedded tabular sandstones and siltstones indicate deposition from low-density and dilute turbidity currents in a relatively unconfined setting. The presence of mud drapes suggests that there was a significant hiatus between events associated with hemipelagic fallout. Alternatively, the mudstone drapes record the very fine-grained fallout from dilute tails of turbidity current (T_d and T_e beds) that mostly bypassed the area (cf., Mutti and Normark, 1987), suggesting that large events were more continuous.

The climbing ripple cross-laminated thick-bedded sandstone and siltstone facies, characterised by the presence of dm-scale sinusoidal stoss-side preserved laminae and low-to-high angle (10˚-40˚) climbing ripple lamination indicates high rates of sediment fallout and tractional deposition that is attributed to rapid expansion and deposition from moderate-to-low concentration turbidity currents (Allen, 1973; Jobe et al. 2012). The erosion surfaces identified in core may indicate some minor-to-moderate reworking of bed-tops by more energetic turbidity currents.

Significance Of Aggradational Bedforms

The dm-scale stoss-side preserved sinusoidal lamination so prevalent throughout C3 is similar in form to the sinusoidal ripple lamination described by Jopling and Walker (1968); Type B and S climbing ripple lamination described by Allen (1973); and the sinusoidal laminae described by Hunter (1977) and Jobe et al. (2012). Climbing ripple lamination results from the action of unidirectional currents (Allen 1973), and require bedload transport and simultaneous high rates of suspended sediment load fallout (Sorby 1859; 1908). These conditions are typical of non-uniform depletive

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flows (Kneller 1995). Sinusoidal lamination is shown to be a form of climbing ripple cross-lamination produced on a spectrum largely dependent on the degree of stoss-side preservation (Jopling and Walker, 1968). According to Jopling and Walker (1968) and Allen (1973), the type of ripple lamination produced depends upon the rate of fallout from suspension; the higher the volume of fine grained material falling out of suspension, the lower the rate of stoss-side erosion, allowing a higher angle of climb and more complete preservation of a lamina. Allen (1971a, 1971b; 1973) noted that climbing ripple lamination is significant as it preserves the only bedform that can be used to determine the short-term rate of deposition. The highly aggradational nature of the sinusoidal laminae within C3 indicates persistent high rates of deposition, which suggests that sediment gravity flows were expanding and depositing rapidly (highly non-uniform, (Kneller 1995)). Locally, the 3D asymmetric bedform formed by the sinusoidal laminae is observed (see Fig. 12b of Kane and Hodgson, 2011). It is likely that the flows were long-lived enough to create sedimentation rates that exceeded rates of erosion at the ripple reattachment point, forming stoss side preserved highly aggradational deposits (Jobe et al. 2012). The lack of high-relief erosional contacts would also suggest that events of this nature were continuous rather than sporadic. This is consistent with the interpretation that the mm-thick mud laminae derive from continuous events and are the products of fine-grained, dilute turbidity current tails (T_d and T_e beds; cf., Mutti and Normark, 1987).

That this sedimentary facies association dominates much of Sub-unit C3 indicates that the processes were governed by flows characterized by high sedimentation rates. Mechanisms that could explain this repeated non-uniform and depletive flow behaviour include the presence of a change in gradient, the abrupt transition from confined to unconfined settings such as at the terminus of confined channels (e.g., Mutti and Normark, 1987; Normark and Piper, 1991; Wynn et al, 2002), or overspilling onto an external levee (Jobe et al. 2012).

SUB-UNIT C3: DEPOSIT GEOMETRY AND FACIES ASSOCIATION DISTRIBUTION

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The geometry and depositional architecture of C3 along the limbs of the Baviaans and Zoutkloof synclines has been documented by mapping the uniformly thick mudstone stratigraphic marker beds that bound C3 and through physical correlation of beds by walking them out between closely spaced measured sections (Fig. 2 and 6).

Along the southern limb of the Baviaans syncline (CD Ridge), C3 thins from 15 m at the nose of the syncline, to less than a meter eastwards over a distance of 2 km across depositional strike (Fig. 6B). Individual beds thin, fine and downlap towards the east onto the underlying mudstone, i.e. the thicker bedded climbing ripple cross-laminated sandstones (FA3 and FA4) thin, fine and downlap, passing into the thin-bedded siltstones laterally (FA2 and FA1). Exposure is curtailed at the 2 km point where a Unit D-aged entrenched slope valley 120 m deep and 2 km wide incises through C3 and earlier deposits (Fig. 6C; Hodgson et al. 2011). However, C3 is present beyond the eastern edge of the Unit D slope valley, manifest as a 1.4 m thick thin bedded (FA1) unit that continues for 8 km, gradually thinning and fining before pinching out (Fig. 6C). C3 is not observed again along the south limb of the Baviaans syncline beyond this pinchout point. No large-scale erosive features within or at the base of C3 have been observed on either side of the Unit D slope valley and paleocurrents record the N-to-NE directed regional paleoflow. The Bav 1A research borehole provides some north-south control: at outcrop close to the borehole position C3 is approximately 7-8 m thick. In the core, approximately 300 m away in the subsurface, it is 15.5 m thick, indicating abrupt thickening (~2.5 m/100 m) to the north.

Along the northern limb of the Baviaans syncline C3 thins westward from 17.5 m to 3 m, then thickens to more than 60 m over ~2 km across depositional strike (2.5 m/100 m), before thinning again to 15 m at the closure of the Baviaans syncline (Fig. 6B). In strike section (Figs. 6B and 7A), two sandstone-prone zones or 'thicks' have aspect ratios of ~50:1 for the western thick and 600:1 for the eastern thick. Where C3 thins from 17.5 m to 3 m, individual beds can be walked out for over 700 m as they thin, become finer grained, and downlap onto the underlying mudstone (Fig. 6B, 7A, 7B, 7C and 8). As these beds thin and fine laterally, the distribution of sedimentary structures varies from

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sinusoidal laminae to climbing ripple lamination in sandstone (Fig. 8) before passing into siltstone. The aspect ratio of 50:1 of the western 'thick' is similar to channelised features and/or HARPs as plotted by Piper and Normark (2001). The lack of major erosional features, the lateral fining and thinning of strata, and the constant thickness of the underlying mudstone indicate that the variable thickness geometry is a consequence of deposition rather than erosion (Fig. 7B and 7C). Therefore a channelised mode of formation of these deposits is unlikely. Where C3 is <3 m thick (e.g. eastern exposures on the CD Ridge, south limb of Zoutkloof syncline) it is thinner bedded and finer grained, comprising 1-3 cm thick beds of interbedded coarse-siltstone to very fine-grained sandstone with planar and locally current ripple cross lamination. Sandstone beds are separated by 1-2 mm-thick mudstone beds with low intensity bioturbation; it is the same facies association that is observed in the lowermost meter of C3. As C3 thickens westward to a maximum of ~60 m (Fig. 6), there is a localised increase in sandstone percentage through the full thickness of the sub-unit, from <20% in the 'thins' (where the unit is 3-17.5 m thick) to over 50% in the 'thicks' (~60 m thick). In the thickest areas individual sandstone beds are typically characterized by sinusoidal laminae. At all of the measured sections on the northern limb of the syncline, paleocurrent directions derived from ripple foresets indicate that flow was towards the N-to-NE (Fig. 6F) following the regional paleoflow direction (within a 40° range). This same northeasterly paleocurrent trend is recorded in beds that thin to the west.

Further north on the southern limb of the Zoutkloof syncline C3 is thinly bedded (comprising the thin-bedded sheet-like sandstones and siltstones of FA1) and has been mapped for 18 km down dip (Fig. 6A). Overall, it varies slightly in thickness (1.5-3 m); however, one section records a thickness of 15.3 m and comprises stacked beds dominated by sinusoidal laminae, representing another depositional sand-prone 'thick' with similar sedimentary facies association. The isopach map shows the distribution of Sub-unit C3 throughout the study area (Fig. 6D).

DISCUSSION

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Depositional Environment of C3

Sub-unit C3 is unlike any other unit observed in the Laingsburg and Fort Brown Formations, with an unusual cross-sectional geometry of low aspect ratio mound shaped sandstone-prone 'thicks' containing beds that downlap towards siltstone-prone thinner areas, or 'thins', with a consistent N-to-NE paleoflow (Figs. 6B, 7B, 7E and 7G). There is no evidence for: (i) substantial erosion at the base or the top of C3; or (ii) erosional channel deposits or surfaces. Furthermore, no increase in the thickness of mudstone above C3 is evident (Figs. 6 and 7), suggesting that there are not a series of mudstone-filled channels to account for the observed thickness variations. Therefore, the C3 mounds are interpreted to be depositional in origin. The occurrence of such depositional units in the absence of erosional confinement, but with the widespread occurrence of physical structures attributable to aggradational bedforms that indicate rapid rates of deposition, does not fit a simple range of deep-water architectural elements (Allen 1973; Jobe et al. 2012). Possible depositional environments and paleogeographic configurations that could explain the stratal geometry and physical sedimentary characteristics are considered.

Levees.---

External levees are wedge-shaped constructional features formed by turbidity currents that overspill channel confinement, and fine, thin and downlap away from the related submarine channels (e.g., Buffington, 1952; Shepard and Dill, 1966; Skene et al. 2002; Kane et al. 2007; Kane and Hodgson 2011; Morris et al. 2014). Commonly, external levees form thin-bedded and mud- and silt-prone successions (e.g. Pirmez et al. 1997; Kane and Hodgson 2011) that typically fine- and thin-upwards as confinement increases (e.g. Walker 1985; Manley et al., 1997; Morris et al. 2014). However, more sand-prone wedges adjacent to channels that are attributed to levee deposition have been interpreted from subsurface data (Mayall and O’Byrne 2002). In external levees, proximal to distal relationships, relative to the genetically-related channel, in terms of the distribution of sand and bed thickness are notable, corresponding to relative flow velocities as interpreted from sedimentary

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structures, i.e. beds are thinner and finer and indicative of lower energy further away from the channel (Piper and Deptuck, 1997; Kane et al. 2007; Morris et al. 2014).

Comparison to C3: The lateral thinning, fining and bed downlap of C3 is comparable to that of an external levee (Fig. 9A). Sedimentologically, C3 shares similarities with the basal deposits of other documented external levees in the Fort Brown Formation (Figueiredo et al. 2010; Hodgson et al. 2011; Di Celma et al. 2011; Brunt et al. 2013b; Morris et al. 2014) although these other examples progressively fine- and thin-upwards into siltstone-prone successions (cf., Manley et al., 1997; Kane and Hodgson 2011; Morris et a. 2014). Commonly, sandstone dominated deposits are found at the base of levees, when flows were less confined and the sandy parts of flows were able to spill into overbank areas (Damuth et al. 1988; Flood et al., 1991; Pirmez and Flood, 1995; Kane and Hodgson 2011). These deposits can also represent earlier frontal splays/lobes that have been incised and overlain by younger levee deposits as the channel lengthened and confinement increase through erosion and/or construction (Gardner et al. 2003; Beaubouef 2004; Ferry et al., 2005). No C3 aged channel has been identified at outcrop throughout the study area, although it is plausible that evidence for it was removed by the later entrenchment of the Unit D slope valley on the southern limb of the Baviaans syncline (Hodgson et al. 2011). Also the low aspect ratio of the sand prone 'thicks' and the mound shape differs from a typical levee wedge (Skene et al. 2002; Kane et al. 2010), which tapers away from the genetically related channel.

Terminal Lobes.---

Terminal lobes form in distal reaches of a distributive system in very low gradient settings, and are typically dominated by tabular (sheet-like), sandstone rich deposits (Etienne et al. 2013). The geometry and distribution of terminal lobe sedimentary facies have been documented in the adjacent Tanqua depocenter (Prélat et al. 2009), and a similar range of facies and stacking patterns have been identified in terminal lobes of Unit A in the underlying Laingsburg Formation (Prélat and Hodgson 2013). Low aspect ratio sand-rich units have been identified in the most distal portions of

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lobes exposed in the Tanqua depocenter (e.g. Rozman 2000; van der Werff and Johnson 2003; Prélat et al. 2009). These features form an uneven geometry in strike section with several 'thins' and 'thicks' up to several hundred meters wide in the distal fringe of the basal lobe in lobe complexes (Prélat et al. 2009). There is no evidence for basal erosion, and in map view these feature form depositional finger-like projections (Rozman 2000; Groenenberg et al. 2010). In terms of sedimentary facies, the fingers most commonly comprise amalgamated fine-grained sandstone abundant of dewatering structures, or turbidites with linked debrites in which upper argillaceous divisions are rich in mudclasts and carbonaceous material (Haughton et al. 2009; Hodgson 2009).

Comparison to C3: C3 is situated on a submarine slope above channel-levee systems (Sub-unit C2), the low aspect ratios and mounded geometry of these features, as well as the highly depositional and aggradational sedimentary facies association dominated by climbing ripple laminae, contrasts with terminal lobes identified on the basin floor in the Karoo Basin (Prélat et al. 2009). For these reasons, C3 in the study area is not interpreted as a terminal lobe complex. Although the distal 'fingers' of terminal lobes in the Tanqua depocenter also form sand-rich units of variable thickness in strike section, and are depositional in origin, their sedimentology and paleogeographic position are markedly different. High aspect ratio fine-grained sandstone packages in Sub-unit C3, with more tabular bedded sandstone deposits that contain turbidites with linked debrites are identified >15km farther into the basin to the east. These deposits meet criteria proposed by Prélat and Hodgson (2013) for the identification of terminal lobes (Fig. 10).

Crevasse Lobes.---

Lateral or crevasse lobes are sand-prone units deposited on levee flanks (Fig. 9C). They are formed by turbidity currents that breach an external levee (Posamentier and Kolla, 2003; Morris et al. 2014), and can precede a channel avulsion (e.g. Fildani and Normark, 2004; Brunt et al. 2013a). Posamentier and Kolla (2003) documented an example from the Gulf of Mexico covering 50 km^2. Commonly, the site of deposition of a crevasse lobe is weakly confined and allows flows to spread

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out and form both parallel and subtly lens-shaped seismic facies (Flood et al. 1991; Pirmez et al. 1997). Cores taken through these deposits as part of IODP leg 155 shows they are characterized by thick-bedded sandstones that are coarse grained in relation to the surrounding levee deposits and are rich in mud clasts in beds exceeding 1 m in thickness (Pirmez et al. 1997).

Comparison to C3: Sinuous channels are commonly invoked to explain the presence of crevasse lobes (Keevil et al. 2006; Peakall et al. 2000). Sinuous channels are interpreted to be mature channels that have been established for relatively long, sustained periods of time (Peakall et al. 2000; Maier et al. 2013). Crevasse lobe deposits has been interpreted within levee successions elsewhere in the field area (Morris et al. 2014), and are only a few metres thick. There is no levee associated with C3 throughout the entire field area, this suggests that it is unlikely that the 'thicks' are the result of crevasse processes from a sinuous channel into an external levee setting.

Frontal Lobes.---

The term frontal lobe, or splay, refers to a relatively unconfined deposit formed basinward of the feeder channel (Posamentier and Kolla 2003) (Figs. 9D and 9E). A series of frontal lobes can stack to form a frontal lobe complex (*sensu* Prélat et al. 2009) as the feeder channel lengthens into the basin. The channel will incise through its own deposit, as a new lobe forms farther basinward. The stacking patterns of the lobes can be either forward stepping where the feeder channel cuts through the axis of the lobe complex (Fig. 9E), or a laterally offset pattern where the feeder channel will deviate to avoid the axis of each lobe (Fig. 9D). As a result of this partial cannibalisation, frontal lobe complexes are preserved as remnants that are cut by genetically-related channels during system progradation (e.g. Brunt et al. 2013a). The channel-lobe transition zone (CTLZ) is defined as the region that, within any turbidite system, separates well-defined channels or channel-fill deposits from well-defined lobes or lobe facies (Mutti & Normark 1987). In modern settings, the CLTZ is characterized by scours and erosional lineations separated by patchily distributed sands (e.g. Wynn et al., 2002; MacDonald et al. 2011). This geographic area can move gradually or abruptly through

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time, depending on changes in parameters such as seabed gradient and flow magnitude. As such the architecture expression of the CLTZ in stratigraphic successions can be elusive (Gardner et al. 2003). Typically, the seismic character of frontal lobes is manifest as part of composite high amplitude continuous reflection packages (HARPs; Damuth et al. 1988; Piper and Normark 2001; Posamentier and Kolla 2003).

Comparison to C3: The sedimentological evidence for persistent rapid deposition from turbidity currents, the distinctive low aspect ratio depositional geometry supports an interpretation of C3 in the Baviaans Farm area as a series of frontal lobes that form a frontal lobe complex (Fig. 10). The presence of C3-aged terminal lobes down-dip indicates that there was sediment bypass in the western part of the Baviaans syncline during the evolution of C3. Therefore, the frontal lobe complex is interpreted to have been fed by an interpreted channel system to the south that followed a ENE path with a similar trend to the entrenched Unit D channel system (Hodgson et al. 2011; Brunt et al. 2013b). This explanation accounts for the consistent direction of paleocurrent data at an angle to the hypothesised ENE-trending channel to the south (Figs. 7G and 10) and the sedimentological evidence of rapid deposition as flows exited the abrupt terminus of a feeder channel that propagated into the basin. The lack of truncation associated with the 'thins' does not support an interpretation of frontal lobes with a forward stepping pattern (Fig. 9E). However, the downlapping pattern, paleocurrents, and depositional geometry are consistent with an off-axis dip section through a series of laterally offset frontal lobes (Fig. 9D). In the main study area (blue box on Fig. 10A), the depositional 'thick' on the north limb of the Baviaans syncline (Figs. 6B, 7A and 10B) comprises dominantly FA3 and FA4 and is interpreted to form part of a frontal lobe axis, and the thinner bedded FA2 and FA3 dominant deposits associated with the depositional 'thins' are interpreted as frontal lobe off-axis to frontal lobe fringe deposits. In sedimentary process terms, the CLTZ records the abrupt downstream transition of flows from a confined to unconfined state, and this change in flow behaviour is recorded in C3 deposits. Frontal lobe deposits are one of an assemblage of depositional and erosional features that can be used to identify CLTZ in the rock

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record. Other features, including mud-draped scour-fills, backset bedding, and depositional barforms (e.g. Ito et al. 2014), are not identified in C3. However, this might be due to the exposures being at the edge of the. Figure 10 illustrates a paleogeographic reconstruction of C3 as a series of laterally offset frontal lobes to the west and terminal lobe deposits to the east, with the main sediment pathway to the south.

Why Is This Deposit Preserved In This Area?

Geometrically, C3 'thicks' are closer in aspect ratio to erosional channels (AR = ~10:1) than to weakly confined lobe/splay deposits (AR = ~100:1) (Clark et al. 1992; Piper and Normark 2001; Prélat et al. 2010). The unusual geometry of the composite C3 deposit could be attributed to the influence of older deposits to the north that formed depositional relief. Di Celma et al. (2011) recognized that Sub-unit C1 attains a maximum thickness of 65 m at Zoutkloof farm (highlighted in Fig. 2), and interpreted that this deposit controlled the change in orientation of C2-aged channel complexes to the east, and the formation of thick C2 external levees in the Zoutkloof area. This inherited depositional relief may have partially confined the flows that comprise C3 deposits, fostering a build-up of significant depositional relief in the Baviaans area, close to channel mouths (Fig. 10).

Di Celma et al. (2011) interpreted that in the study area Sub-unit C1 consists of lobe deposits, and C2 is a channel-levee complex set. Considering that C3 is interpreted as a frontal lobe complex, the Unit C composite sequence, therefore, is interpreted to represent a progradational-to-retrogradational stepping lowstand sequence set of lower to mid slope deposits overlain by the draping C-D mudstone, which forms the combined transgressive/highstand sequence set (Flint et al., 2011; Di Celma et al., 2011). C3 represents the retrogradational section of the Unit C sequence set, following the basinward advance of C2. At this late stage in the lowstand sequence set it is suggested that the flows feeding the frontal lobes of C3 did not have the power to incise through the previously deposited sandstone-prone 'thicks', inhibiting further basinward propagation of the channels.

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The physical structures of Sub-unit C3 are consistent with non-uniform flow and rapid expansion and deposition from moderate-to-low concentration turbidity currents. An abrupt shift from confined to unconfined conditions at the terminus of channels is envisioned, perhaps enhanced by a reduction in gradient. The scale, the low aspect ratio of the C3 mounds, the presence of the highly tractional bedforms and the slope setting support a frontal lobe complex interpretation for the 'thicks' and 'thins' of C3. According to Groenenberg et al. (2010), sediment gravity flows that supply terminal lobes on the basin floor are influenced by much more subtle topography and are less likely to undergo rapid deposition.

Can Frontal Lobes Form Parts Of External Levee Successions?

Comparison to the Unit D external levee – CD Ridge.---
C3 shares some sedimentological characteristics with the basal parts of external levees in the Fort Brown Formation (Morris et al. 2014), but lacks the distinctive fining- and thinning-upward siltstone-prone character of many external levees (cf., Manley et al., 1997). The Unit D external levee (*sensu* Kane and Hodgson, 2011) has a distinctive facies association distribution in 1D allowing the identification of two main depositional phases that are responsible for the resultant levee deposit (Morris et al. 2014). In Bav 1A, Unit D is ~70 m thick, the lowermost 20-25 m of Unit D has a similar facies association and facies distribution to that observed in C3 with FA1 dominant in the basal 1m, overlain by FA2, FA3 and FA4 comprising thick-bedded (0.1-0.4 m) coarse siltstone and very fine sandstone, dominated by sinusoidal laminae (Morris et al. 2014). Overlying this 20-25 m interval, Unit D is siltstone dominated (~5-10% very fine sandstone) and thinner bedded. The prevalent sinusoidal, aggradational bedforms are still observed, however planar lamination is the dominant sedimentary structure. Not only are there sedimentary facies association similarities between the lower part of Unit D and C3, but studies completed on the western external levee of the CD Ridge (Kane and Hodgson 2011; Morris et al. 2014) show that individual beds at the base of Unit D thin and

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fine in grain-size, as they downlap onto the underlying mudstone, away from the main channel, similar to the pattern observed in C3 (Fig. 7B and 8). The highly aggradational nature and apparent unidirectional current laminations present in Unit D suggest that large volumes of sediment were rapidly deposited. The vertical change in facies within the Unit D external levee succession suggests that higher and more dilute parts of flows spilled onto the levee as the distance between the base of the channel and the levee crest increased through a combination of erosion and construction.

The similarity in facies association and geometry of the basal 20-25 m of the Unit D external levee and C3 in Bav 1A suggests a similar set of formative processes, and therefore, that the vertical facies association change through Unit D developed in response to the change from weakly- to highly-confined. More specifically, we speculate that the lower part of the external levee wedge is a preserved remnant of a frontal lobe that formed prior to the establishment of a confined channel conduit. Once the channel was established, only dilute parts of flows were delivered to the overbank area (Hodgson et al. 2011). Shallow subsurface (Flood and Piper 1997; Lopez 2001; Babonneau et al. 2002; Fonnesu 2003; Ferry et al. 2005; Bastia et al. 2010; and Maier et al. 2013) and outcrop (Gardner et al. 2003; Beaubouef 2004; Kane and Hodgson 2011) datasets have recorded similar observations of sand-rich intervals partially eroded by a genetically related channel and later overlain by external levee deposits. The lack of an overlying external levee facies above C3 in the study area suggests that a large entrenched levee-confined channel system did not develop, possibly due to the long term waning sediment supply consistent with the backstepping trend in this last sequence of the Unit C lowstand sequence set.

Comparison with Subsurface Examples

A series of subsurface examples highlighting high amplitude, apparent sandstone-dominated wedge-shaped deposits adjacent to submarine channels are presented in Figure 1. Within the constraints of the seismic data, the sand-prone wedges can be interpreted in different ways: (1) sand-prone levees derived from spill of flows from an adjacent channel (Mayall and O'Byrne 2002); or (2) frontal lobes

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arranged in a forward-stepping or laterally-offset stacking pattern deposited at the terminus of a channel that lengthened and partially eroded through its own deposits (Fig. 9D and 9E). The precise stratigraphic relationship between the channel and the sand-prone wedges and the environment of deposition of the high-amplitude wedges is difficult to constrain. Furthermore, the lithology and sedimentary facies association of these deposits are not calibrated by cores. Here, we present a high-resolution subsurface dataset of interpreted frontal lobes that integrates 3-D seismic data with well logs and cores from the Giza Field, offshore Egypt. The integrated dataset provides insight into the seismic architecture, internal geometry, stacking patterns and sedimentary facies associations of a deposit considered analogous to that studied in Sub-Unit C3 in the Fort Brown Formation.

Giza Field West Nile Delta: weakly confined frontal lobes.---

The Giza Field, West Nile Delta, is in a Pliocene upper-slope channel complex set (composite submarine conduit fill) characterised by an erosionally bound 160m thick deposit that is 2.5 km wide and drapes a 20 x 10 km wide plunging anticline (Butterworth and Verhaeghe, 2012). This conduit can be tracked for a distance of >100 km, and it transitions into a constructional (i.e., levee-confined) system on the lower slope. A four stage evolution has been interpreted from mapping that comprises (i) incision, (ii) sediment bypass, (iii) aggradational fill above the basal erosion surface, and (iv) constructional fill and abandonment adjacent to levee confinement (Butterworth and Verhaeghe 2012). Seismically well imaged high amplitude reflectors in the latest stage of the constructional fill are penetrated by wells with conventional core data. The suitability of these high-amplitude reflectors as subsurface analogues to the C3 frontal lobes is considered. Within the weakly confined setting of the Giza Field, the seismic expression of these architectural elements in seismic profile is a number of wedges that thin away from a channel (Fig. 11). Geometrically, this relationship would support an interpretation of a conventional constructional levee. However, the high seismic resolution in map-view indicates that these architectural elements are a series of down-slope

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shingled lobate bodies deposited during the late-stage abandonment of the slope channel complex set (Fig. 12).

Sedimentology and stratigraphy.---

The late stage weakly confined lobes comprise a 24 m thick succession bounded at the base by a thin poorly sorted muddy sand with rafted, deformed sandstones that overlies a décollement surface interpreted as a debrite (Fig. 11). The lower 12 m thick unit is dominated by amalgamated medium to fine grained structureless sandstones with abundant pipe and dish dewatering structures intercalated with thin layers of small mudclasts.

The lower unit is overlain by a 10 m thick stratified siltstone and very fine-grained sandstone succession. Thin sandstone beds are current ripple laminated, with thicker beds containing climbing ripple lamination. These are interpreted as the deposits of low-density turbidity currents that decelerated and deposited rapidly (Fig. 11). A diverse ichnofacies assemblage, with a predominance of *Chondrites* and *Planolites* is consistent with episodic deposition. The entire succession is interpreted to represent initial deposition of high concentration turbidity currents in front of feeder channels that became unconfined, overlain by deposits from low concentration turbidity current that spilt out from adjacent channels during supply of sand to the next lobe down the depositional slope (Fig. 11).

Seismic Expression.---

Each frontal lobe covers around 2 km^2 and in strike section is characterized by asymmetric low aspect ratio wedges at the apex of each lobe, separated by a single channel element (~250 m wide and ~15 m deep) (Fig. 12). The seismic facies expression of each lobe is characterized by a distributive pattern of small channel-form features emanating from the apex of each lobe that passes down-dip into a frondescent fringe (Fig. 12). As the channel lengthened a series of lobes developed to form a lobe complex with a downslope offset stacking pattern. In part, the highly asymmetric cross-sectional geometry of each lobe reflects the style of channel lengthening whereby the thickest part of each frontal lobe is avoided as the feeder channel lengthens. The consistent

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dimensions of these lobes (1 km wide, 2 km long) reflects the available accommodation within this weakly confined setting, and is attributed to the development of shallow syn-sedimentary slides on the down-dip side of the deeper seated structural closure (Butterworth and Verhaeghe 2012).

In summary, the seismic expression integrated with the sedimentology and stacking pattern of high amplitude architectural elements deposited in a weakly confined setting are interpreted as frontal lobes with a downslope stacking pattern overlain by levees that formed as the feeder channel lengthened.

Comparison to Sub-unit C3---

The evolution of a deep-water system is controlled by a unique interaction of intrinsic and extrinsic factors, which means that comparisons drawn from an interpreted analogue system should be made with caution. This is particularly important to consider when assessing the similarity of an outcrop and subsurface dataset. Nonetheless, the weakly confined frontal lobes of the Giza Field, West Nile, share some key similarities with the C3 succession, which could help the development of diagnostic criteria for the identification and prediction of frontal lobes in other systems.

The scale and geometry of the wedge-shaped low aspect ratio architectural elements in both systems are comparable (Figs. 10 and 11). Furthermore, the architectural elements are sand-rich, form depositional relief and downlap patterns. In terms of geographic setting, both systems show evidence of weak confinement. In the case of the Giza Field this was generated by constructional relief and underlying structural control and in the case of C3 by interpreted inherited depositional relief. In both systems, the frontal lobes are formed, and preferentially preserved, during the abandonment stage of a long-term regressive to transgressive cycle (Di Celma et al. 2011; Butterworth and Verhaege, 2012). However, in terms of sequence hierarchy it is not clear if both systems represent similar scales or durations. The 3D visualisation image (Fig. 12) shows a downslope stacking of lobes, in a laterally offset pattern, to form a frontal lobe complex on the

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upper slope similar to the map view paleogeographic interpretation of C3 in a lower slope setting (Fig. 10). Finally, the process sedimentology of the two systems shares affinities. The narrow grain-size range in Sub-unit C3 results in differences in the exact sedimentary structures observed; however, in process terms there is evidence of rapid deposition from turbidity currents in both systems. One difference is that no overspill deposits have been identified above the C3 frontal lobes. This is attributed to the geographic cut of the outcrop being off-axis from the feeder channel.

With similarities drawn between the interpreted frontal lobes in a subsurface dataset and an exhumed system diagnostic criteria can be developed to help in the identification of frontal lobe at outcrop, and prediction of their characteristics in the subsurface where there is a paucity of high resolution data. Key attributes that can be used for the interpretation of frontal lobes include: i) sedimentary structures that indicate rapid deposition from turbidity currents as flows pass from confined to unconfined; ii) evidence for weak confinement and/or gradient changes that promote rapid changes in flow behaviour and limit lateral stacking of sedimentary bodies; iii) close stratigraphic and spatial association with a feeder channel; iv) the low aspect ratio geometry of architectural elements with depositional relief; v) a stratigraphic evolution from frontal deposits to channel-overbank deposits as levees are established as the feeder channel lengthens; and vi) preferential preservation during periods of overall waning sediment supply. If frontal lobes develop during the waxing stage of a sediment supply cycle their preservation potential is lower, and they are likely to be overlain by external levee successions. More examples from ancient systems at outcrop and the subsurface and their integration with numerical and physical modelling studies are needed to help refine these initial observational criteria for the identification of frontal lobes.

CONCLUSIONS

A rare example of an exhumed deep-marine frontal lobe complex that formed in a lower slope position prior to deposition of terminal lobes farther down-dip is interpreted from the Fort Brown Formation, Karoo Basin (sub unit C3). Identification is facilitated due to the absence of overlying

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external levee or channel deposits. The absence of C3 equivalent channel or overlying levee is attributed to a combination of routing of the feeder channel to the south of the deposit studied due to depositional relief formed by underlying deposits and the position of C3 as the retrogradational sequence in the Unit C lowstand sequence set, likely reduced the tendency of the channel to lengthen and incise, thereby limiting the development of an overlying levee. The mounded geometry of 'thicks' and 'thins' mapped and correlated at outcrop is interpreted to be depositional in origin, as beds are observed to thin and downlap onto the underlying mudstone rather than being truncated by erosion surfaces. Characteristic aggradational, dm-scale sinusoidal laminae (stoss-side preserved), with low-high angle climbing ripple laminated fine-grained sandstones, indicates high rates of sediment fallout that is attributed to the rapid expansion and deposition from turbidity currents at the abrupt termini of feeder channels.

Deposits that are similar in cross-sectional geometry and consistent with the map view paleogeographic interpretation of the outcrop have been imaged in seismic data from the Giza field (Egypt). In seismic, frontal lobes are represented by high amplitude sheet-like reflection packages (HARPs) that are generally cut by a channel. As slope channels lengthen and incise through earlier frontal lobes, they deposit a new lobe farther basinward in either a forward stepping or a laterally offset pattern. The partial cannibalisation by parent channels is one reason why the identification of frontal lobes is challenging at outcrop. The distinctive sedimentary facies association of the outcrop, dominated by climbing ripple laminae (with and without stoss-side preservation) and the unusual mound-like geometry of the low aspect ratio 'thicks' and 'thins', could permit identification of frontal lobe deposits in lower slope settings elsewhere in outcrop and in seismic datasets. This interpretation would imply that there was an abrupt change in flow confinement, and that frontal lobes are an important component in channel-lobe transition zones. This is significant as frontal lobe complexes are sandstone-prone units with abrupt terminations and presumed ideal rock properties (e.g., high porosity and permeability) with good connectivity; they therefore have the potential to

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act as hydrocarbon reservoirs, but do not conform to simple models of deep-water sand deposition in the axes of channel-fill or terminal lobes.

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Figure captions:

Figure 1. A selection of annotated seismic images in both map and cross-section views (A-D) showing high aspect ratio sand-rich wedges on submarine slopes. The yellow and white lines on the map view sections of A-C show the positions of the cross-section slices (through submarine channels, levees and lobes). D is an expanded view of the cross-section in A), showing a series of stacked low-relief channel-levees with bright amplitudes, separated by mudstone intervals.

Figure 2. A) Stratigraphic column showing the stratigraphy of the study area. Unit C is highlighted. B) Expanded log highlighting Units C and D, showing the internal tripartite stratigraphy of Unit C and the broad depositional environments associated with each sub-unit. C) Location map highlighting the northern and southern field areas (Zoutkloof and Baviaans synclines respectively) near the town of Laingsburg, Western Cape, South Africa. The pale grey area marks the outcrops of the Laingsburg Formation and the dark grey shows the outcrop pattern of the Fort Brown Formation. The white and black dots represent sedimentary log positions, the red and black dots highlight the positions of the Bav 1A and Bav 6 boreholes, and the green and black dot shows the location of the sedimentary log in Fig. 4. The dark purple, purple and blue lines highlight the positions of the correlation panels in Figure. 6C) Map of Baviaans syncline study area, with the CD ridge highlighted showing the Unit D slope valley incised into Unit C (see Hodgson et al, 2011 for more details).

Figure 3. The four main facies associations identified within Sub-unit C3.

Figure 4. Sedimentary log and representative photographs of sedimentary facies associations. A) Sedimentary log through Sub-unit C3 (northern limb of Baviaans syncline, green and black dots shown on Fig. 2C), Upper C mudstone shown below and C-D mudstone above. B) Low angle climbing ripple lamination in very fine-grained sandstone. C) Rippled upper bed contact of very coarse siltstone bed within C3. D) Sigmoidal laminae in very fine-grained sandstone (50 cm thick bed). E)

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Very coarse siltstone with sinusoidal laminae and lenses of very fine-grained sandstone. F) Sinusoidal laminae transitioning to ripple laminated strata in the upper 5 cm of the very fine-grained sandstone bed. G) Climbing ripple lamination in very fine-grained sandstone, with stoss side preservation. H) Interbedded very fine-grained sandstone and very coarse siltstone with sinusoidal laminae. Scales: pencil (15 cm); lens cap (6.5 cm); compass (9 cm); coin (1.5 cm); geologist (1.70 m).

Figure 5. A) Gamma-ray log and B) sedimentary log through Sub-unit C3 in Bav 1A. C) Core photographs showing examples of the sedimentary facies associations identified in C3: Ci), Ciii) and Civ) are magnified sections of very fine-grained sandstone beds with concave- to convex-up laminae (FA3 and FA4) – these laminae are the expression of asymmetric sinusoidal bedforms in core, as in simple line sketch of part E). Cii) is a magnified section of the lowermost meter of C3, featuring thinly interbedded sandstone and siltstone with mudstone drapes, low intensity bioturbation and occasional current ripple lamination (FA1). D) Interpreted core photos from Part C. E) Representative sketch (normally 15-20 cm thick) of the sinusoidal laminae and how they appear in core as a series of concave up through convex up laminae.

Figure 6. Correlation panels showing the geometry of sub-unit C3 throughout the study area. Panel A) records C3 on the south limb of the Zoutkloof syncline, panels B) and C) show C3 on the northern and southern limbs of the Baviaans syncline respectively. The outcrop has been measured and described in over 50-logged sections for 22 km down dip. The northern limb of the Baviaans syncline (B) records the most significant lateral variability in the thickness of this unit. The paleocurrent trend of each panel is shown in the rose diagrams. D) Isopach map showing the distribution of Unit C3 throughout the study area. E) Paleocurrent data recorded on the south limb of the Zoutkloof syncline, F) the north limb of the Baviaans syncline and, G) the south limb of the Baviaans syncline. H) The total paleocurrent trend of C3 throughout the study area. Note that inset boxes highlight the locations of outcrop and core photographs presented in Figures 4 and 5.

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Figure 7. A) Expanded view of the correlation panel in Figure 6B showing the depositional 'thicks' and 'thins'. B) Close-up correlation panel crop from the Baviaans North correlation panel highlighting the downlapping beds, variability in facies associations across the 'thicks' and 'thins', as well as the locations of the sedimentary log in Fig. 4A and the bed-scale correlation panel of Fig. 8. C) Aerial photograph showing Sub-unit C3 in pale yellow; the top surface of C2 and the basal surface of D highlight the presence of the bounding mudstones. The sedimentary characteristics of the 'thicks' and 'thins' are shown with facies association code labels.

Figure 8. Detail of 22 logs through a single bed over 150 m, oriented along strike to paleoflow. This highlights the lateral distribution of sedimentary structures as the bed thins through a series of photographs (also shown above). The position of this transect on the northern limb of the Baviaans syncline is highlighted on Figure 7B.

Figure 9: Summary sketch showing the main depositional environments under consideration to account for the depositional geometry and sedimentary facies associations of Sub-unit C3. The inset cross-sections A-E show the different stratal termination patterns expected for each depositional environment: A) External levees; B) Sediment waves, or large-scale bedforms; C) Crevasse lobes ; D) Offset stacked frontal lobes and E) forward stepping frontal lobes.

Figure 10: A) Map view of the paleogeographic reconstruction of Sub-unit C3 as a set of laterally offset frontal lobes (the outcrop extent of the Fort Brown Formation is superimposed. The blue box contains the main study area as recorded in the correlation panels of Figure 6. B) Cross-section view of the A-A' section line. This line follows the approximate position of the outcrop –correlation panel (Fig. 6B) on the northern limb of the Baviaans syncline. Towards the west, the pale yellow and dark green areas on both the map and the cross-section represent sand-rich frontal lobe deposits (FA2, FA3 and FA4) and the brown is fringe deposits (FA1), whilst the terminal lobes are represented

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towards the east in yellow and red-brown. On the cross-section, the pale grey is the C-D mudstone and the dark grey is the Upper C mudstone.

Figure 11: (A) 2D strike-oriented seismic reflection section showing the Giza North channel-levee-complex set and the position of the Giza North-1 well with gamma ray and resistivity logs displays. (B) Giza North-1 shale petrophysical log through the Giza Field channel-levee complex set highlighting the late stage stacking patterns within the weakly confined lobes; scale is 0-100%, green for shale, yellow for sandstone, blue for water and red for gas saturation. The conventional core images of the facies associations identified include: i) décollement surface overlain by debrite; ii) amalgamated, dewatered sandstone punctuated by mudstone clast conglomerates; and ii) upper thin-bedded climbing ripple cross-laminated, bioturbated sandstones, and their position is corss-referenced on the shale petrophysical log.

Figure 12: (A) 3D seismic reflectivity horizon slice of the late stage weakly confined constructional fill of the Giza channel complex set (southward view up depositional dip), draping the southerly plunging limb of a 3-way structural anticline. Higher amplitude responses reflect thicker intervals (up to 15m) with higher net: gross (>0.60), based on calibration to the Giza North-1 well. (B) Cartoon visualisation of the Giza Field late stage laterally offsetting elongate lobes. Lobe dimensions are around $2km^2$, which is interpreted to reflect the generation of accommodation by shallow detached slide scars. Frontal lobes are offset stacked and fed by a channel element that propagated through switching to alternate sides of the weakly confined channel complex set. In seismic cross-section the frontal lobes display a profile similar to that of an external levee.